NSW GOVERNMENT | Chief Scientist & Engineer

Independent review into the design, use and impacts of synthetic turf in public open spaces

Final report

13 October 2022

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Final Report

First published: October 2022

NSW GOVERNMENT | Chief Scientist & Engineer

The Hon Anthony Roberts MP
Minister for Planning and Minister for Homes
52 Martin Place
SYDNEY NSW 2000

Dear Minister

In November 2021, the Hon Rob Stokes MP, the (then) Minister for Planning and Public Spaces requested the NSW Chief Scientist & Engineer provide expert advice on the use of synthetic turf in public open spaces in NSW (the Review).

I submit this final report of the Review.

Concurrent with the Review, the Department of Planning and Environment (DPE) has been tasked with developing guidance for councils in relation to synthetic surfaces in public open space. The Review has been structured to assist with that process.

The Review and further guidance developed by DPE build on a 2021 study commissioned by the (now) DPE, which was undertaken by Ethos Urban and titled the Synthetic Turf Study in Public Open Space (the 2021 Report).

During the Review, stakeholders commented on the increasing use of synthetic turf in public and private settings across NSW. The Review found that little is known about the volumes, composition or impacts of the different materials applied. Given these findings, recommendations are made to understand and manage potential environmental and human health risks and improve decision-making.

Scientific, technical and engineering experts were commissioned to support the Review. I would like to thank them for the significant contribution they have made and am pleased to present their final advice in full.

I would like also to acknowledge and thank the many individuals and organisations who were generous with their time and advice and patiently answered our questions.

Yours sincerely

H. Durrant-Whyte

Professor Hugh Durrant-Whyte
Chief Scientist and Engineer

13 October 2022

Executive summary

Synthetic turf has become ubiquitous in both public and private settings, and there is interest in understanding the impacts of materials used in its installation. In November 2021, the Hon. Rob Stokes MP, (then) Minister for Planning and Public Spaces, requested the NSW Chief Scientist & Engineer (CSE) provide expert advice on the use of synthetic turf in public open space in NSW.

Following the Terms of Reference, the Office of the Chief Scientist and Engineer (OCSE) has completed its independent review (the Review). To inform the Review, OCSE has drawn on available data and research, commissioned expert analysis, and undertaken consultation with key stakeholders and experts.

This report presents an overview of key insights and makes recommendations to guide the use of and improve the management of synthetic turf in NSW. Findings and recommendations will inform guidance being developed by the Department of Planning and Environment (DPE) for councils that are proposing new synthetic fields, as well as informing applications and management of synthetic turf in other settings. Detailed findings and the expert advice informing the review are also provided in the appendices of this report.

To address the Terms of Reference, the Review's analysis and insights focussed on four key questions:

- What do we know about synthetic turf materials and their use in NSW?
- What are the trends and initiatives and their applicability to NSW?
- What are the potential health impacts of synthetic turf?
- What are the potential environmental and ecological impacts of synthetic turf?

Key insights

What do we know about synthetic turf materials and their use in NSW?

Precise figures of the number and location of synthetic turf fields installed in NSW are difficult to confirm but it is clear the rate of installation is increasing. It was intended that data on the installation of synthetic turf in a range of public spaces in NSW, including shared recreational spaces managed by councils or in developments as well as playgrounds and parks, would be analysed by the Review. However, this Review primarily draws information from synthetic turf installed in sporting fields as these applications had data available.

A conservative estimate indicates there are currently approximately 181 synthetic turf sports fields in NSW, an increase from approximately 24 in 2014 and 30 in 2018.[1] Replacement of existing natural fields in residential areas with a synthetic field appears associated with the highest level of concern and dissatisfaction for nearby residents.

Many synthetic sports fields in NSW feature long synthetic blades supported by infill, the most commonly used infill is styrene butadiene rubber (SBR) crumb sourced from recycled tyres. SBR crumb is the material most associated with community concerns about contamination. Currently, there is insufficient information and a lack of standards about the materials and chemical composition of synthetic turf.

To aid decision-making, more accessible data regarding the installation, volumes, and composition of synthetic turf in public and private settings across NSW is required. Data on

[1] Detailed in Appendix 2

the composition of fields is particularly important to inform end of life disposal plans, given many of the synthetic fields installed in NSW will reach their end of life over the next decade.

What are the trends and initiatives and their applicability to NSW?

The Review identified policy, as well as scientific and technical initiatives in other jurisdictions to address key knowledge gaps and potential risks. Influential trends and drivers for the use of synthetic turf, new materials and alternatives such as natural turf were identified. Research and its applicability to NSW was examined given differences in material inputs, climate, environmental conditions and use.

Demographics: Increasing population density is driving demand for green space, while constraining availability of open space. Overallocation of existing sport and recreation facilities is a driver increasing the installation of synthetic turf in areas of higher population density. While growth was highest in the Sydney Metropolitan region previously, COVID-19 has seen a shift in demand in some regional areas, potentially requiring updated analysis on facilities that are under-utilised or over capacity. Strategies to manage demand, and to increase sports participation, access to infrastructure and performance development pathways across all levels of play include regional hubs and synthetic turf fields line-marked for multi-purpose use.

Climate and weather: The changing climate will impact the safety, health and wellbeing of citizens and biodiversity, as well as the durability and resilience of built infrastructure and urban ecosystems. The Review was undertaken during a time with periods of high intensity rainfall events and devastating floods in NSW and Queensland, while recovery efforts continued in response to the recent drought and bushfires.

Future extremes of flooding, heat and fire risk will affect the performance of different types of both synthetic and natural turf. There are concerns around the impact of intense rainfall and flood on the durability of synthetic turf surfaces and increased water runoff and pollution impacts. Increased heat effects are also a concern, as synthetic turf lacks the cooling and latent heat loss of natural turf; and high surface temperatures have been recorded from unshaded synthetic turf.

Overall, it is not clear whether expectations about the longevity and carrying capacity of synthetic fields can be met under Australian climatic conditions, potentially influencing decisions about installation and cost-benefit considerations.

Sustainability: Decarbonisation and appropriate end of life solutions are driving change in government policy, regulatory frameworks, and business models globally. Trends in Europe towards restricting the use of intentionally added microplastics, and recent legislation in NSW such as the *Plastic Reduction and Circular Economy Act 2021* ensure responsibility for products across their life cycle and reduce the impacts of waste.

With government and industry involvement, there are ways in which the synthetic turf industry can become more circular. This includes technical and scientific considerations as well as requirements for product information and standards for materials involved. This is particularly relevant to SBR crumb infill, given the lack of import standards for waste tyres, which are known to contain contaminants and heavy metals.

New materials and alternatives: Policy shifts are driving industry research into alternative synthetic turf materials and substitutes for chemicals or compounds of concern. Biopolymers that are recyclable and/or compostable are emerging as an alternative material. Factors driving the increased installation of synthetic turf in NSW are cited to be increased field carrying capacity, reduced water use and greater resilience to wear compared to natural turf fields. Best practice guidelines for improving the performance of natural turf have been developed in NSW. If applied to installation and ongoing management of natural turf sporting fields, these practices may allow increased performance of natural turf fields to meet demand.

What are the potential health impacts of synthetic turf?

Overall, literature reviews and expert advice did not identify major health risks associated with synthetic turf, although there are knowledge gaps, particularly around Australian-specific studies.

The Review and experts examined national and international research as well as anecdotal advice regarding potential for increased risk of physical injuries from synthetic turf. Sports-related injuries such as lower body, head and abrasion injuries may occur on both synthetic and natural turf fields at comparable levels, although some evidence was found that synthetic turf can generate greater stress on players' feet.

Heat-related impacts were identified as a priority area for focus. The interplay of factors influencing thermal comfort is complex. Technologies designed to increase solar reflectivity and low heat absorption in synthetic turf surfaces may have the effect of increasing heat strain due to the exposure of individuals to higher loads of directly reflected solar radiation. Improving water retention or increasing irrigation may increase humidity and worsen human thermal comfort and heat strain. The interaction of environment, user profile and activity level is also complex, with a need to consider low-level activities of more vulnerable populations, including children.

The Review has been advised that health risks through direct (such as dermal, ingestion and inhalation) or indirect contact (such as leachate and microplastic runoff) from synthetic turf is likely to be low. However, restrictive measures to limit potentially harmful chemicals, leachates and microplastics in synthetic turf components may reduce unforeseen consequences to health, such as restrictions enacted by the EU and US.

Aspects of mental health, well-being and social cohesion were identified, and while their nature is very site specific, important considerations for planners and councils are discussed. These include community access and continued use; and consequences of field type and infrastructure, such as odour resulting from synthetic materials and increased artificial light that may be associated with synthetic turf sporting facilities.

What are the potential environmental and ecological impacts of synthetic turf?

Areas of concern regarding environmental and ecological impacts identified by the Review include water contamination and soil health. Research on drainage and stormwater impacts of synthetic turf fields is limited. However, there is evidence that both rubber infill and turf fibre blades from synthetic turf fields are found in waterways in NSW.

Expert advice to the Review estimated that a synthetic turf field without structures to reduce infill loss will wash tens to hundreds of kilograms of infill per year into stormwater systems or waterways. The amount of turf fibres lost from a synthetic turf field is likely to be in the 100s of kilograms per year, with the amount increasing for fields near the end of life or under poor maintenance. International studies have also found a large difference between the amount of microplastics shed from different types of synthetic turf.

Weathering, UV exposure and the association of microbes with plastic material influences leaching of chemicals into the environment. Research under Australian conditions has found mixed contaminants including heavy metals, have higher toxicity and bioavailability than those in isolation.

Changes to habitat resulting from synthetic turf installation replacing grass or vegetation may include habitat loss, disruption of ecological functions, increased heat and increased artificial light at night. Increased light at night is a risk associated with synthetic turf sporting facilities that are installed with lights to increase their playing capacity; and has been recognised to fragment nocturnal habitat and impact biodiversity. Measures to mitigate these impacts are discussed in the Review. The value of strategic planting of vegetation is highlighted as ameliorating habitat loss, heat effects on fauna and light spill and is broadly effective across a range of habitats.

Recommendations

Based on the findings of the review, OCSE developed a set of recommendations to meet the requirements of the Terms of Reference. These recommendations will allow NSW to adopt an accelerated ‘learn and adapt’ approach to the use of synthetic turf under NSW conditions and directing future investments to deliver optimal outcomes for users, and address concerns around human and environmental health. If applied, they will allow NSW to set the scene over the next decade, using new fields as a testbed to contribute to innovation and data-driven decisions.

The recommendations can be grouped into four main categories and are summarised below:

Recommendation Group 1: Planning and approvals

Given longer-term climate and heat projections, attention should be given to mitigating environmental risk in existing and planned synthetic turf installations, implementing best practice natural turf management, advancing materials research into new alternative materials. A set of requirements for approval and funding of synthetic turf fields is needed to assist with the management of identified environmental issues, and the identified data gaps that currently limit decision-making and innovation.

Specific recommendations have been developed to allow NSW to reduce potential human health and environmental impact of synthetic turf through planning, design, and mitigation measures. These focus initially on managing pollutant ‘runoff’ and ‘walk-off’ risks and exploring the potential of best-practice design and maintenance of natural turf fields to meet increasing use requirements.

Recommendation Group 2: Sustainability and end of life

Given the use of synthetic turf in public and private settings is increasing across NSW, a staged plan across government and non-government settings and sectors is required to develop appropriate standards and end of life solutions. A starting point is understanding the volumes, composition and fate of products used. The process should draw on the considerable expertise in mapping systems and material demonstrated by the NSW Government net zero target and circularity policies. The responsibility for sustainability and end of life solutions is greater than a single NSW Government agency or land manager and requires industry engagement.

Consideration of emerging science and new materials is required, as well as alternatives such as natural turf. The adoption of best practice guidelines and benchmarks for natural turf in open spaces will support the capacity of natural turf sporting fields to meet demands for use.

Given the observed risk of deteriorating fields, synthetic turf installation should be subject to a set of requirements to ensure best practice use during the product lifespan and appropriate end of life planning and disposal to avoid stranded assets.

Recommendation Group 3: Data

The scale of public investment in sporting infrastructure requires a more systematic and data-driven approach to decision-making. There is a vast amount of existing information from different sources about the design, management, and performance of sporting fields, but these are not readily available or collated. A more accessible and reliable source of verified information is required. To enable informed investment decisions about surfaces installed in public open space, specific recommendations have been made to allow for the establishment of minimum open data standards for sporting fields, with the aim to broaden data capture to include other applications of synthetic turf across NSW.

This could be integrated with other data sets to support forward planning and investments, test assumptions and, over time, ground-truth observations, support transparency and accelerate innovation.

Recommendation Group 4: Research program

This Review identified significant knowledge gaps in key areas of concern, which hinders effective decision-making. Data collection should be complemented by the research program to address key knowledge gaps in human health and environmental impacts.

A key research priority recognised by several contributing experts to the Review is understanding the characteristics and composition, including the chemical composition, of materials used in synthetic turf and associated layers.

Contents

1. Introduction

1.1. Context and background

1.1.1 What is public open space?

Public open space refers to land that has been set aside from development to accommodate recreation or relief from the built environment. Open space can be used for purposes such as personal and social recreation, sport and physical activity, active transport corridors, waterway and riparian corridors, biodiversity and fauna conservation, and visual and landscape amenity. Such settings include natural areas and linkages, foreshore areas, informal parkland, sports grounds and courts, children's playgrounds, historical sites, formal gardens, and linear walking, cycling, and equestrian tracks.

1.1.2 What is synthetic turf?

Synthetic turf first appeared as 'Astroturf' in the US in 1966 as an easily maintainable surface that could be used all year round in northern hemisphere conditions. The third generation (3G) synthetic turf technology commonly used today has been developed to provide sports participants with more shock-absorption and decrease abrasion risk. Turf blades for fibres are typically made of polypropylene, polyethylene or nylon, held in place by a polyurethane backing. The fibres may be monofilament (solid) or fibrillated (longitudinally perforated). The length of the turf blades ('pile') is typically 40 to 65 mm long, but the pile varies according to the sport or use it is designed for. For example, some hockey fields contain 8-12 mm nylon fibres and can be wet dressed for smoother movement of the ball, while rugby league uses 40-65 mm polyethylene monofilament yarn.

While specific application may vary between sites and different design uses, 3G synthetic turf consists of several layers (summarised in Figure 1), including:

- waterproof liner
- base of gravel sized stones, asphalt or geotextile
- drainage system may be included
- leveling layer such as finer aggregate stone or sand
- shock pad may be included, depending on the design use
- synthetic turf mat or carpet
- infill may be placed between the fibres for stability and/or performance.

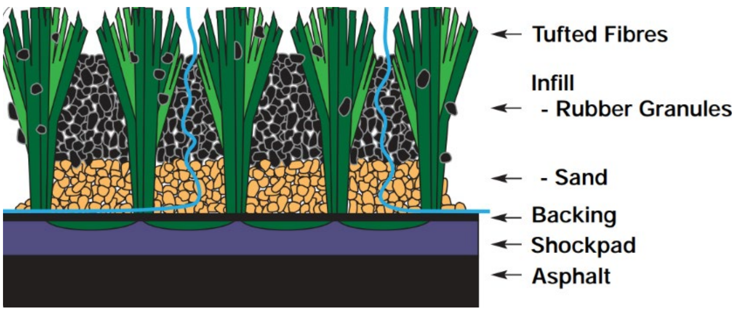

Figure 1: Simplified cross section of 3G synthetic turf
Reproduced from: DCPD (2011)[2]

[2] DPCD. (2011). Artificial grass for sport. Melbourne: Department of Planning and Community Development. https://sport.vic.gov.au/publications-and-resources/community-sport-resources/artificial-grass-sport-guide

Where infill is used, sand is typically placed at the bottom to support the pile. The performance layer is commonly rubber crumb (of various types) but organic options such as cork are also used.

A hybrid turf is a combination of synthetic and natural turf in a single product. This includes (1) where a backing similar to those used in synthetic turf reinforces natural turf growing from the mat, (2) where natural turf is grown within a base of synthetic turf fibres and also (3) where synthetic turf is used in areas of more wear such as at the goal mouth of otherwise natural turf fields. While hybrid surfaces are used in NSW, they do not feature predominantly and unless specifically indicated in the Review, should be read as part of synthetic turf.

Fourth generation synthetic turf has evolved from the 3G, with performance characteristics tailored for specific sports but also with the aim to remove the need for rubber crumb infill (Appendix 5). More information regarding synthetic turf types, materials and use is detailed in Appendix 3, 4, 5 (see Table 1 and 2) and 7.

1.1.3 Background

The Synthetic Turf Study in Public Open Space Report[3] (2021) commissioned by the (now) Department of Planning and Environment (DPE) made the following recommendations:

- undertake further research into the potential human health and environmental impacts of the use of synthetic turf.
- develop guidance to assist councils who are proposing new synthetic fields. DPE is preparing these guidelines concurrent with this Review.

As a result of the first of these recommendations, the NSW Chief Scientist & Engineer was requested to provide expert advice on the use of synthetic turf in public open spaces in NSW (this Review).

The initial Report was released in February 2022.[4]

1.2. Review Terms of Reference

The Chief Scientist & Engineer will conduct an independent review and provide expert advice on potential risks to the environment and human health from the use of synthetic turf in public open space in NSW and alternative approaches and technologies.

In undertaking the review, the Chief Scientist & Engineer (CSE) through the Waratah Network and noting areas of expressed public concern will:

1. Identify, describe and provide advice on:
    a. key scientific and technical issues associated with the use of synthetic turf compared with grass surfaces in public spaces
    b. available data, including:
        - data on the installation of synthetic turf in public spaces in NSW, including location, scale, type, composition, age and installation methods.
        - performance data, including intended purpose (activities), rates of use, maintenance requirements, lifespan and replacement schedules
        - experiential data from the use of synthetic turf in NSW and other Australian and select international jurisdictions, including data on environmental and human health impacts

[3] https://www.planning.nsw.gov.au/Policy-and-Legislation/Open-space-and-parklands/Synthetic-Turf-Study
[4] See Independent review into the design, use and impacts of synthetic turf in pubic open spaces: Progress report. https://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0010/496450/CSE-Synthetic-Turf-Review_Progress-report-2022.pdf

- comparative data on synthetic and grass surfaces in NSW, including current and projected scale of installation; examples of mixed installation of grass and synthetic surfaces; any trends of note.

c. knowledge gaps, including initiatives in other jurisdictions to address these.
d. applicability to NSW of scientific studies and experiential data from other Australian and international jurisdictions.

2. Provide advice on:
   a. potential air and water pollution impacts associated with use of different materials in construction and installation of synthetic turf (e.g. synthetic fibres, cork infill, rubber crumb infill).
   b. potential health impacts of synthetic turf in public open spaces and sports fields including:
      - on immediate users, including the rate of use of open spaces; exposure to chemicals, heat impacts and the rate and type of injuries
      - on proximate residential areas, including but not confined to potential impacts on temperature
      - relevance of geographic and/or spatial factors, including differences relating to urban and regional locations, areas under development etc.
   c. potential environmental and ecological impacts of synthetic turf compared to natural turf including but not limited to water runoff and local impacts, urban heat island effect, use in bushfire-prone areas, changes to fauna habitat and wildlife corridors and light pollution.
   d. technical and scientific considerations associated with the use of synthetic turf.

3. Provide advice on:
   a. emerging science and new materials that could be used in conjunction with or as an alternate to existing natural and synthetic surfaces (including identifying new components and potential prototypes, and advances in materials and biological sciences)
   b. best management practices in the design, installation, maintenance, disposal and recycling of synthetic turf
   c. scientific and technical factors for consideration by local government and other organisations when considering natural and synthetic surfaces.

4. Develop a research program including:
   a. a description of in-field, laboratory and other studies that will help address key knowledge gaps in the short, medium and longer term and priorities for future data collections.
   b. commissioning tests of existing materials under different conditions such as heat, humidity, increased water flow and UV exposure to understand impacts, including substances released into the natural environment.

5. As needed, the Chief Scientist & Engineer may:
   a. seek advice from relevant Government agencies and other organisations
   b. consult with key stakeholders on technical and scientific matters
   c. draw on additional sources of advice and expertise or engage experts as needed
   d. commission or recommend studies.

6. The Chief Scientist and Engineer will:
   a. provide an initial report by 7 February 2022
   b. provide a final report by mid-2022.

1.3. Review approach

1.3.1. Initial activities

The Review began with an initial review of literature related to the potential health and environmental impacts of synthetic turf surfaces. Urban Ethos provided the review terms and sources of information utilised in the 2021 Study.

A consultation process had been undertaken as part of the 2021 Study. The Review therefore focused on targeted requests for advice focusing on scientific and technical questions relevant to the Review. A webpage and dedicated email address were established to enable interested stakeholders to submit information relevant to the Review Terms of Reference. Members of the community provided the Review with a range of studies and links to information resources.

A request was made to NSW Deputy Vice-Chancellors (Research) for information about experts that might support specific components of the Terms of Reference. The Review wrote formally to NSW government agencies to request advice on scientific studies and issues as well as policy and regulatory frameworks. A working group of NSW Government agencies with scientific expertise and/or relevant policy remit was established during early 2022 to provide initial advice on technical issues and regulatory frameworks and to develop a core set of search terms across topic areas. This included invited representatives from:

- NSW Department of Planning and Environment (DPE)
- NSW Department of Primary Industries (DPI)
- NSW Environmental Protection Authority (EPA)
- NSW Health
- NSW Office of Energy and Climate Change (OECC)
- NSW Office of Sport (OOS)
- Resilience NSW

1.3.2. Expert Roundtables

The Review team invited experts from the research sector and government agencies to three thematic roundtables to identify key knowledge gaps, inform activities to be undertaken to address information needs and identify longer term strategies best suited to fill knowledge gaps. Topics included:

- Research Roundtable 1 -Thermal considerations of different surfaces and water runoff
- Research Roundtable 2 - Air quality and bushfires considerations of different surfaces
- Research Roundtable 3 - Soil and environmental health considerations of different surfaces

Roundtables were structured to refine and prioritise critical issues, data and research approaches, identify factors or variables to be considered in study design and understand research strengths and expertise. Feedback from the roundtables was used to determine targeted literature searches and helped shape the Review contents.

1.3.3. Structure

The body of this Review highlights the main issues and findings from analysis relevant to the Terms of Reference, based on research, observations, expert advice and stakeholder meetings. Chapters 1-5 summarise background information and some key findings from expert advice and from roundtables and stakeholder meetings. Information is then bought together in Chapters 6-9 (Recommendation Groups). The findings and discussion may overlap between areas of advice as the topics are inter-related and benefit from cross-disciplinary perspective and knowledge sharing.

The Terms of Reference (TOR) are addressed in the following sections of this Review:

- TOR 1a and 1b on key scientific and technical uses and data on synthetic turf in public spaces in NSW were addressed in Chapter 2.
- TOR 1c and 1d on knowledge gaps and applicability of studies from other jurisdictions in NSW were addressed in Chapter 3
- TOR 2.b and 2.d on potential health impacts of turf use were addressed in Chapter 4 with more detail in Appendices.
- TOR 2.a, 2.c and 2.d on potential water, environmental and ecological impacts of turf use were addressed in Chapter 5 with more detail in Appendices.
- TOR 3 on emerging science, practices and factors considered for planning were addressed throughout the sections, especially in Chapter 2 and in Recommendations Chapters (Chapters 6-9)
- TOR 4 on research program development were addressed in Chapter 9 on Recommendation Group 4 and detailed through the Appendices.
- TOR 5 on the Review process were addressed through roundtables and consultations with NSW government agencies, local government, academia and industry representatives, and sport associations.

Expert advice was sought and commissioned by the Review on areas including materials science, chemistry, odorants, biodiversity, hydrology, air quality, bushfires, environmental health, human health, sustainability frameworks, risk and study design. Experts were asked to consider available literature, application of available evidence to the Australian context, knowledge gaps and mitigating actions to address identified issues. The commissioned advice appears in full in the Appendices, complete reading of each is recommended in order to understand the topics covered and to see the full reference list (all relevant references are not necessarily replicated in the body of this Review).

The advice sought was informed by feedback from stakeholder consultations and observations from site visits. A more detailed outline of engagement is set out at Appendix 1.

This Review builds on and does not seek to replicate the work of previous reports.[5] It presents insights and solutions that science, engineering, technology and data can bring to the use of synthetic turf as set out in the Terms of Reference.

[5] See, for example, Department of Sport and Recreation WA Government. (2011). *Natural Grass vs Synthetic Turf Study Report.* https://www.dlgsc.wa.gov.au/department/publications/publication/natural-grass-vs-synthetic-turf-study-report. Department of Planning and Community Development VIC Government. (2011). Artificial Grass for Sport. https://sport.vic.gov.au/__data/assets/pdf_file/0025/55591/download.pdf

List of acronyms used in the Review

3G: Third generation synthetic turf fields

4G: Fourth generation synthetic turf fields

ACCC: Australian Competition and Consumer Commission

AIHW: Australian Institute of Health and Welfare

ALAN: Artificial lights at night

ANZECC: Australian and New Zealand Environment and Conservation Council

ARC: Australian Research Council

ARFA: Australian Resilient Flooring Association

BAL: Bushfire Attack Level

CAP: Conservation Action Plan

CHF: Critical heat flux

CRC: Cooperative Research Centres

CSE: Chief Scientist & Engineer (NSW)

DPE: Department of Planning and Environment

DPI: Department of Primary Industries

ECHA: European Chemical Agency

EOL: End of life

EPA: Environmental Protection Authority

EP&A: Environmental Planning and Assessment

EPDM: Ethylene propylene diene monomer

EPL: Environmental Protection License

EPR: Extended Producer Responsibility

EU: European Union

EUH: Equivalent use hours

GHG: Greenhouse gasses

IDMF: Infrastructure Data Management Framework

IUCN: International Union for the Conservation of Nature

LAN: Light at night

LCA: Life Cycle Assessment

LEP: Local Environment Plan

LGA: Local Government Association

LGNSW: Local Government NSW

MECLA: Materials and Embodied Carbon Leadership Alliance

MRSA: Methicillin-resistant *Staphylococcus aureus*

MRT: Mean Radiant Temperature

NARCliM: NSW climate projections using NSW and ACT Regional Climate Modelling

NSIDA: National Sports Injury Data Strategy

NSSN: NSW Smart Sensing Network

OCSE: Office of the Chief Scientist & Engineer (NSW)

OECC: Office of Energy and Climate Change

OOS: Office of Sport

OTR: Off-the-road

PAH: Polycyclic aromatic hydrocarbon

PFAS: Per- and poly-fluoroalkyl substances

PFOA: Perfluorooctanoic acid

PFOS: Perfluorooctane sulfonate

PIC: Place-based Infrastructure Compact

POEO: Protection of the Environment Operations

REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals

REF: Review of Environmental Factors

SA1: Statistical Area Level 1

SBR: Styrene butadiene rubber

SEED: Sharing and Enabling Environmental Data

SISA: Strategic Infrastructure and Services Assessment

SSO: State sporting organisations

SVOC: Semivolatile Organic Compound

TAG: Technical Advisory Group

TOR: Terms of reference

TPE: Thermoplastic elastomers

TSA: Tyre Stewardship Australia

UHI: Urban heat island

UV: Ultraviolet

VOC: Volatile Organic Compound

2. Synthetic turf materials and their use in NSW

Terms of Reference 1.1 and 1.2 seek to identify and provide advice on the available data related to installation, use and performance of synthetic turf in NSW. This Chapter focuses on data collected for sporting fields in NSW and advises data collection methods to address the gap as described below:

- number and location of both synthetic and natural sporting fields for comparison (Section 2.1)
- type, volume of materials used and potentially lost from synthetic sporting fields (Section 2.2)
- parameters to capture field performance and use (Section 2.3).

Detail on location and approximate size of fields and major data sets and portals to support planning and decision-making is in Appendix 2.

Links to papers: Appendix 2, Appendix 5, Appendix 11.

2.1 Number and location of fields in NSW

Precise figures of the number and rate of increase of synthetic turf fields installed in NSW are difficult to confirm. Previous reports indicate that there were approximately 24 synthetic turf sports fields in 2014, and 30 in 2018. Currently there are approximately 181 synthetic turf sports fields in NSW.[6] This figure represents approximately 3.7 percent of all major sports fields and approximately 2 percent of total field surface area. This may be a conservative measure based on advice from major sporting codes and since not all sports (e.g. lawn bowls) are included.

Comparative data on current sports fields with natural turf and synthetic turf surfaces in NSW is summarised in Table 1, Figure 2 and Figure 3a and b. The Sydney Metropolitan region contains the most synthetic sporting fields, with density of fields generally decreasing with distance from Sydney. The Far West region records no synthetic sporting fields and the lowest density of natural turf fields.

The Review is aware of new installations planned, and this current number will be exceeded relatively quickly should approvals be granted. Therefore, while still small proportionally, the rate of installation is increasing. There are also indications that the use of synthetic turf in applications other than sporting fields and in private residential and business sectors is increasing.

The review drew on analysis and manual cleaning of data collected by the Office of Sport to identify the number and location of fields. Numbers have been updated through consultation with various councils and with input from relevant sporting associations. Note, there may be variation in total figures supplied by sporting associations through potential double-counting of fields. A more detailed breakdown of the location and approximate area of synthetic turf fields, and natural turf fields for reference is shown in Table 2 in Appendix 2.

The Review contacted a working group of over 30 NSW councils established by DPE that expressed interest in providing advice on developing guidance for the use of synthetic turf. Councils were followed up individually to obtain further information, including information about maintenance records, lifespan and replacement of fields. Exploration of a method to identify synthetic turf sporting fields through spatial data analysis using 10 m resolution imagery is described in Appendix 2.2.

[6] Details of this approximation are given in Appendix 2

Table 1: Summary of the number of fields and approximate of area synthetic turf compared to natural turf grass in regions of NSW
See Table 2 in Appendix 2 for more detail

Region	Natural Turf:		Synthetic Turf:	
	Number of playing fields	Approximate area (m²)	Number of playing fields	Approximate area (m²)
Sydney Metropolitan	2,501	27,431,594	103	756,400
Hunter	471	6,577,297	24	69,196
Central West and Orana	172	3,375,555	11	55,297
North Coast	451	5,146,767	10	50,270
Illawarra Shoalhaven	301	3,617,343	8	44,442
Central Coast	132	1,719,498	7	15,304
New England and North West	125	2,240,091	7	35,189
South East and Tablelands	139	2,387,503	6	30,162
Riverina Murray	285	4,681,168	5	25,135
Far West	92	1,344,336	0	0
Grand Total	**4,669**	**58,521,152**	**181**	**1,081,395**

The number, location and type of synthetic sporting fields was not readily available at the outset of the Review. There is no single dataset containing spatially referenced information about surface type or where synthetic turf has been installed. Several databases and spatial layers in NSW store information about zoning, council planning, urbanisation, green space, soils, and vegetation cover. There is an increasing number of planning documents, reports and analysis relating to synthetic turf and alternative surfaces in public open space from state agencies, councils, sporting and stakeholder. However, this information is not easily collated.

A complicating factor in identifying fields was consistency in categorisation and avoidance of double counting. For example, a single sports field may be used to play multiple sports and have a variety of line marking. The Office of Sport categorises each field by the sport with the largest field marking played on that field. Other sports activities played are listed separately. In cleaning the data, efforts have been made to count each field once only, regardless of the number of different sports played and to check these numbers with the relevant sporting associations. As sporting associations may report fields slightly differently, numbers are displayed for both NSW Office of Sport and those provided by sporting associations (Appendix 2.1, Table 1).

The analysis in this section only includes public outdoor sporting areas that are accessible to the broader community in some form, even if this might require payment or affords only limited access. Counting rules were established for consistency:

- Facilities on school grounds are not included, although it is recognised that some allow access to the wider community.
- Sporting areas in universities and those that only allow restricted access to the public and are owned by clubs or associations are included.
- Some outdoor sports facilities with synthetic turf surfaces are not listed due to insufficient information or difficulty distinguishing between synthetic turf and other synthetic surfaces in the datasets. These include miniature golf, lawn bowls/ pétanque/ boule, playgrounds and leisure areas, shooting ranges, tennis, netball, volleyball, horse/harness racing and other horse-riding arenas.

Examples of publicly available sport facility data in other jurisdictions include Victoria[7] and Tasmania.[8] To aid planning in NSW, data collated by the Office of Sport and verified by sporting associations and clubs should be made available in a way that is consistent with the spatial data approaches of the DPE Green and Resilient Places and Greater Cities Commission and can be used in conjunction with Land Zoning (Principle Planning and Environmental Planning Instruments) and the Existing Green Assets spatial layers. Minimum data requirements to strengthen the current sporting field data set are set out in Recommendation Group 3.

[7] VIC Department of Jobs, Precincts and Regions. (2020). Sport and Recreational Facilities list. https://discover.data.vic.gov.au/dataset/sport-and-recreational-facilities-list

[8] TAS Department of Primary Industries, Parks, Water and Environment. (2022). Tasmania Sport & Recreation Facility Locations – 2015. https://data.aurin.org.au/dataset/tas-govt-dpipwe-tas-sport-recreation-2015-na

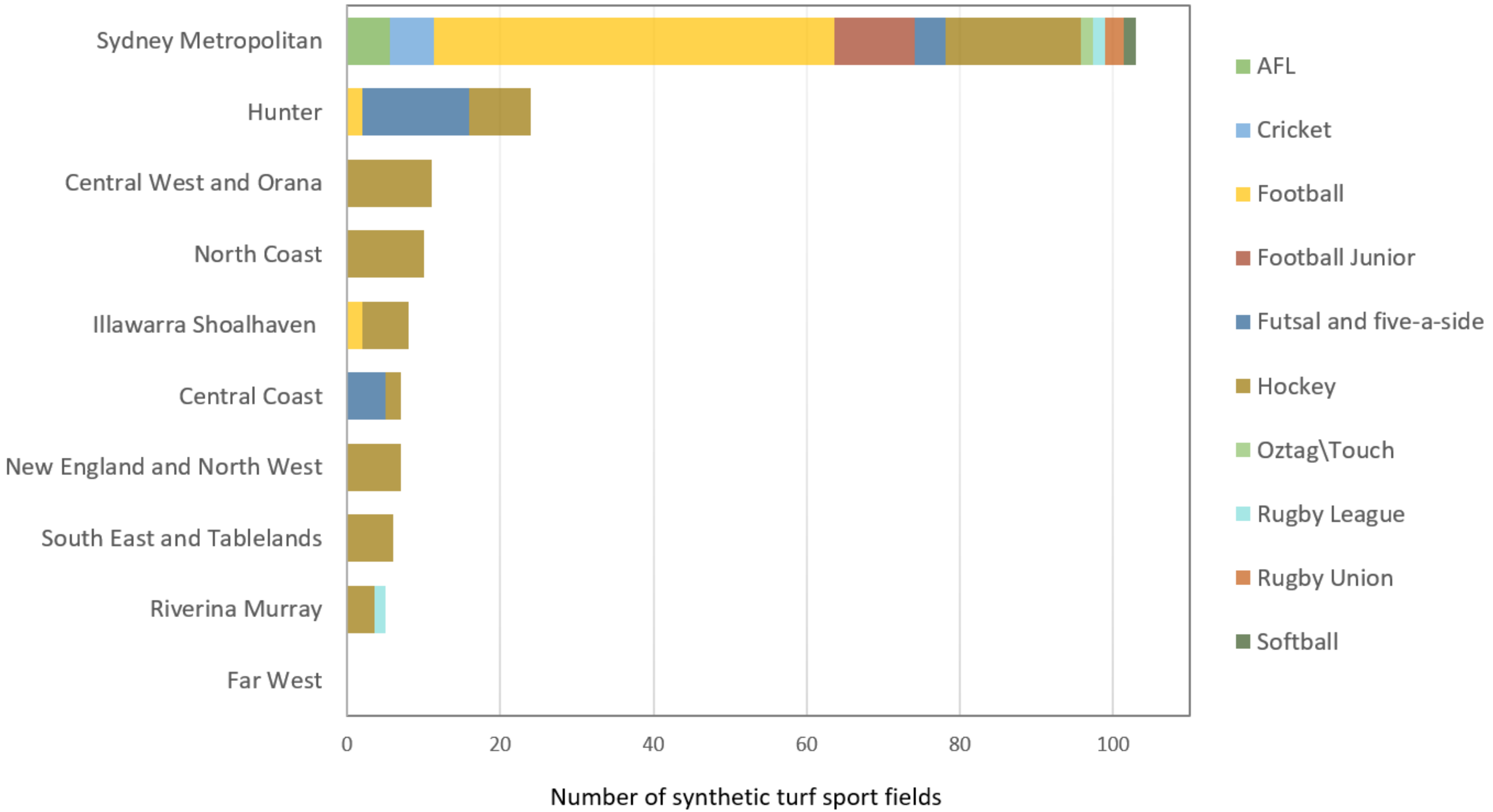

Figure 2: Summary of the number of synthetic turf fields in regions of NSW
Colour legend shows proportions of synthetic turf fields in a region that are used for particular sports. Numbers as reported by the NSW Office of Sport in a collated dataset for all sport in NSW, with efforts made to avoid double-counting of fields and to record all formal sports use. Numbers have been updated through consultation with various councils and with input from relevant sporting associations. Note there may be variation in total figures supplied by sporting associations through double-counting of figures, see Table 2 in Appendix 2.1 for more detail

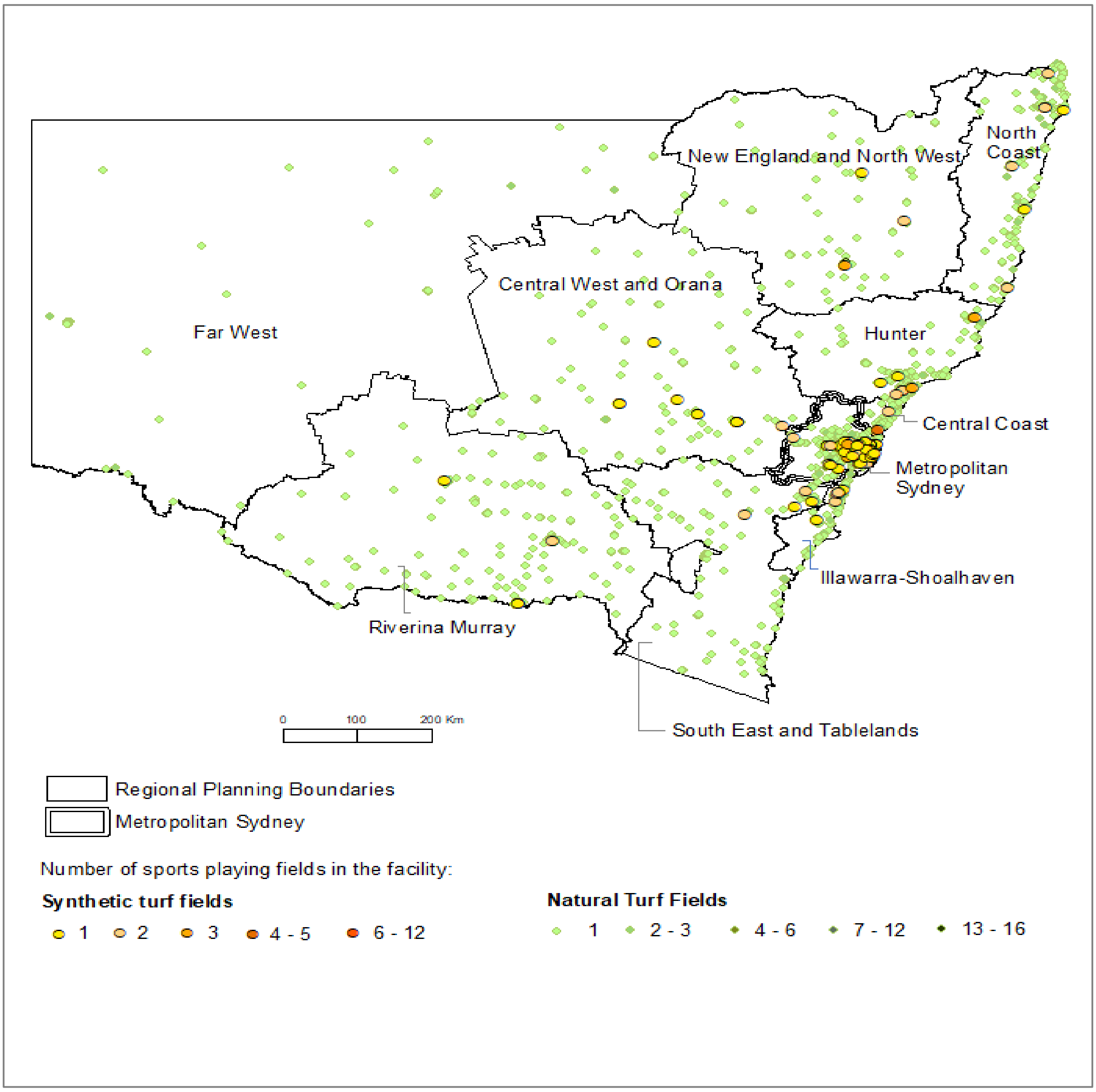

Figure 3a: Locations of synthetic and natural turf surface playing fields in the regions of NSW

Data source: NSW Office of Sport, updated through consultation with various councils and with input from relevant sporting associations

Notes: Where there is more than one playing area at a facility this is indicated by darker colours. Boundaries within NSW show the regional planning areas. These figures only include fields as listed in Table 1, cricket pitches and baseball batting cages are not included

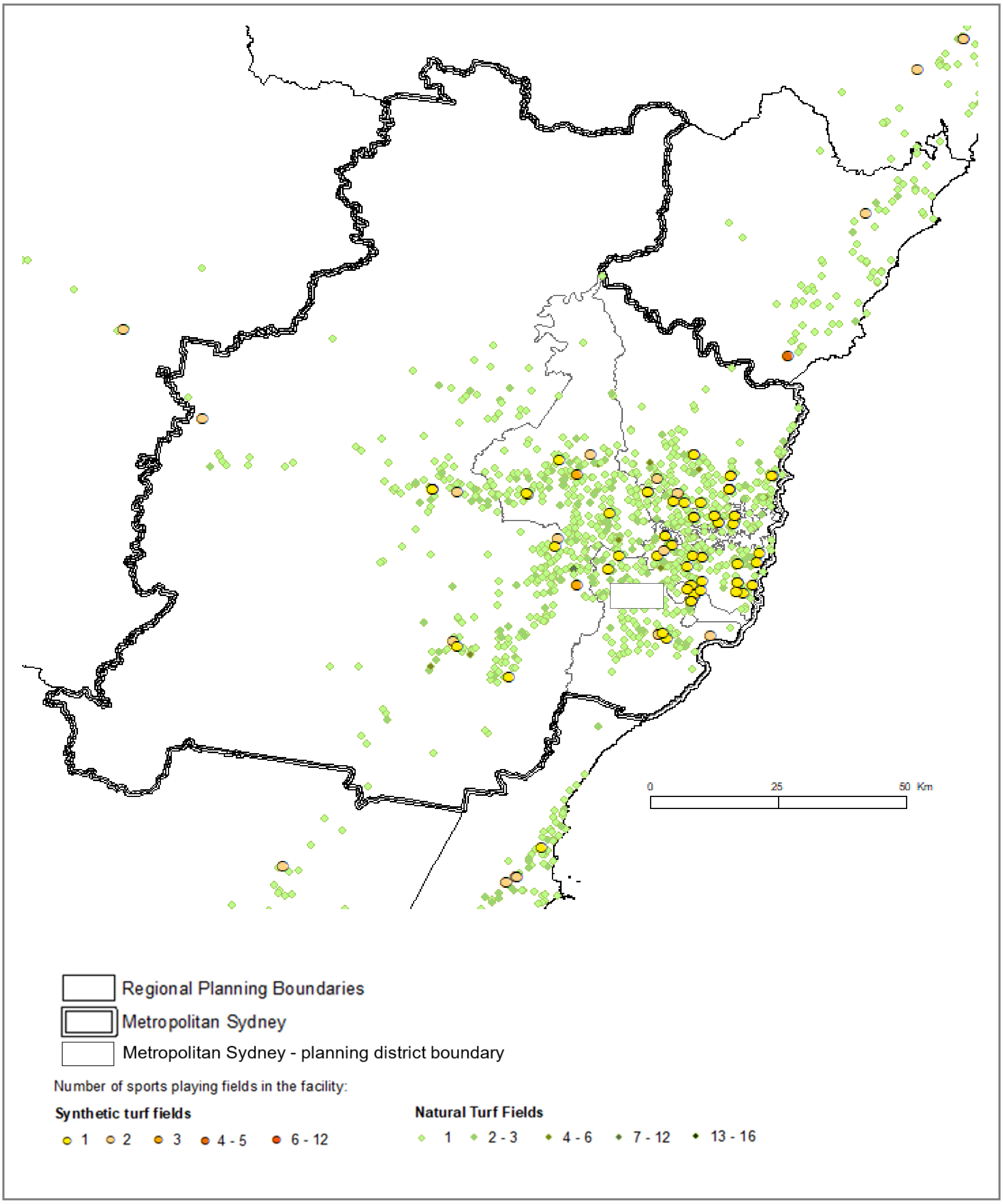

Figure 3b: Locations of synthetic and natural turf surface playing fields in Metropolitan Sydney regional planning area, which has the greatest number of synthetic turf playing fields
Data source: NSW Office of Sport, updated through consultation with various councils and with input from relevant sporting associations
Notes: Where there is more than one playing area at a facility this is indicated by darker colours. Boundaries within NSW show the regional planning areas. These figures only include fields as listed in Table 1, cricket pitches and baseball batting cages are not included

2.1.1 Other applications of synthetic turf

Beyond sporting fields, the location, volume and composition of synthetic turf installed in public spaces in NSW is not known. Feedback indicates increasing applications in recreation or high traffic areas, public schools, playgrounds and small parks. Some stakeholders consulted during the Review commented on the increasing uptake in the private residential and business sectors.

2.2 The volume and type of materials

Given there is currently no comprehensive data on the number of synthetic turf fields in NSW, it is difficult to determine the associated volume of materials used and lost. However, the Review sought to use available information to understand the main types of synthetic turf use and estimate volumes. Estimation of volumes used and lost encompasses understanding how often a synthetic field requires replacement of the whole turf or sections, the amount of material lost from a field towards EOL or requiring replacement as the synthetic turf blades break down and begin to shed, and how regularly and how much infill material is used to 'top-up' fields as a maintenance activity or replace infill lost after heavy rains.

To aid this process, Jazbec and Florin (Appendix 5) were commissioned to provide advice on the characteristics and chemical composition of materials used in synthetic turf fields. This includes a breakdown of rubber and plastics by polymer type and estimates of the main materials used by sporting code field type. The volume will be influenced by a range of factors including the type of surface, infill, use, climatic conditions, how well it is installed and maintained, and the maintenance methods used.

Based on the number of fields in NSW, input volumes were calculated for each sport and material type (including types of polymer, rubber, sand and organic matter). By proportion, sand was found to account for half of all input materials, SBR (styrene butadiene rubber) 18 percent, with polyurethane and polyethylene accounting for ten and ~seven percent respectively (Jazbec and Florin, Appendix 5).

Information was requested from service companies and councils on actual materials and infill replacement volumes. Data obtained during the Review from councils on the types and volumes of synthetic turf and layers used is shown in Table 2. One maintenance company informed the Review that on average, a field with SBR infill will require approximately 25 additional tonnes of infill over the life of the field, while fields with cork infill will require an additional 100 tonnes over the life of the field.[9] Many of the fields detailed in Table 2 and already installed in NSW will reach their end of life (EOL) over the next decade and will require replacement.

Table 2: Types and volumes of synthetic turf and infill used for a portion of synthetic turf fields in NSW
Source: NSW councils in response to a request for advice from the Review
Data from 21 fields out of 181 known synthetic sports fields in NSW

Turf type and area	Infill type and volume	Base layer and other systems
AFL		
Area approx. 15,000 m^2	Cork	Drainage, tree root barriers

[9] Styrene-butadiene rubber crumb is mostly recycled from vehicle tyres. SBR is made up of 75 percent styrene and 25 percent butadiene joined in a co-polymer)

3G turf, Fieldturf 70 mm. Area approx. 16,000 m^2; replaced natural turf	SBR crumb and sand; grooming every two to four weeks redistributes infill	No shock pad; drainage system with retention tank and splash-back on perimeter fencing to reduce runoff; stormwater pits with filter
3G turf, Tuff Turf 50mm. Area approx. 22,400 m^2	SBR crumb and sand	
Football		
3G turf. Area approx. 7,884 m^2; replaced natural turf	SBR crumb and precoated silicate sand	Drainage cell and prefabricated shockpad
Ligaturf HB250; 6,800 m^2; replaced natural turf	SBR crumb and sand; groomed fortnightly with approximately quarterly deep clean; infill topped up where needed	
3G turf, Vmax50. Area approx. 22,000 m^2	SBR crumb and sand	Trocellen ProGame XC 5010 shockpad. 300 mm triple wash sand filtration layer; layers of aggregates and a geocomposite membrane on-top of subgrade
3G turf. Area > 7,480 m^2	SBR crumb	
Area approx. 8,360 m^2	Infill Pro SBR crumb	
Ligaturf Hybrid 50 mm synthetic turf. Area approx. 7,820 m^2; replaced natural turf	SBR crumb and kiln dried sand; groomed fortnightly redistributes infill	30 mm Nero drainage cell; irrigation and controlled drainage system
60 mm Liga Turf Hybrid synthetic grass. Area approx. 7,884 m^2; replaced natural turf	SBR crumb, 101,605 kg on installation, additional 30,481 kg within five years of install	Pro Play 23 mm shock pad
3G turf, Polytan 50mm. Area approx. 9,500 m^2; replaced 10 year old synthetic turf	Cork infill and sand	Shock pad
3G turf, Polytan 50 mm; Area approx. 8,250 m^2; replaced natural turf	SBR crumb and sand	
3G turf; maintained monthly but at end of life at 10 years old and in poor condition, grass blades breaking off and infill rising to surface. Area approx. 7,884 m^2	SBR crumb	
Hockey		
Water based synthetic turf. Multiple fields, area approx. 6,209 m^2; replaced natural turf	No infill	Compacted stabilised road base, bituminous layer, rubber shock pad
Hybrid synthetic turf; Carpet and shock pad replaced at least once since original construction due to age and wear of carpet. Multiple fields, area approx. 11,267 m^2; new fields when installed with synthetic turf	No infill	Compacted stabilised road base, bituminous layer, rubber shock pad
Hybrid turf, not used as a water base; was replaced after 17 years as quality of the first hybrid turf had begun to deteriorate due to wear and age. Area approx. 6,100 m^2; originally installed on public open space		
Synthetic turf; has been replaced twice, both times seven years after installation as surface had begun to deteriorate due to wear and age. Area approx. 5c,529 m^2; originally installed on public open space	Sand	

Water based synthetic turf	No infill	Compacted granular pavement and a Tensar grid on top of subgrade; stormwater runoff captured in retention tank for irrigation
Rugby League		
Eclipse Stabilised Turf Hybrid, using AgriDark natural couch grass with synthetic fibres tufted into an open weave backing; Liga Turf synthetic perimeter. Area approx. 12,000 m^2; replaced natural turf		Vacuum-ventilation drainage and aeration system and stormwater network; Butyl rubber liner; 150mm drainage gravel layer and 260mm sand profile blended with 5% coir fibre. automated irrigation system with IQ Control
3G turf, Ligaturf. Area approx. 3,840 m^2; new field		
Rugby Union		
Area approx. 7,875 m^2; replaced natural turf	SBR crumb, additional 520 kg bags infill added annually to high wear areas over 5 years	
3G turf	Cork	

2.2.1 Estimating the volume of material lost

Data on the volume of additional infill should not be used to directly infer amount lost to the field as compaction will also influence the amount of additional infill required. Various calculations have been undertaken to estimate the potential loss of infill and plastic from synthetic turf blades from fields in northern Europe. Research in Sweden estimated the amount of microplastic runoff by calculating the extent of different synthetic sport and recreation surfaces, and the amount of microplastics shed into washing water from a standard sample from different synthetic turf fields. Interestingly, some types of synthetic turf shed significantly more (~50 times more) fibres than others.[10] Another project calculated the input of microplastics from synthetic turf into marine environments.[11] Potential pathways for loss include compaction, residues on maintenance machinery, player 'walk-off' and loss to soil and water. Microplastics lost through snow removal is an important consideration in Europe.

Eunomia and ICF calculated that from 51,616 pitches in Europe with an installed area of 112 million square metres and using infill density of 16.1 kg/m^2, the total infill estimated to be installed in Europe was 1.8 million tonnes. The total microplastic pollution generated from infill loss through waste disposal, surface drains, internal drains and into surrounding soil and grass was calculated between 18,000 tonnes and 72,000 tonnes per year.[12]

Glamore et al. (Appendix 4) summarises results from studies in Northern Europe that measured and estimated microplastic loss of synthetic turf blade fibres and rubber crumb:

- Accounting for compaction, studies estimate loss of hundreds of kilograms of rubber crumb infill loss per year.
- Using measurements from Sharma et al. (2016) and Hann et al. (2018) and assuming a five percent loss rate results in an estimated loss of turf fibres of 320 to

[10] Olshammar M., Graae L., Robijn A., Nilsson., F. (2021) Microplastic from cast rubber granulate and granulate-free artificial grass surfaces Report 7021. The Swedish Environmental Protection Agency. https://www.diva-portal.org/smash/get/diva2:1663995/FULLTEXT01.pdf

[11] Magnusson, K., et al. (2016). Swedish sources and pathways for microplastics to the marine environment. https://www.ivl.se/english/ivl/publications/publications/swedish-sources-and-pathways-for-microplastics-to-the-marine-environment.html

[12] Eunomia Research & Consulting and ICF. (2018). Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/microplastics_final_report_v5_full.pdf

560 kg/year. Using a higher estimate of loss from Lassen et al. (2015) of five to ten percent loss rate equates to a loss of 500 to 900 kg/year.

- Hann et al. (2018) report an estimated loss of 64 to 40 kg/year. However this relates to fibre tips only, not loss of entire fibres which has been observed to occur.[13]

Based on the above, Glamore et al. (Appendix 4) conclude that:

"In the absence of Australian specific data, it can be reasonably estimated that around 10 to 100 kg of infill per year is likely to be transported to the stormwater system or waterways for a synthetic turf field with no strategies to reduce infill migration in place. However, there are currently no exact estimates of crumb infill transport into water networks. The amount of turf fibres lost from a [synthetic turf] ST field per year is likely to be in the 100s of kilograms per year, however this type of loss from ST field is far less studied, and no estimates of transport into water networks currently exists. Due to the lower density of the turf fibres and hence higher mobility, they may pose a greater pollution risk for aquatic environments than infill."

2.3 Field performance and use

Increasing or anticipated demand for use of particular sport field facilities has been identified as a driver in the rate of synthetic sport field installations in NSW. Synthetic turf has been quoted to provide higher playing capacity compared to natural turf and to allow play to continue with fewer cancellations resulting from the impact of extreme weather such as intense rainfall and drought.

In order to understand the performance or capacity of individual synthetic or natural turf sporting fields, accurate information on the extent and the type of current use is required.

Detailed information on the level of maintenance is also necessary. All turf surfaces, both natural and synthetic, require regular and high-quality maintenance to maximise performance, carrying capacity, safety of users and longevity. Maintenance reports sighted by the Review contained useful information, however these are not collated or readily available. Feedback to the Review also indicates there can be tension in making sports fields available for regular maintenance due to use demands, requiring managers to balance field performance and use with maintenance demands.

For organised sport, acceptable levels of field performance are defined largely by international sporting code accreditation and standards, which span from professional to community level participation. There are an array of factors affecting field performance that would need to be considered if comparing fields and the relative performance of turf types. These include climate and weather, field configuration and size, surface type, soil type/health/quality, maintenance regimes such as additives pest and weed control, renovation frequency, site management participant numbers and profiles, type of use (e.g. sporting code), hours of use and intensity of use.[14]

The question of how to accurately and appropriately calculate hours of use and sporting field carrying capacity were raised consistently by stakeholders during the Review, particularly local government.[15]

Currently, field closures due to weather conditions are communicated through local government websites and by sporting associations. However, information about closures of

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[13] References per Glamore et al Appendix 4, Section 4.3

[14] McAuliffe, K. and Roche, M.B. (2009). Best use modelling for sustainable Australia sports field surfaces.

[15] Carrying capacity of a natural turf sport field, typically expressed in hours per week, refers to the amount of wear that the sport field can sustain before significant damage to the turf occurs. McAuliffe, K. and Roche, M.B. (2009). *Best use modelling for sustainable Australia sports field surfaces*.

synthetic or natural fields due to weather (both wet and heat) are not collated. Therefore, ability to draw analysis between field performance, surface and reduced hours of use due to rainfall or heat conditions is limited.

Booking hours (the number of hours a field is booked for) have frequently been used to assess field capacity. The approach is both simple and feasible. However, this appears a poor proxy for calculating actual use hours. A 2021 report highlighted the deficiencies of using this approach in isolation.[16] Using data provided by 24 councils across NSW, the study found 'blanket booking' (reserving fields for longer times than played use) occurs frequently. The reasons are understandable - real usage hours are limited by timeslots around life commitments (sleep, work and school), set up, winter daylight hours and weather. Importantly, the study found fields with a similar number of booked hours showed variation in wear levels.

Participant numbers also appear problematic for field comparison purposes. Issues include accounting for variability associated with player size and intensity of training and play. For example, the impact of participant 'head counts' doesn't capture the differential between 10-15 adult players versus the same number of ten-year-olds. Sporting fields are often 'halved' or quartered' for use, effectively doubling or quadrupling the number but not necessarily the impact of those on the field. Even if captured, these figures need to be reconciled with other influencing factors outlined above.

Considerable effort has been made to calculate effective hours of use, although the details of the analysis or calculation are not always publicly available. Methods include using a 'sports ground usage index' (calculated in metres square per person hour per week) combined with modelled weightings to account for some of the other factors cited above.[17] Another includes a foot traffic calculator to enable comparisons of wear and use between natural and synthetic fields.[18]

2.3.1 Technological solutions to data collection on use

Penrith Council in Western Sydney has installed a system to collect data on the use of a sporting field. Combining sensors, data analytics and machine learning, the system monitors and reports on cumulative player hours, use hours, maintenance hours and equivalent use hours (EUH). EUH is calculated by the number of hours the field has operated at the capacity it was designed for. Alert reports are available, including the number of days maintenance was overdue. Also, trend data on field activity (day, month) and heat maps on use (including by field quarter). Personal privacy is stated to be managed by real time analysis of anonymised data with the video discarded. It is understood that outside Australia the technology has been applied to both natural and synthetic fields.

Machine learning can inform the relative performance of fields, sensors and apps can facilitate capture and uploads of real time data. In time this data can inform on user experience and best-practice constructed and maintained fields. To obtain broader insights on the potential and relative sophistication of available technology to understand better intensity and actual use of fields, advice was sought from the NSW Smart Sensing Network (NSSN, Appendix 11).

The NSSN reviewed available and emerging sensing, software, hardware and analytical requirements and challenges. Specific advice requested included the ability of different technologies to avoid 'double counting', to distinguish characteristics such as player size

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[16] Battam, M. (2022). Winter usage, wear and carrying capacity of sporting fields in the Sydney Basin.
[17] IPOS Total Turf Management. (2020). *Sports Ground Usage and Capacity Model.* https://ipos.net.au/our-services/sports-ground-usagecapacity/ and Fact Sheet. (2018). https://ipos.net.au/wp-content/uploads/2019/05/UsageCapacity_Fact_Sheet_Final_190506.pdf
[18] AgEnviro Solutions. Carrying Capacity and Wear Level Assessment for Sports Fields. https://agenviro.com/services/capacity-assessment/

and capture intensity of play. Advice was also requested on issues such as distinguishing players from on-field observers. The latter was included given feedback from councils on the potential impact of large spectator crowds on surface condition at the edge of open fields.

Some councils reported cost as a limiting take-up of the technology. Therefore, in addition to technological feasibility, information was sought on the costs of different options that might encourage more wide-spread capture of real time data on player numbers and impact. Advice included ‘out of the box’, modifications to off the shelf products and DIY/designed systems. For the purposes of the Review, commercial information has not been included, but is available from the NSSN on request. Appendix 11 details advice and options, including a proposed pilot.

Findings and insights:

- While there is a large amount of data and information already collected, there is lack of collated and accessible data about synthetic turf used in open space in NSW in terms of location, types of material, volumes of material added and lost, performance and use.
- Real-time data collection for maintenance and use data, and reporting of user experience will be important additions to the knowledge-base.
- Data can inform utilisation of existing fields, expected lifespan, planning and potential environmental impacts of the fields.
- Technological solutions can be employed for more accurate data collection.

3. Trends and initiatives and their applicability to NSW

Terms of Reference 1.3 and 1.4 seek to identify knowledge gaps and data trends including environmental and human health that impact the use of synthetic turf and the applicability of data and studies from other jurisdictions in NSW.

This Chapter discusses the data and notes any trends or initiatives that may impact the use of synthetic turf surfaces, including:

- change in population and demographics (Section 3.1)
- environment and extreme weather events (Section 3.2)
- sustainability frameworks and end of life consideration (Section 3.3)
- material innovation and best practice guidelines (Section 3.4).

Much of the research this Review draws-on is from Europe and North America due to the earlier and substantially larger use of synthetic turf on these continents. Estimated numbers of synthetic turf sporting fields are 52,000 in the European Union (EU) and 16,000 in North America.[19] The extent to which NSW (and Australia) can confidently draw on and apply findings about the use of synthetic turf from independent research undertaken overseas and other jurisdictions is discussed in this Chapter.

Links to papers: Appendix 4, Appendix 5, Appendix 6, Appendix 10, Appendix 18.

3.1 Demographics

Increasing population density is driving demand for greenspace, while constraining availability of open space. While women in organised sport remain under-represented, increasing levels of participation of women in sport is driving demand for access to training, game time and facilities.[20] Regional Sport and Recreation Plans have been developed to provide a planned approach to increased participation, access to infrastructure and performance development pathways across all levels of play.[21] Sporting codes and local councils report the need to accommodate both organised, non-formal sport as well as recreational use, particularly influenced by COVID-19.[22]

DPE population projections show:

- *"NSW is expected to grow on average by over 85,000 people each year until 2041.*
- *Based on recent trends regional NSW's population will increase by 570,000 to 3.7 million in 2041.*

[19] The European Synthetic Turf industry reports (2020) there are 52,000 fields in the EU, the majority football. https://www.sdab.se/media/1610/oecd-21-01-22.pdf. Synthetic Turf Council (2022) estimates 16,000 fields in North America https://www.wgbh.org/news/local-news/2022/05/10/more-games-or-more-grass-fields-turf-wars-play-out-across-massachusetts

[20] Eime et al. (2021). Five-Year Changes in Community-Level Sport Participation, and the Role of Gender Strategies. https://www.frontiersin.org/articles/10.3389/fspor.2021.710666/full; Office of Sport (23 August 2022) Media Release. Upgrades to sports grounds deliver female friendly facilities. https://www.sport.nsw.gov.au/media-releases/upgrades-to-sports-grounds-deliver-female-friendly-facilities

[21] NSW Office of Sport. NSW Regional Sport and Active Recreation Plans 2018-2023. https://www.sport.nsw.gov.au/regional-delivery/regional-sport-and-active-recreation-plans

[22] AusPlay data (2021 compared with 2019), in Australian Sports Commission (July 2022) How Australians' participation in sport and physical activity is adapting to COVID-normal. https://www.clearinghouseforsport.gov.au/__data/assets/pdf_file/0010/1060399/Ausplay-COVID-update-July-2022.pdf; NSWRL. (August 2022). https://www.nswrl.com.au/news/2021/08/12/female-participants-flocking-to-play-game-in-nsw/; Northern NSW Football. (April 2021). https://northernnswfootball.com.au/female-football-exceeds-expectations-across-northern-nsw/

- *Greater Sydney's population will grow to approximately 6.1 million by 2041 - over a million more people than currently live in the region."[23]*

An increasing population will increase demand for public open space, including greenspaces and sporting facilities able to support high numbers of participants. Prior to COVID-19, population growth has been a driver for the installation of synthetic turf in Greater Sydney. COVID-19 impacted on the CBD and specific regional areas, driving regional population growth. In 2020-21, growth in regional areas overtook capital city growth (Figure 4). With regional NSW increasing from 0.8 the previous year to 1.0 per cent, and Sydney (-0.1 per cent) recording the first year of negative population growth since 1952-53. Regional NSW also experienced positive net overseas migration in 2020-21, likely driven by returning residents. The Hunter Valley recorded particularly high growth in 2020-21 (2.1 per cent).[24]

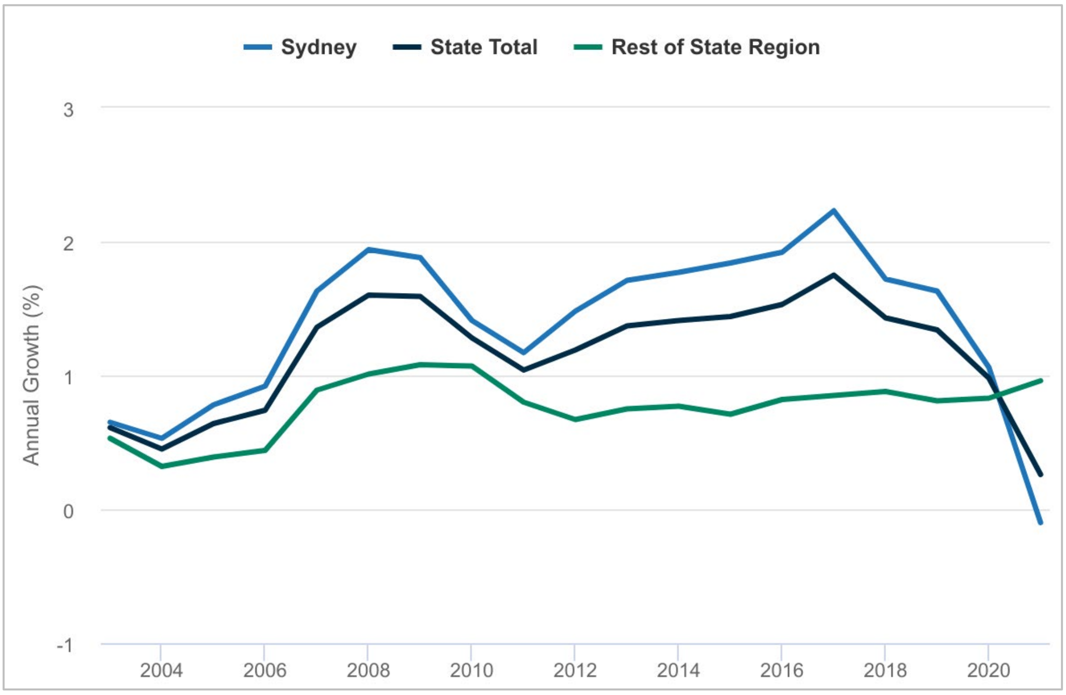

Figure 4: Population growth rate (per cent) in Sydney, regional NSW and NSW total from 2002-03 to 2020-21
Reproduced from: Australian Government, Centre for Population, Regional Population 2020-21[25]

> **Finding and insight**: Over allocation of existing sport and recreation facilities has been identified as a driver increasing the installation of synthetic turf in areas of higher population density. This has been the case in the Sydney Metropolitan region. However, during COVID-19, population increases in some regional areas may see a shift in this demand, potentially requiring updated analysis on facilities that are under-utilised or over capacity.

[23] NSW Department of Planning and Environment. Population projections. https://www.planning.nsw.gov.au/Research-and-Demography/Population-projections
[24] Australian Government, Centre for Population. (2022). Regional Population 2020-21. https://population.gov.au/data-and-forecasts/key-data-releases/regional-population-2020-21
[25] https://population.gov.au/data-and-forecasts/key-data-releases/regional-population-2020-21

3.2 Climate and weather: Extreme flooding, heat and bushfire hazards

NSW climate projections using NSW and ACT Regional Climate Modelling (NARCliM) suggest higher temperatures, increased number of hot days, fewer colder nights, changes in seasonal patterns of rainfall, and more extreme rainfall and storm events with lingering dry spells in-between. Severe fire weather and the length of bushfire season is projected to increase.[26]

The changing climate will impact the safety, health and wellbeing of citizens and biodiversity, as well as the durability and resilience of built infrastructure and urban ecosystems.[27] The Review was undertaken at a time of La Niña climate drivers, with periods of high intensity rainfall events and devastating floods in NSW and Queensland.[28] While recovery and response efforts to the 2017-2020 drought and 2019-20 bushfires continue.[29]

While La Niña is typically associated with cooler daytime temperatures south of the tropics, 2021 was reported as warmer than any previous La Niña year, reflecting a long-term warming trend.[30] La Niña conditions have been confirmed for spring 2022, bringing continued rain into already-saturated surfaces. In recent decades there has been a reduction in cool season rainfall in Southern Australia, and a general trend towards a greater proportion of rainfall from high intensity short duration rainfall events.[31]

This section addresses components of Term of Reference 2c regarding the potential impacts of the use of synthetic turf compared to natural turf in extreme events, including bushfire-prone areas. It draws on reviews undertaken by the Water Research Laboratory UNSW Sydney and the Australian Research Council (ARC) Training Centre for Fire Retardant Materials and Safety Technologies, UNSW Sydney.

3.2.1 Flooding

Many sports fields are located on marginal land, with a relatively high risk of flooding. Flooding can occur as overland flow, with water moving at speed through slower floodplain inundation. The risk of infill and pollutant runoff from synthetic fields and mitigation strategies is discussed in Section 2.2 and Chapter 5.

Major flooding events can substantially damage infrastructure through deposition of sediment and debris, a risk for both natural and synthetic fields. In May 2022, the NSW Government announced a $55M Sport Infrastructure Recovery Fund to support flood effected communities.[32] The Review notes Recommendation 20 of the NSW Flood Inquiry recommends that the value of floodplain lands be utilised, including productive and lower-

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[26] Adapt NSW. (2022). Interactive climate change projections map. https://www.climatechange.environment.nsw.gov.au/projections-map
[27] The Commonwealth of Australia. (2021). Australian State of environment Report. https://soe.dcceew.gov.au/urban/pressures/climate-change
[28] BOM, Bureau of Meteorology. (2020). *Climate Drivers in the Pacific, Indian and Southern oceans and the Tropics, Shift towards La Niña continues*
[29] The Australian Disaster Resilience Hub reports there were more than 11,400 bush and grass fires across NSW, with fires burning 6.2 per cent of the state, resulting in 26 lives lost and 2,448 homes destroyed. https://knowledge.aidr.org.au/resources/black-summer-bushfires-nsw-2019-20/. ABARE (2021) estimates the NVP of national loss to be $63B, with $53B attributable to drought and $10B from bushfires, excluding valuation of losses from human lives lost, flora, fauna or forestry destruction. The advice concludes that "in the longer term, adaptation and policy responses will need to reflect the expectation of increased frequency of adverse climatic events". https://onlinelibrary.wiley.com/doi/abs/10.1111/1467-8489.12441
[30] BOM, Bureau of Meteorology. (2022). Climate Driver Update. http://www.bom.gov.au/climate/enso/
[31] BOM, State of the Climate. (2020). http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml
[32] NSW Office of Sport. (2022). $55 million to help sports to recover from floods.https://www.sport.nsw.gov.au/media-releases/55-million-to-help-sports-recover-from-floods

risk uses that minimise risk to life during major weather events, such as sporting and recreational activities.[33]

Such an approach would be consistent with established approaches to using retention basins for natural turf sporting fields.[34] Some natural turf fields located in flood prone areas were designed to assist water flow or act as a buffer between urbanised areas and natural bushland. While suitable for a permeable grass surface, synthetic turf surfaces in these locations may have adverse environmental impacts.

Damage to drainage pores in synthetic fields as a result of flooding events may necessitate partial or entire replacement. Aside from runoff, extreme flooding events have moved and lifted entire synthetic turf fields, as observed in the February-March 2022 rainfall events.[35]

Finding and insight: Given the risks and associated costs, sporting bodies, some experts and many councils consulted during the Review recommend against siting synthetic fields in locations with a higher likelihood of flooding.

3.2.2 Heat

The effect of intense ultraviolet (UV) conditions in Australia may accelerate the degradation of turf fibres beyond expected averages (Glamore et al., Appendix 4). It is not clear whether expectations about the longevity and carrying capacity of synthetic fields can be met under Australian climatic conditions, including environmental factors such as UV radiation and heat. Sixty hours per week or more of play is quoted as a synthetic turf industry standard but attracts a lower warranty period (seven years) compared with ten years at 40 hours of use. Advances in materials science combined with data on relative performance, and better management of natural turf fields can help address this and manage increasing participation demand.

The high surface temperatures recorded from synthetic turf can worsen due to material ageing and compaction of surface and infill materials. Some materials, such as the commonly-used SBR crumb infill are associated with producing higher heat. Use of cork and similar materials are expected to provide a cooler surface and are biodegradable but are more expensive and their performance and longevity is yet to be established. Studies indicate other synthetic turf variables that affect surface temperature include blade length and the depth and thickness of infill.

Industry-based research is being undertaken into improved UV performance under Australian conditions. Advances in materials science combined with data on relative performance, and better management of natural turf fields can help address this and manage increasing participation demand.

Comparison of the performance of natural and synthetic turf

Lacking natural moisture and irrigation, synthetic turf lacks the cooling and latent heat loss of natural turf. Unshaded synthetic turf is known to reach very high surface temperatures in hot summer climates. High surface temperatures and low human thermal comfort can also be experienced on days with moderate air temperatures (below 30 °C).

[33] 2022 NSW Flood Inquiry Volume Two: Full Report. https://www.nsw.gov.au/sites/default/files/noindex/2022-08/VOLUME_TWO_Full%20report.pdf
[34] See for example, Naturally Resilient Communities Floodwater Detention and Retention Basins. https://nrcsolutions.org/floodwater-detention/
[35] This included loss of cork infill

Findings and insights:

- It is not clear whether expectations about the longevity and carrying capacity of synthetic fields can be met under Australian climatic conditions, potentially influencing decisions about installation and cost-benefit considerations.
- The surface temperature and thermal impact of synthetic turf can worsen due to material ageing and compacting and the use of SBR crumb infill.

3.2.3 Bushfires

The Final Report of the of the NSW Bushfire Inquiry noted that:

"Fires will not be of the scale and type seen in the 2019-20 season every year. However, a repeat of fires of that scale, or worse, is a realistic prospect. Indeed, we should expect to see serious fires more frequently." (Final Report p.79)

The risk of ember attacks challenged the safety of sports ovals as designated Safer Places:

"There are already designated bush fire Neighbourhood Safer Places, which include open spaces (e.g. sports ovals). However, as some fires were characterised by significant spotting and ember attacks it was unsafe for people to be in the open, and they instead needed a closed shelter… There is a need to ensure remote bush fire-prone areas have an indoor Neighbourhood Safer Place, so people can take shelter when open spaces are too dangerous due to fire conditions." (Final Report p.146) [36]

Yeoh and Wang (Appendix 10) provided advice on bushfire behaviours, the combustion and ignition profile of polymeric materials, current testing standards, strategies to address the fire performance of synthetic turf and its use in bushfire areas. Their focus was on third generation infilled sports fields, and in particular, the structures above the shock-pad.

Potential bushfire risks on synthetic turf

As with other infrastructure, synthetic turf may be subject to an approaching bushfire via three forms of attack: radiant attack, ember attack and direct flame contact. The main cause of house loss in bushfires is due to ember attack. Glowing embers commonly blown in front of an advancing bushfire have a temperature of around 700−800^{0}C and burning leaves above 1000^{0}C.

Polymers used in synthetic turf have a low melting point (~100-170^{0}C). Heating degrades the polymers, with ignition occurring from around 330^{0}C, comparable to dead dry grass. The polymers used in synthetic turf can therefore be ignited in bushfire settings. The materials may cause additional risks due to toxic gasses and noxious emissions being released.

Critical heat flux (CHF) is used to define the lowest energy a fire requires to keep burning and is expressed in kW/m^2. Studies of synthetic turf products found those tested had a CHF of below 3 kW/m^2, well below bushfire rating standards (25-40 kW/m^2), and therefore, are classified as easily flammable.

Strategy to reduce bushfire risks from material perspective

From a fire safety perspective, sand represents an important ingredient in the synthetic turf system. Comparing the fire safety performance of backing alone, backing plus pile and

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[36] Final Report of the NSW Bushfire Inquiry (2020) https://www.dpc.nsw.gov.au/assets/dpc-nsw-gov-au/publications/NSW-Bushfire-Inquiry-1630/Final-Report-of-the-NSW-Bushfire-Inquiry.pdf

backing plus pile and sand, the latter reduces heat release rates significantly of ~ 50 kW/m^2 compared with the performance of the first two (225 kW/m^2 and 275 kW/m^2).

A common infill material is SBR (styrene butadiene rubber) crumb sourced from recycled tyres. Alternate infill materials include: natural materials such as cork, ethylene propylene diene monomer (EPDM), a synthetic manufactured rubber and TPE or thermoplastic elastomers (copolymers or a mix of polymers such as a plastic and a rubber with thermoplastic and elastomeric properties). Although more expensive, these materials experience lower peak heat release rates compared with SBR, with a comparative reduction in flammability as much as 60 percent. Tree derived cork can self-extinguish more quickly than either EPDM and TPE and is biodegradable and was therefore deemed the preferred infill material from a fire-safety perspective.

Conventional flame retardant fillers used to improve fire properties were also reviewed. This included a comparison of performance limitations and management strategies. Limitations of note include a propensity to leech over time and reduced effectiveness associated with exposure to UV light, temperature and humidity. For example, polymer degradation associated with photo-oxidation and other processes can reduce polymer lifespan by as much as 40 percent.

Yeoh and Wang conclude conventional fillers combined with binders such as zinc oxide, nano clay and glass fibre may improve fire retardant performance as well as introducing hydrophobicity to protect wood-based and wood-plastic composites infills. They propose this be tested further.

Fire testing standards

In terms of standards, identified gaps are a lack of common international ignition or fire testing standard for outdoor applications of synthetic turf and appropriate testing methods for the scale of sports fields in bushfire wind and temperature conditions. Commonly used tests (designed for building materials) include AS/NZS2111.18:1997, AS/ISO 9239-1:2003 and international equivalents (e.g. UK EN 13238:2001, Germany DIN 4102). These are conducted absent wind impact or with relevant temperatures, with floor coverings exposed to a radiative intensity of 11 kW/m^2 compared with 12.5−40 kW/m^2 found in bushfires. Yeoh and Wang recommend cone calorimetry is adopted as an appropriate industry testing standard.

Comparison of the performance of natural and synthetic turf under bushfire conditions

Currently there is no direct study that compares the performance of natural and synthetic turf performance under bushfire conditions. GHD and CSIRO were engaged by Hort Innovation (2020) to undertake literature review on the flammability of natural turf and perform combustibility experiments for typical natural turf species.[37]

Natural turf could serve as an Asset Protection Zone (APZ), as a fuel reduced area that it is not easily ignitable by bushfire when maintained in in a short green condition. The high moisture content can prevent ignition from ember attack and delay the ignition from radiant heat exposure until all moisture is removed.

The combustibility of natural turf species was determined using point ignition tests at various fuel moisture contents and wind speeds. The bulk density of the turf, leaf blade length and moisture content were found to be the major factors that influenced the combustibility of the turf. It was recommended that keeping well-maintained grass that is mown regularly, well-irrigated and free of combustible debris such as dead lawn clippings

[37] Horticulture Innovation Australia Limited. (2020). Living turf fire benefits study – Literature review. Plucinski, M.P. (2020). The combustibility of turf lawns. CSIRO Land and Water Client Report No. EP201008, Canberra, Australia. Hort Innovation is a grower-owned not-for-profit research and development corporation for Australian horticulture.

and leaf litter can serve as a buffer zone around property and infrastructure in bushfire-prone areas. However, the degree of fire risk that can be withstood is unclear.

Future study assessing the performance of natural and synthetic turf under different radiant heat or bushfire attack level (BAL) can inform decisions about which type of turf surface is suitable for certain conditions.

Findings and insights:

- Synthetic turf products that have been tested are classified as easily flammable.
- Materials used in other layers and infill vary significantly in flammability. Sand reduces heat release rates while SBR exhibits higher peak heat release rates and flammability.
- There are no relevant ignition or fire testing standards for outdoor applications of synthetic turf experiencing bushfire wind and temperature conditions.

3.3 Sustainability

Climate change, decarbonisation and circularity considerations are driving change in government policy, regulatory frameworks and business models globally. Terms of Reference 3b requests advice on best management practices in the design, installation, maintenance, disposal and recycling of synthetic turf. This section describes the regulatory framework in Australia and international developments, approaches and tools that could be applied, both in relation to synthetic turf sporting fields and applications in other sectors.

Jazbec and Florin (Appendix 5) and Abbas et al (Appendix 6) were commissioned to provide advice on the composition of materials used in synthetic turf fields, relevant standards and sustainability tools that might be applied. A detailed outline of the characteristics and chemical composition of materials is provided in these appendices.

3.3.1 Global trends

In Europe and United States the larger scale of synthetic fields[38] is expected to drive momentum for the design and production of more environmentally sensitive materials. While earlier focus was on playability considerations for athletes, increasing attention has been given to microplastics and chemicals of concern, particularly those contained in SBR crumb. Technological and alternate materials being trialled and implemented include use of plant-based infills and development of biopolymers.

The trend towards more sustainable materials is also evident in policy direction.[39] The Dutch Government has announced an intention to phase out all crumb rubber infill by 2030. At the request of the European Commission, in 2019 ECHA proposed a restriction on intentionally added microplastics in products to avoid or reduce their release into the environment.[40]

[38] The European Synthetic Turf industry reports (2020) there are 52,000 fields in the EU, the majority football. https://www.sdab.se/media/1610/oecd-21-01-22.pdf. Synthetic Turf Council (2022) estimates 16,000 fields in North America https://www.wgbh.org/news/local-news/2022/05/10/more-games-or-more-grass-fields-turf-wars-play-out-across-massachusetts

[39] Zuccaro, P., Thompson, D.C., De Boer, J., Watterson, A., Wang, Q., Tang, S., Shi, X., Llompart, M., Ratola, N. and Vasiliou, V., (2022). Artificial Turf and Crumb Rubber Infill: An International Policy Review Concerning the Current State of Regulations. Environmental Challenges, p.100620. https://doi.org/10.1016/j.envc.2022.100620

[40] European Chemicals Agency. Consideration is also being given to reduce release of unintentionally formed microplastics in the aquatic environment https://echa.europa.eu/hot-topics/microplastics

The EU legislation Registration, Evaluation, Authorisation and Restriction of Chemicals, (REACH) aims to improve the protection of human health and the environment by making provisions on certain hazardous substances, mixtures and articles placed on the market. Restrictions in the EU under REACH were applied to the top layer of synthetic turf products placed on the market, this was amended to clarify that this includes situations where the products were installed general public has access (irrespective of public or private ownership). New restrictions under REACH mean that from late 2022, restrictions on the eight polycyclic aromatic hydrocarbons (PAHs) listed in the carcinogenic category also apply to granules or mulches used as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications. The sum of the eight PAHs will be limited to 20 mg/kg (2021/1199 of 20 July 2021 amending Annex XVII to Regulation (EC) No 1907/2006) PAHs, Regulation 2021/1199).[41]

The EU has established the Product Environmental Footprint to measure environmental performance, with pilots underway and synthetic turf manufactures contributing to the program.[42,43] Customary lead times to give effect to compliance with new EU standards and directives range from four to ten years.

3.3.2 Australian regulatory and policy frameworks

The Australian *Recycling and Waste Reduction Act 2020* (the Act) provides a national framework to manage the environmental health and safety of products across their lifecycle. Under the Act and associated rules, from the end of 2021 limits on export of waste tyres including processed SBR from Australian took effect.[44]

Product stewardship vests responsibility in whoever designs, produces, sells, or uses a product for minimising its environmental impact, including end of life management. Extended Producer Responsibility (EPR) schemes are a form of product stewardship but vest primary responsibility 'upstream' in product producers and importers. This may include requirements to fund EPR activities. The Act provides for voluntary, co-regulatory and mandatory product stewardship arrangements. Under the Act the Minister is required to publish an annual list of classes of products identified as priorities for possible accreditation or regulation.[45]

Product Stewardship and EPR are strategies to give effect to circular economy principles to design out waste and achieve environmentally sustainable management of resources by keeping products and materials in use for as long as possible (e.g. through reuse, repurposing or recycling) and to regenerate natural systems.

Relevant product stewardship schemes in Australia include the Tyre Product Stewardship Scheme, a voluntary Australian Competition and Consumer Commission (ACCC) authorised, industry framework to reduce the impacts of tyres that have reached end of

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[41] ECHA. (2006). Regulation (EC) No 1907/2006. EUR-Lex - 32006R1907 - EN - EUR-Lex (europa.eu); ECHA. (2018). Guideline on the scope of restriction entry 50 Annex XVII to REACH: https://echa.europa.eu/documents/10162/106086/guideline_entry_50_pahs_en.pdf/f12ac8e7-51b3-5cd3-b3a4-57bfc2405d04; and ECHA. (2021). Commission Regulation (EU) 2021/1199. EUR-Lex - 32021R1199 - EN - EUR-Lex (europa.eu)

[42] European Commission (2012). Product Environmental Footprint (PEF) Guide. https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

[43] European Commission Environmental Footprint Pilots; and transition phase. https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm; https://ec.europa.eu/environment/eussd/smgp/ef_transition.htm

[44] *Waste Reduction (Export – Waste Tyres) Rules 2021.* Details at https://www.dcceew.gov.au/environment/protection/waste/exports/tyres#:~:text=From%201%20December%202021%2C%20you,use%20as%20tyre%20derived%20fuel

[45] Minister's Priority List https://haveyoursay.agriculture.gov.au/ministers-product-stewardship-priority-list-nominations

life.[46] The Review was advised that truck tyres are used for the crumb in synthetic turf[47], there is a high turn-over of truck tyres on the road with an estimated lifespan of 1.5 years.[48]

While Australia has design rules, no tyres have been manufactured in Australia since 2010. Even though all tyres are imported, Australia does not have import standards, and the composition of materials in imported tyres is unknown. Uncertainty about domestic tyre composition has contributed to the decision of some councils to import SBR crumb. SBR crumb contains PAHs and heavy metals amongst other contaminants.[49] Owing to EU regulations under REACH, the highly aromatic oils have largely been replaced, which may not be the case for tyres imported to Australia. Carbon black, however, is still used and contributes to the PAHs in tyre rubber.

The Scheme is administered by Tyre Stewardship Australia (TSA), which is funded via a levy on tyre importers (25 cents per passenger tyre). The work of TSA focuses on accrediting recyclers, funding research activities and identifying suitable applications. A current TSA focus is chemical and physical testing of a selection of tyres to understand the chemical make-up of tyres and any contaminants of concern.

The Australian Resilient Flooring Association (ARFA)[50] is investigating an industry stewardship scheme for vinyl flooring waste through ResiLoop, a government funded project to develop a business case and proof of concept for resilient floor coverings. While not directly applicable, this could provide a good model for synthetic turf materials.

NSW frameworks

The *NSW Plastic Reduction and Circular Economy Act 2021* makes provision for managing regulated products. Objectives (s3) include protection of human and environmental health, to promote and support the circular economy, ensure responsibility for products across their life cycle and reduce the impacts of waste. Part 2 (s8) provides for development of design standards and Part 3 product stewardship requirements and targets.

The NSW Waste and Sustainable Materials Strategy 2041 includes targets to phase out problematic and unnecessary plastics by 2025 and ten-year targets to reduce waste and increase recovery, including increasing diversion rates of waste from landfill. [51] It is estimated that while 55 percent of emissions can be addressed by transition to renewables, the remaining 45 percent will come from how land is managed and the production and management of products and food. Circular strategies will therefore have an important contribution to make towards NSW Net Zero Targets.[52]

3.3.3 Circular economy tools

Circular economy frameworks set out an approach for sustainable practices across a product supply chain. Reviewing potential circular strategies Abbas et al. (Appendix 6) identified approaches that may prove most suitable for the synthetic turf industry. An image of a potential circular systems model is reproduced in Figure 5. Examples of circular approaches to synthetic turf include:

- design: eliminating adhesives, problematic chemicals and complex polymer blends
- material sourcing and substitution: utilising recycled/waste material such as biomass from other sectors
- manufacture: use of renewables in production

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[46] Tyre Stewardship Australia. https://www.tyrestewardship.org.au/
[47] Review consultation with TSA 4 August 2022
[48] Schandl et al. (2020) in Jazbec and Florin (Appendix 5)
[49] These originate from the highly aromatic oils that are added as extender oils and from the carbon black which is added as a reinforcement filler during the production (Appendix 5)
[50] Australian Resilient Flooring Association (ARFA) https://www.arfa.org.au/
[51] NSW Waste and Sustainable Materials Strategy. https://www.dpie.nsw.gov.au/__data/assets/pdf_file/0006/385683/NSW-Waste-and-Sustainable-Materials-Strategy-2041.pdf
[52] NSW Net Zero Plan Stage 1: 2020-2030. https://www.environment.nsw.gov.au/topics/climate-change/net-zero-plan

- disposal: extended producer responsibility, incentivised recycling
- recycling and recovery: material passport mechanisms may prove useful, particularly given differences in global regulatory requirements. Material passports could include the properties of the material across the supply chain. Establishing the provenance of materials and their flows is important where there is a risk of introducing contaminated materials or potentially hazardous and/or toxic chemicals into the recycling stream.[53] Certifications could be used to account for the maintenance as well as construction of fields
- distribution and sales: selecting suppliers with strong service after sales is also identified to improve the longevity of the product's lifespan, as well as adopting an infill-free system and improving shock-pad design to mitigate the need for replacement.

3.3.4 Recycling methods for synthetic turf

Recycling methods used in Europe are predominantly separation and mechanical recycling (Abbas et al., Appendix 6), alongside other approaches internationally including disposal to landfill or incineration (Jazbec and Florin, Appendix 5). Media reports from North America also include stockpiling on the side of fields or dumping.[54] Use of biological enzymes and chemical recycling is under development through a consortium in Spain, although this is still at the research stage.[55]

In NSW, incineration is not an option for the synthetic turf carpet although tyre crumb is an approved eligible fuel in cement kilns. Existing guidance by the Environment Protection Authority is disposal to landfill.

Disposal will become a pressing issue in NSW in the coming decade as existing synthetic fields reach end of life. Councils reported challenges in finding suitable end of life strategies. Proposed approaches cited included cutting up carpets and distributing pieces to other users and shipping to an overseas recycling facility. Having observed aged and disintegrating fields, the practice of cutting up and 'redistributing' end of life fields is not supported by this Review.

Shipment overseas was cited as less expensive than disposal to landfill, although the environmental gain is limited due to the weight of material as the shipment would only be accepted with inclusion of the sand, currently in global demand and short supply.

There is not much information available about suitability or methods to recycle hybrid turf. The Review has been advised that recycling hybrid turf may be more complex in applications where natural turf is combined with synthetic materials, either by attachment to a mat or where it is in growing amongst a base of synthetic turf fibres.

Australia's first synthetic turf recycling facility is being established in Victoria and is expected to be operational in 2023 with a reported processing capacity of 7,000 tonnes of used turf annually. The company reports an intent to process a mix of sporting fields and domestic surfaces using mechanical recycling techniques.

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[53] Jazbec and Florin, Appendix 5
[54] York Daily Record. (2019). Running out of room. https://www.ydr.com/in-depth/news/2019/11/18/old-artificial-turf-fields-pose-huge-waste-problem-environmental-concerns-across-nation/2314353001/
[55] Reciturf: turning fake lawn green (2021). https://circulareconomy.europa.eu/platform/en/news-and-events/all-news/reciturf-turning-fake-lawn-green

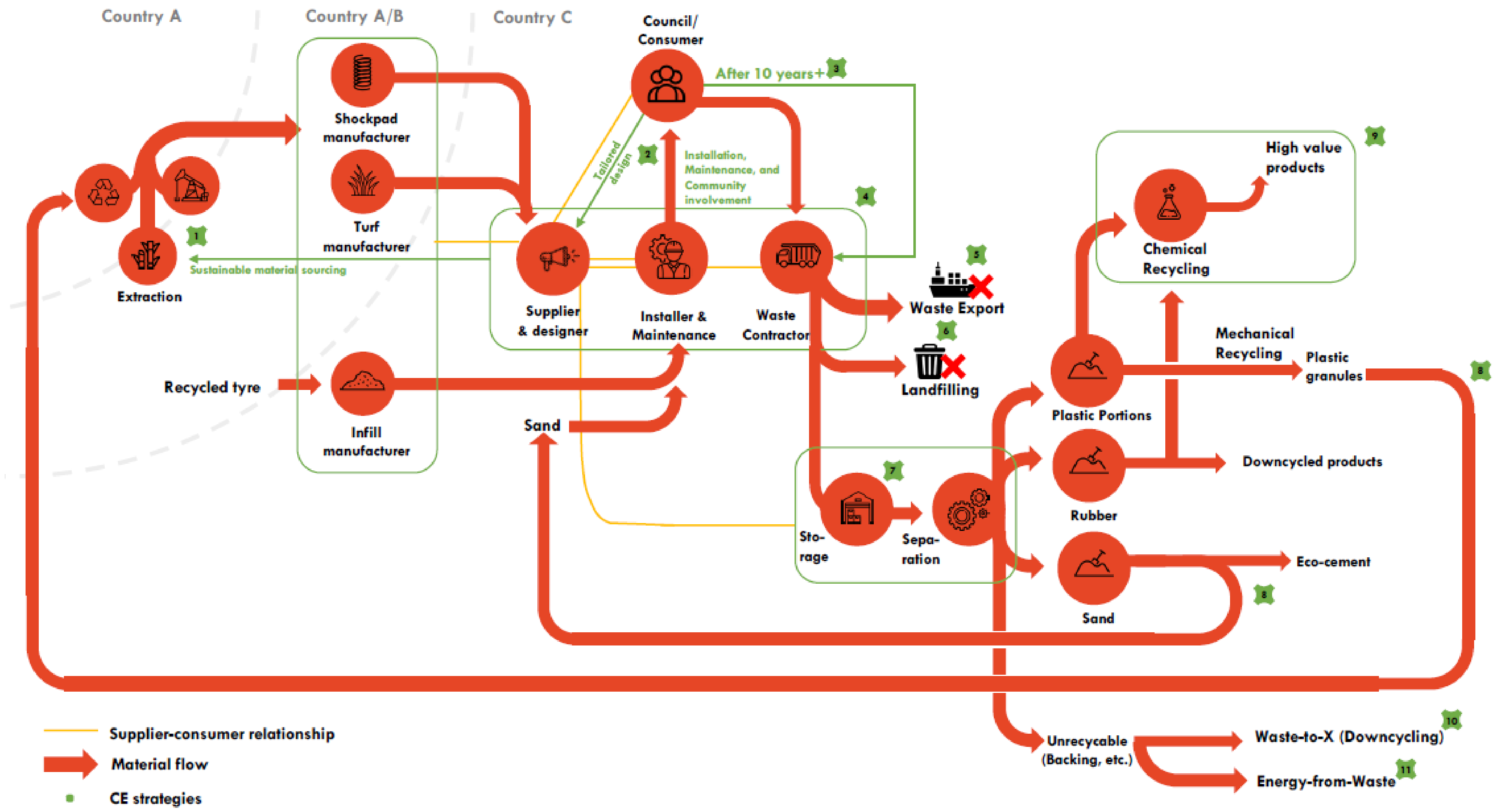

Figure 5: Towards circular business model for the synthetic turf industry (reproduced from Abbas et al. Appendix 6, Figure 2)

3.3.5 Life Cycle Assessment

Abbas et al. (Appendix 6) undertook a review of Life Cycle Assessments (LCAs) of synthetic turf fields and management from a circular economy perspective. LCA is a standardised technique for assessing the totality of environmental impacts of certain products, processes, or services. An example of a potential circular systems model for synthetic turf is shown in Figure 5.

Eight LCA studies were reviewed for comparison. One study only assessed the life cycle of natural turf types with a lifespan of 1-10 years, whereas the rest compared the environmental impact of synthetic turf to its respective natural turf base scenario by calculating the relative difference of environmental impacts between the two scenarios. Across the seven cases studied, synthetic turf was favoured over natural turf on the basis of reduced water and resource consumption, which also reduces the eutrophication impact and pollutants emitted during the maintenance stage.[56] It should be noted that the LCAs did not specify whether the natural turfs were maintained with best practice, such as using recycled stormwater for irrigation.

Synthetic turf requires a higher energy consumption and generates more greenhouse gases (GHG), associated with plastic material production. These impacts can be reduced by using recycled materials or extending the longevity of use. In contrast, production of natural turf has lower GHG and energy requirements to be produced and natural turf may also act as a carbon sink. Of the LCA studies reviewed, most did not identify substantial lifecycle cost differences. However, this would be offset by higher usability time and intensity of use. To substantiate this, data on location, climate conditions, hours of use, sport activity and rate of replacement would be required.

Although LCA is a powerful tool, application to synthetic turf is limited by available data, underlying assumptions and need for proper end of life assessment to enable a best practice LCA framework to be established. Suggested approaches independently verifying manufacturers claims, reviewing two or more data sets for each product under different operating conditions to help eliminate any biases, and collecting data on fields which are in close proximity with each other and have similar activities.

Improved data collection should enable the development of future LCA frameworks suitable for synthetic turf. Developments in the EU should be monitored and used when possible. However, caution should be exercised in translating to the Australian context given differences in climate, material inputs, lack of tyre standards and available end of life infrastructure, among others.

Findings and insights:

- Australia does not produce tyres. It imports them but does not have import standards. SBR crumb is produced from tyres and is known to contain contaminants such as PAHs and heavy metals. Unless the crumb is imported from an overseas facility with testing regulations, the exact chemical composition of SBR crumb used for infill is unknown.
- The *NSW Plastic Reduction and Circular Economy Act 2021* makes provision for managing regulated products.
- Having observed aged and disintegrating fields, the practice of cutting up and ‘redistributing’ EOL fields is not supported by this Review.
- With government and industry involvement, the synthetic turf industry can become more circular by designing out waste.
- LCA tools may be useful for considering the sustainability of turf options, but results are influenced and limited by the framework and data used.

[56] Eutrophication being nutrient enrichment, leading to changes to the availability of light and nutrients to an ecosystem.

3.4 New materials and alternatives

Term of Reference 3a sought advice on emerging science and new materials that could be used in conjunction with or as an alternate to existing natural and synthetic surfaces. Term of Reference 3c considered scientific and technical factors relevant to decision making and management of natural and synthetic turf. This section explores both the emerging science of new materials and best-practice management of natural turf as better management of natural turf fields can make a significant contribution to managing demand for sports participation and accessible public open space. More detail on emerging materials can be found in Appendices 3,4, 5, 6 and 10.

Links to papers: Appendix 3, Appendix 4, Appendix 5, Appendix 6, Appendix 10, Appendix 18.

3.4.1 Manufactured surfaces

Much of the research and policy focus has been on reducing or eliminating SBR infill. Options include use of EPDM and TPE in place of SBR (discussed in Appendix 5) and plant-based materials such as cork, coconut husks, a combination of organic materials or organic-manufactured combinations which can be recycled or composted. Interest in plant-based products has been driven by environmental concerns about microplastics, potential human health impacts associated with rubber infill and reduction of surface heat. Proposals by the European Chemical Agency (ECHA) to introduce restrictions on the use of intentionally added microplastics has also driven innovation.[57] Reservations about plant-based infills include rate of degradation (breakdown) as well as maintenance and replacement costs.[58]

Fourth generation (4G) synthetic surfaces are reported that use different yarn blends in tandem with shock pads to meet fall (safety) requirements, eliminate infill microplastics and reduce heat associated with rubber infill.[59]

Bioplastics are emerging as an alternative to conventional polymeric infill. A product made of biodegradable thermoplastic polyesters is commercially available.[60] Claims include that the product does not contain PAHs or any hazardous substances under European REACH regulations.[61] Reported properties include the ability to be degraded in soil and in compositing facilities, or mechanically recycled at end of life. Published reports about the durability of the product in real-world conditions were not identified although product specifications indicate it meets FIFA testing requirements.[62]

In 2019 the Dutch Ministry of Health, Welfare and Sport issued a tender for proposals for end of life solutions for synthetic turf systems. The successful collaboration has installed a 1000 m^2 field synthetic turf system at EHS’85 in Emmen.[63] Product details are not

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[57] European Chemicals Agency, https://echa.europa.eu/hot-topics/microplastics#:~:text=In%20January%202019%2C%20ECHA%20proposed,ECHA%20received%20477%20individual%20comments.

[58] Smart Guide 4:Synthetic Sports Surfaces (Challenges, Perceptions and Reality). (2021). Smart Connections Consultancy. https://www.smartconnection.net.au/wp-content/uploads/2021/03/Smart-Guide-Vol-4-Challenges-Perceptions-and-Reality-v2.01-Mar2021-5CD8162D3H.pdf

[59] See for example SportEng (2021) Dawn of 4th Generation synthetic turf systems in Australia. https://blog.sporteng.com.au/4th-generation-synthetic-turf-systems-in-australia and https://www.greenfields.eu/ECO-range/Why-GreenFields-ECO-range

[60] https://www.senbis.com/wp-content/uploads/2022/03/brochure-senbis-greenfill.pdf

[61] REACH refers to European Commission regulation No. 1907/2006 of the European Parliament and of the Council of 18 December 2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals. https://osha.europa.eu/en/legislation/directives/regulation-ec-no-1907-2006-of-the-european-parliament-and-of-the-council

[62] FIFA. (2015). FIFA quality programme for football turf Test Manual 1 – Test Methods. https://digitalhub.fifa.com/m/f13b1cd18027f40/original/FIFA-quality-programme-for-football-turf-Test-Manual-I-Test-Methods-2015v-3-4.pdf

[63] Sportsfields.info (2021) https://sportsfields.info/worlds-first-biodegradable-artificial-turf-field/

available, but the system is claimed to be fully recyclable and compostable. Field performance will be monitored as part of the pilot project.

A biobased synthetic turf also been produced. Using polyethylene produced from sugar cane and combined with a soy-based backing technology.[64]

Other industry-based research is being undertaken into features such as new yarn types and replacement binders and glues. Products are commercial in confidence. However, an open data platform can play an important role in tracking types and location of fields and combing this information with other data on maintenance, durability, playability etc.

3.4.2 The performance of natural turf

Comparison of the performance of natural and synthetic turf

The Review was not able to obtain sufficient data to draw conclusions about the relative performance of synthetic compared with natural turf. However, no surface type is 'low cost', and none will perform well under 'set and forget' conditions. Performance under both extreme heat conditions, and saturation due to rainfall need to be accounted for. During the Review, many hours were spent inspecting saturated fields, and the desire of sporting communities for greater certainty is recognised. In the extreme wet weather and flooding experienced in 2022, many newer synthetic fields allowed play to continue. Although there were cases of fields that sustained significant damage, and it was sobering to observe older synthetic fields disintegrating into unfiltered drains, for which no replacement funding was available. At the same time, some natural fields seemed to hold up well.

Improved management of natural turf

Beyond its role in sporting grounds, social, recreational and environmental benefits of natural turf include its contribution to open space policies and climate change impact mitigation. There is a growing body of knowledge to guide the management of natural turf, to optimise its resilience, carrying capacity, wet weather performance and water use (Appendix 18).

Factors cited for increased installation of synthetic instead of natural turf over the past decade include field carrying capacity, reduced water use and resilience to wear and tear. All materials have limitations on use, which manifests itself either as a reduced lifespan or increased maintenance requirements. As biota, natural turf has demonstrated a high capacity for recovery, as shown on turf farms. For Australian sporting fields, supporting the recovery phase of natural turf surfaces after winter sport does not require the field closure. In many cases, rotation from winter sport which is generally high wear to summer sport which is generally low wear should suffice. Time needed post winter sports depends on several factors. This includes the amount of wear, soil health, the turf cultivar, management practices user practices (to distribute wear from sport across the site).

All organised sporting bodies advised that synthetic fields represented an important part of their forward projections to meet demand. However, with the exception of codes played almost exclusively on synthetic turf (e.g. hockey), improving natural turf management was perceived by state sports bodies as having a significant role in managing demand and access to sporting fields.

Many local councils were aware of significant results achieved for natural turf elite sporting grounds (stadium surfaces) but commented on the associated scale of budgets available for the construction and maintenance of elite fields.[65] However, an important difference of

[64] See, for example, https://synlawn.com.au/ and https://www.enviro-loc.com/

[65] Elite stadiums generally have sand topsoil with specific characteristics with an underlying gravel layer (perched water table design), automatic irrigation and drainage.

elite fields is that they are constructed with sand profiles whereas the majority of community sporting fields are constructed with soil profiles.[66] Understanding of the role of soil structure in turf health is an emerging field. Soil structure is a critical physical element in soil profiles, whereas soil texture class is not a reliable indicator of soil ability to drain and grow healthy turf. Soils in the same texture class (e.g. sandy loam) can display vast differences in behaviour.

Councils commented that significant funds are expended in maintaining natural turf fields as well as local parks and playgrounds. Conversely, feedback also recognised that what is currently implemented may not reflect contemporary best practise and expertise. Cost constraints can mean that optimal approaches are not implemented.

Best practice guidelines for natural turf surfaces

Projects undertaken over the last decade to improve management of natural turf fields indicate that significantly more can be done to improve their playability and longevity. This Section discusses key guidelines: Henderson et al. (2007), Sydney Water (2011) and Hunter Water (in press).

In 2007, Henderson et al. undertook a project to assess and support improved management of community-level natural turf sporting fields.[67] Drivers included optimising available access and improved community health. The project also noted the significant resources made by state government in field installation and management, and the need for accurate data to inform investment choices. The project investigated using a standardised system for measuring playing surface performance, with parameters such as ground cover percent and composition, water infiltration rate, surface hardness, traction, levelness and root depth measured.

In 2011 Sydney Water published best practice guidelines for holistic open space turf management in Sydney, focusing on the importance of soil care, turfgrass species selection and irrigation to improve surface resilience and minimise water requirements.[68] Similar initiatives have been adopted in other jurisdictions.[69]

More recently, best practice guidelines for natural turf surfaces in the Lower Hunter have been developed through a grant from the NSW Environment Protection Authority (EPA) *Waste Less Recycle More* program. A collaboration between Hunter Water, local councils and natural turf experts, the guidance is due for public release in late 2022.[70] A presentation of the work was provided at the 2022 OzWater conference. The paper described the best practice benchmarks and summarised the guidelines from a water industry perspective.[71]

The Lower Hunter guidelines incorporate fundamental principles of soil science, turf management and irrigation with locally gathered data and evidence. Encompassing technical elements (soils, turf cultivar, drainage, irrigation) and process matters across the field lifecycle (planning, design, construction, maintenance and use). [72] The integration of planning, design, budgetary, project management, maintenance and drought response plans are critical to ensure the fields that are planned and designed can be constructed

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[66] A sample of 840 community sporting fields identified 98 percent had soil profiles. Battam, M. and Lamble P. (2019). Planning for Park and Sport Field Carrying Capacity. https://www.parksleisure.com.au/includes/download.ashx?ID=155497
[67] Henderson, C., et al. (2007). Best management practices for sustainable and safe playing surface of Australian Football League sports fields. Project Report. TU02007. Horticulture Australia, Sydney, Australia.
[68] Sydney Water. (2011). Best practice guidelines for holistic open space turf management in Sydney.
[69] See for example, G & M Connellan Consultants. (2015). *Best Practice Guideline for Functional Open Space in Victoria* https://www.clearwatervic.com.au/user-data/research-projects/swf-files/bpg-final.pdf;
[70] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter.
[71] Available at OzWater 2022 https://awa.sharefile.com/share/view/sabe7935022fc4e808f1306bd2af79de0/fo6ae8b4-9dd1-4ba8-a121-9e1401cf20c3
[72] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter.

and maintained within the available resources (e.g. budgets, staff, machinery, water). The importance of integrating best practice throughout the project lifecycle is also reflected.[73]

The Lower Hunter guidelines describe how financial and resilience indicators can be used to determine optimal approaches and outcomes and provide construction, maintenance and lifecycle costs comparisons for different construction types. The lifecycle cost per unit of carrying capacity for best practice natural turf fields is ~ 50 to 70 percent lower than commonly considered alternatives.[74] The amendment of poorly structured soils in underperforming fields in Southern Sydney has resulted in substantial cost savings by reducing the amount of turf patching required each year.[75]

There are some recent examples of drainage upgrades planned for natural turf fields on the NSW Central Coast.[76] Monitoring the performance of these fields in terms of water management, wear recovery and health of the turf will be very informative.

Common features of best practice natural turf guidance assessed by the Review include water management, soil health and cultivar selection. Communicating evolving thinking on natural turf requirements and transitioning from standard/current to best practice appear equally important in optimising the capacity and longevity of natural playing fields. There is a need to communicate to stakeholders the value, impact and returns on good natural turf management more effectively. This is particularly the case for the natural 'underground architecture' - soils supporting turf. Many stakeholders recognised the significant challenges facing local councils when making investment choices about sporting fields when faced with competing demands across their responsibilities, including roads, cultural centres, health and other services. In this context, natural turf struggles to compete with more visible above ground infrastructure.

Weather extremes such as drought and the higher rainfall and flooding events in 2021-22 pose short and long terms risks to turf health.[77] These events have posed significant challenges to turf farmers and field managers and are a reminder of the risks within flood plain areas. The impact of flooding on the field and turf and therefore the measures required for post flood recovery are site and event specific.[78] Factors such as field construction type, turf cultivar, depth and duration of inundation, depth of material deposition and the timing of the flood are all relevant considerations.

Work undertaken more broadly to manage weather extremes, including adapting to changes to water resources and embedding drought resilience in urban areas, will inform future practices.[79]

Given the scale and significant investments in natural turf playing fields and other open spaces there is an urgent need to revisit what elements are critical to natural turf management, using real data to inform a knowledge base as a tool for open space managers and decision makers.

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[73] Neylan, J. (2021*). Australian Turfgrass Management* 23.5, 30-34. September-October 2021.
[74] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter.
[75] For example, a project in southern Sydney to apply waste organics to improve soil health and resilience of sports fields, resulting in a decreased in maintenance costs *Compost kicks goals on playing fields* NSW Environment Protection Authority https://www.epa.nsw.gov.au/working-together/grants/organics-infrastructure-fund
[76] Central Coast Football (2022). CCF INVESTS $260,000 IN FIELD DRAINAGE UPGRADES. https://ccfootball.com.au/2022/09/28/ccf-invests-in-260000-field-drainage-upgrades/
[77] AgEnviro Solutions (2022). Impact of March 2022 floods on western Sydney turf farms and sporting fields.
[78] McPhee, B. (2022*). Australian Turfgrass Management* 24..2, 26-28. SPORTENG (2021). What are the consequences of flooding on sportfield natural turf? https://blog.sporteng.com.au/what-are-the-consequences-of-flooding-on-sportfield-natural-turf
[79] See for example, Adapt NSW Climate Change impacts on our water resources, https://www.climatechange.environment.nsw.gov.au/water-resources ; Greater Cities Commission, exposure to natural and urban hazards, https://greatercities.au/metropolis-of-three-cities/sustainability/resilient-city/exposure-natural-and-urban-hazards-reduced; Sydney Water (2022) Innovative water management for the Aerotropolis Precinct https://www.sydneywater.com.au/content/dam/sydneywater/documents/iwcm-summary-report-2022.pdf

Findings and insights:

- Biopolymers that are recyclable and/or compostable are emerging as an alternative surface product.
- Factors driving the increased installation of synthetic turf in NSW are cited to be increased field carrying capacity, reduced water use and greater resilience to wear compared to natural turf fields.
- Best practice guidelines for improving the performance of natural turf have been developed in NSW.

4. Human health

Terms of Reference 2b and 2d request advice on potential health impacts of the use of synthetic turf in public open spaces. This Chapter draws on the expertise of the commissioned experts, and explores the identified health risks, which include:

- lower body, head or abrasion injury (Section 4.1)
- heat-related illness, thermal comfort and Urban Heat Island (UHI) effect (Section 4.2 and 4.3)
- chemical, microplastic and microbiological health risks (Section 4.4)
- air pollutants and odour (Section 4.5 and 4.6)
- mental and the social dimensions of health. This section includes community access and impacts on nearby residents relating to wellbeing and social cohesion (Section 4.7).

In accordance with Term of Reference 2b, a literature review was undertaken on the potential physical, chemical and biological risks of synthetic turf use in public open space on human health and the wider implications on population health at the neighbourhood or city-scale (NSW Health, Appendix 3).

Early consultations identified heat-related impacts as a priority area for focus. Consequently, additional expert advice on thermal comfort, heat and heat-related health risks for individuals was commissioned - Nazarian and Mohseni (Appendix 8), and Singh and Stevens (Appendix 9) as well as Pfautsch and Wujeska-Klause (Appendix 7) on impacts of urban heat. Following further consultations, additional advice on the National Sports Injury Data Strategy (Appendix 12), per- and poly-fluoroalkyl substances (PFAS, Appendix 13), air pollutants (Karatela, Appendix 15) and plastic (Palanisami, Appendix 19) was sought. Odour was identified as an issue of amenity for some residents living in proximity to fields but highly variable in its perception and impacts (Stuetz et al., Appendix 14).

Overall, the commissioned reports and literature review did not identify major health risks associated with the use of synthetic turf, although it was noted that significant knowledge gaps remain. There is a specific lack of empirical evidence around the indirect and longer-term cumulative health impacts with a general lack of field studies, epidemiological studies and health risk assessments in the Australian context.

Links to papers: Appendix 3, Appendix 7, Appendix 8, Appendix 9, Appendix 12, Appendix 13, Appendix 14, Appendix 15, Appendix 19.

4.1 Lower body, head and abrasion injuries

The potential impacts of synthetic turf to human health vary depending on the frequency and duration of the use of the fields, the age of the users, the type of use (e.g. sport, player position) and/or the ongoing exposure. The condition of natural and synthetic grass surfaces can vary significantly across and between fields, so generalisations are difficult. Factors including shock absorbency, vertical deformation and rotational resistance affect safety and injury risk. These are tested as part of international certification processes for the major sporting codes, are summarised in Appendix 5 and published on sporting code websites.

Factors that may contribute to injury include fitness level, age, sport type, level and intensity of competition, footwear, heat and climate conditions, age of field and field condition. For example, studies performed on elite, adult professional athletes may not be applicable to junior amateur athletes even within the same sport.

Overall there is inconsistent evidence to link higher rates of head or lower body injury or skin abrasion to synthetic turf over natural turf surfaces (NSW Health, Appendix 3). However, synthetic turf has been found to generate greater stress on the players' feet, with some studies suggesting players experience greater rotational torque from the shoe-surface interaction, and the material can heat to very high temperatures

Limited anecdotal feedback from players and field managers during site visits confirmed the mixed observations found in the literature, including:

- the surface of synthetic turf can be 'hard on their legs' (football[80]) and takes some adjustment
- there can be heat impacts on very hot days (children removing shoes)
- abrasion injuries are noticeable (rugby and football[80]) but not necessarily to a level that medical attention would be sought.

These observations were typically accompanied by a counterfactual about game cancellations during high rainfall events on natural fields and the fact that play could continue on synthetic fields. Industry and sporting bodies are acutely aware that concerns about the impact of heat on participants is stimulating development of alternatives and performance under Australian summer conditions.

The Australian Institute of Health and Welfare (AIHW) is working on a National Sport Injury Project, which aims to improve and develop national sport injury data to inform injury prevention and increase participation. The AIHW published a draft National Sports Injury Data Strategy[81] which outlines the proposed approach to develop a National Sports Injury Data Asset (NSIDA). Further details are in Appendix 12.

There is a need to obtain data and conduct epidemiological studies that are up to date and made publicly available to allow for an analysis of injury rates and injury types compared to surface type and sport. Some useful data parameters include the user, sport, injury type, severity, surface type, condition of the surface and whether or how the surface contributed to the injury. Initiatives to capture broader 'on field' observations from players would also assist.

Overall, it is concluded that sports-related injuries may occur on both synthetic and natural turf fields, and it is difficult to conclude with confidence which physical characteristics of synthetic turf might account for a small number of reported differences. More systematic data collection would assist to address this.

Findings and insights:

- Sports-related injury may occur on both synthetic and natural turf fields at comparable levels and a good field maintenance regime is required to ensure player safety.
- Synthetic turf can generate greater stress on the players' feet.

4.2 Heat impacts

The surface of unshaded synthetic turf can become significantly hotter than that of natural turf under the same ambient temperature on hot days, which may worsen thermal discomfort within its proximity (Pfautsch and Wujeska-Klause, Appendix 7). Environmental conditions, especially solar radiation and ambient temperature, as well as the material composition, design and age of synthetic turf all influence surface temperature. On hot

[80] Refers to soccer
[81] AIHW. 2022. National sports injury data strategy: draft consultation report. https://www.aihw.gov.au/getmedia/6e6da567-dac2-4163-b3df-4409395c93c7/aihw-injcat-222.pdf.aspx?inline=true

summer days with air temperatures reaching mid-30ºC or higher, synthetic turf surface temperature can be up to 38ºC higher than that of natural turf. However, the air temperatures within the microenvironment of synthetic turf fields do not tend to rise as significantly nor correlate with surface temperatures.

The daytime energy balance of natural turf relative to synthetic turf (Figure 6 from Pfautsch and Wujeska-Klause, Appendix 7) illustrates the essential role of moisture in maintaining low surface temperatures in natural turf, which dry grass and synthetic turf lack. Natural turf absorbs a significant proportion of the incoming shortwave radiation, the remaining is reflected onto the underlying soil surface. Even with the continuous rise of solar radiation, natural turf maintains low surface temperatures due to cooling by evapotranspiration, high water content, and low thermal mass. In contrast, synthetic turf reflects less and absorbs more incoming solar radiation than natural turf and can become a ‘hot spot’ in unshaded outdoor areas. Notably, effects can be felt even during relatively cooler ambient air temperatures below 30°C.

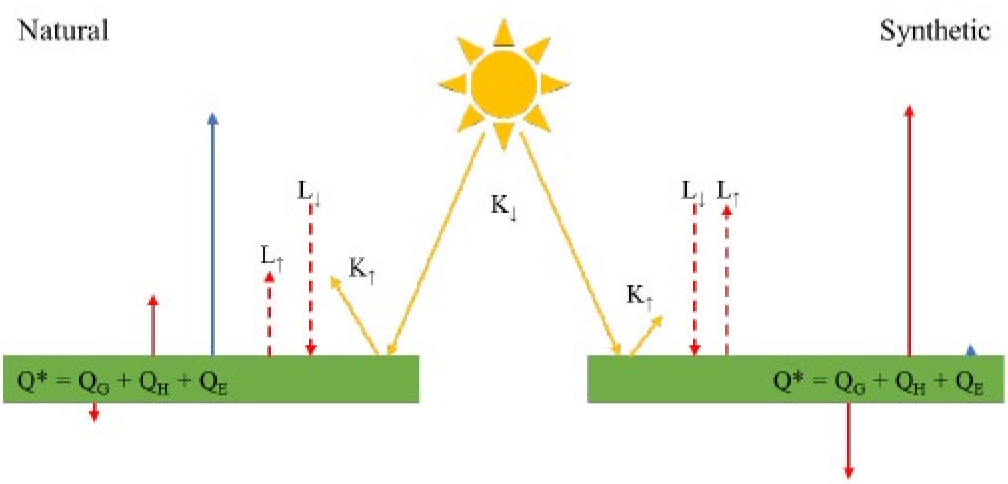

Figure 6: The daytime energy balance of well-watered natural turf (left) and dry synthetic turf (right)
Reproduced from: Pfautsch and Wujeska-Klause, Appendix 7, Figure 2 – see Appendix 7 for explanation of variables and symbols

The UHI effect occurs when surfaces and air in the cities are hotter than nearby vegetated reference sites. Contributing factors include heat-retaining urban materials such as synthetic turf as well as roofs and pavement, and tight urban geometry that traps radiation and blocks its reflection back to the sky. The cooling benefits of blue and green spaces, including natural sports fields have been well-documented. Scientific literature on the contribution of synthetic turf types to UHI is limited.

Contribution of synthetic turf fields to the UHI effect is likely to be small, contained within the spatial footprint of the surface, but the cumulative depletion of grass surfaces over time may exacerbate heat exposure risk in the population, particularly vulnerable populations (e.g. children). No systematic assessments based on scientific studies are available to provide guidance on synthetic turf suitability, particularly for the Australian climate.

Identified mitigation measures include shading, infill choice, new product choices and irrigation. There is work underway on a practical measure of thermal suitability of synthetic turf compared to natural turf. That aims to advise on the suitability of synthetic turf for particular sites based on the thermal comfort experiences on sports field and playgrounds, such as the nine-point thermal suitability index by Shi and Jim (2022).[82]

[82] Shi, Y. and Jim, C.Y. (2022). Developing a thermal suitability index to assess artificial turf applications for various site-weather and user-activity scenarios. *Landscape and Urban Planning* 217, 104276. https://doi.org/10.1016/j.landurbplan.2021.104276

4.3 Thermal comfort and heat strain

A combination of air temperature, radiative heat exchange (characterised as Mean Radiant Temperature, MRT), airflow and humidity are key environmental factors that determine the impact of synthetic turf on the thermal environment and subsequent potential for increased heat exposure of individuals (Figure 7, reproduced from Nazarian and Mohseni, Appendix 8). There is a complex interaction of environmental drivers with human behavioural and physiological responses to heat exposure that lead to individual sensitivity, heat strain and thermal comfort (Figure 8, reproduced from Nazarian and Mohseni, Appendix 8). Heat stress occurs when there is an imbalance between metabolic heat production and heat loss in the environment, resulting in high core body temperatures (Singh and Stevens, Appendix 9).

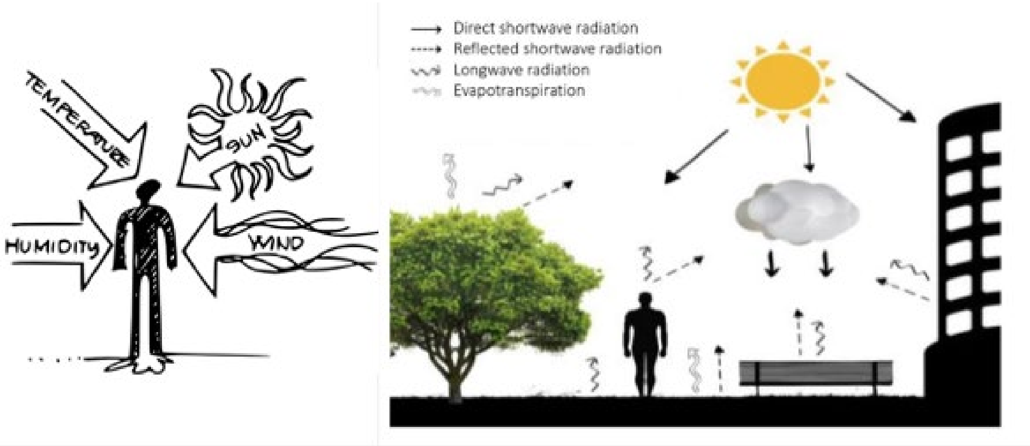

Figure 7: Left: Key microclimate parameters affecting human thermal comfort; Right: Radiation components in urban environments that determine mean radiant temperature
Reproduced from: Nazarian and Mohseni, Appendix 8

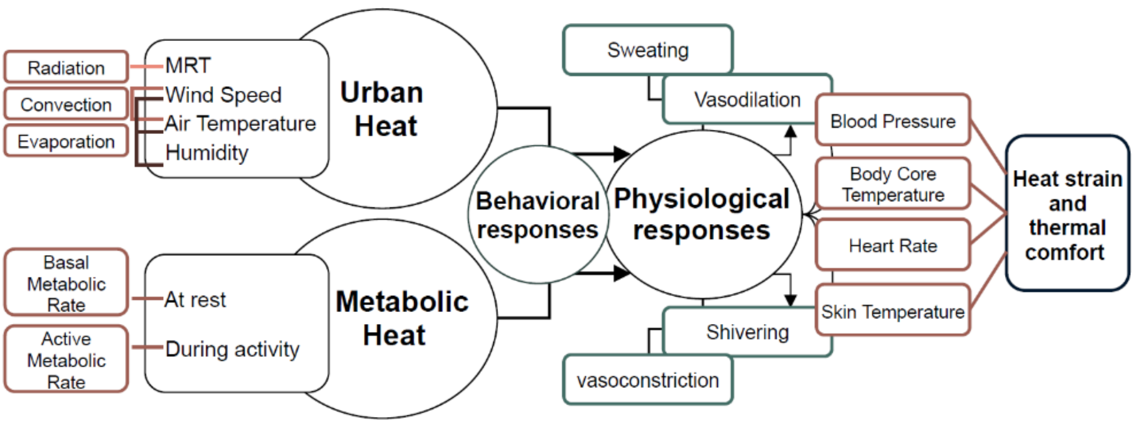

Figure 8: Physical, physiological and behavioural mechanisms in response to heat
Reproduced from: Nazarian and Mohseni, Appendix 8

In modifying the thermal environment, synthetic turf can create potential hazards for different groups of vulnerable populations. This includes children due to their high ratios of metabolism-to-surface area, surface area to body mass, lower sweating rates, more sensitive skin and a body mass closer to the heated surfaces. Other vulnerable populations include younger athletes due to their greater physiological sensitivity, and parents and other spectators due to risk associated with longer exposure.

Developing appropriate heat-health advisories and guidelines is critical for mitigating and addressing the heat-health risks in various settings. The heat retaining property of synthetic turf surfaces is a characteristic that can impact health during hot conditions. Their use should only be recommended during suitable weather for users on or around the field, particularly for children and exercising individuals who are susceptible to heat exhaustion (NSW Health, Appendix 3).

Currently, the most comprehensive and evidence-based guideline of cooling strategies at the individual level was developed by Jay et al. for Sports Medicine Australia.[83] Within the guideline a sport risk classification considers the combined thermal effects of activity intensity and clothing/equipment worn across popular sports in Australia. The heat stress risk and thresholds are applied using the corresponding temperature and humidity graph. Recommended actions to mitigate heat stress accompany each rating and particular risk factors for individuals (based on age, health etc.) are noted. These guidelines are followed or referenced by all major sporting codes. Singh and Stevens (Appendix 9) discuss investigations into whether synthetic turf surfaces affect markers of heat stress and thermoregulation and whether modifications to current sport heat policies are required for synthetic turf surfaces.

Research priorities to address knowledge gaps include datasets and modelling of thermal environments, quantifying thermal exposure using appropriate parameters and sensing methods and comprehensively assessing and communicating risk.

Findings and insights:

- The interplay of the synthetic turf material design, environment, user profile and activity level influencing thermal comfort is complex.
- The heat retaining property of synthetic turf surfaces is a characteristic that can impact health during hot conditions and their use should only be recommended during suitable weather for users on or around the field, in particularly for children and exercising individuals who are susceptible to heat exhaustion.
- The contribution of synthetic turf fields to the UHI effect at scale is likely small, but the cumulative depletion of grass surfaces over time may exacerbate UHI effects and increase heat exposure risk in the population.

4.4 Chemical, microplastic and microbiological exposure

Potential human health impacts from direct contact (such as dermal, ingestion and inhalation) and indirect contact (such as leachate and microplastic runoff) from synthetic turf is likely low, especially when mitigation measures are in place.

4.4.1 Microbiological

Health concerns have been raised regarding the harbourage of methicillin-resistant *Staphylococcus aureus* (MRSA) bacteria in synthetic turf that may cause skin infections and potentially severe health complications. Evidence from the literature does not support synthetic turf as a source of MRSA infection. It is unlikely that synthetic turf materials would be the source of the MRSA due to unfavourable survival conditions for the bacteria such as high temperatures and the presence of UV in outdoor fields.

[83] Sports Medicine Australia (2021). Extreme Heat Policy V1.0 February 2021. https://sma.org.au/sma-site-content/uploads/2021/02/SMA-Extreme-Heat-Policy-2021-Final.pdf

4.4.2 Chemicals and plastics

The chemical signature of synthetic turf may be associated with health risks through pathways including ingestion (direct or indirect), inhalation, or dermal absorption.

PAHs can volatilise into the breathing zone of the synthetic turf user or deposit onto the skin. Therefore, direct inhalation and dermal contact of PAHs are assumed to be the potential primary routes of exposure. Ingestion of crumb rubber or dust particles from the field, and exposure to leachates released into the environment is considered secondary.

Current literature indicates that:

- the excess lifetime cancer risk of exposure to PAHs in crumb rubber by inhalation, ingestion and dermal contact has been shown to fall within acceptable limits.
- the excess lifetime cancer risk and non-cancer risk of exposure to heavy metals in crumb rubber by ingestion, dermal contact or inhalation have generally been shown to fall within acceptable limits and hazard guidelines.
- preliminary studies indicate that leachates containing metal and PAHs are low and generally below drinking water standards, although leaching dynamics of synthetic turf chemicals are not currently well understood.

Advice from experts engaged to assist the Review is that further investigations should prioritise the potential health impacts of chemicals such as PAHs and some heavy metals.

Certain PAHs have been recognised for their toxicity, carcinogenic potential and prevalence in the environment. The US EPA designated 16 PAHs as chemicals of concern. The EU has bought in restrictions on eight identified carcinogenic PAHs, limiting concentrations to 20 mg/kg in crumb rubber used as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications.[84]

When considering heavy metals, lead is also of particular concern due to its non-threshold developmental neurotoxic effects for infants and children. Lead has been found in crumb rubber and plastic pile blades (attributed to certain pigments used) at concentrations generally below 30 mg/kg, which are generally below various nation soil quality guidelines (e.g. 200 mg/kg from USA, 300 mg/kg from Australia and 1,000 mg/kg from Germany.[85] Despite this, more research is required before definitive statements can be made on causality or risk to human health.

Preliminary studies suggest that microplastics from synthetic turf fields may contaminate surrounding soil or drainage systems, with unknown health impacts (Palanisami, Appendix 19). Environmental impacts are discussed in Chapter 5 of this Review.

The presence of per- and poly-fluoroalkyl substances (PFAS) was raised with the Review by local community members. Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) compounds have been found in low concentrations in synthetic turf in some preliminary testing studies, most likely through production of pile blades and the carpet. Studies identify a link between PFAS exposure and several health effects. Advice was sought from the NSW Technical Advisory Group (TAG) on this issue (Appendix 13):

- Based on their knowledge TAG suggest that the presence of PFAS in synthetic turf may be due to a number of reasons including its presence in the feedstock used to make the synthetic turf or the material used in the recycling process for either the feedstock or the infill. It may also be present due to the chemical being added as an extrusion aid during the making of the pile blades. TAG notes that depending on the

[84] ECHA. (2021). Commission Regulation (EU) 2021/1199. EUR-Lex - 32021R1199 - EN - EUR-Lex (europa.eu)
[85] He, Z., et al. (2015). Heavy metal contamination of soils: Sources, indicators and assessment. *Journal of Environmental Indicators*, 9(17-18). https://scholar.uwindsor.ca/cgi/viewcontent.cgi?article=1020&context=icei2015

source of the feedstock the chemicals present, and their concentrations will be highly variable.
- In respect to PFAS exposure due to synthetic turf, TAG suggests that expected exposure pathways may include accidental ingestion and dermal contact. Ecological exposure due to PFAS leaching from the synthetic turf and rubber infill should also be considered.
- TAG notes that in respect to human health risks, studies undertaken on the concentration of PFAS in synthetic turf show concentrations lower than the typical laboratory reporting limits in many matrices and it is unlikely that PFAS from synthetic turf would reach those levels found in the environment where PFAS is emanating from Defence bases where fire-fight foams have historically been used.
- The presence of PFAS in synthetic turf needs to be considered in the context of other contaminants that may be present in the feedstock and rubber infill as well as the potential exposure pathways where synthetic turf is used. TAG further notes that it should be considered in the context of other more prevalent chemicals such as PAHs and some heavy metals.
- Based on the current knowledge on concentrations of PFAS in synthetic turf and its contribution of exposure pathways, the resultant health impacts would be minimal.

Findings and insights:

- Restrictions on eight PAHs, limiting concentrations in crumb rubber used as infill material in on playgrounds or in sport applications have been recently applied in the EU.
- Even though the health risks of chemicals in synthetic turf are likely to be very low, progressive restrictive measures to limit potentially harmful chemicals in synthetic turf components may reduce unforeseen consequences to health.
- Although leachate and microplastic run-off from synthetic turf fields are likely to be very low, measures to reduce chemical and microplastic pollution serve to reduce potential cumulative harm to aquatic and soil life, the environment and ultimately human health.

4.5 Air pollutants

The health risks of other synthetic turf chemicals including Volatile Organic Compounds (VOCs), plasticizers, antioxidants and additives are less well studied. Generally, their levels of detection were generally low and unlikely to pose appreciable health effects.

There is evidence that suggests that certain gasses, including PAHs, VOCs and Semivolatile Organic Compounds (SVOCs) found in infill and other components are released from the synthetic turf into the air at higher temperatures, with the main route of exposure via inhalation. Deterioration of materials and resuspension of aerosol deposition on the surface may also contribute.

Studies of sufficient sample size and longitudinal studies are needed to understand long term effects. Very few studies have looked at effects on children. Young children may be at a higher of exposure to gasses relative to adults due to their small size and developing bodies (Karatela, Appendix 15).

4.6 Odorants

Odours from synthetic turf can impact the quality of life and experience for players on the field and the local community (Stuetz et al., Appendix 14).

Unpleasant odours (malodours) have featured in previous reports about synthetic turf fields and were raised with the Review in correspondence and meetings with community members. Expressed concerns include that the odour signals a health risk, particularly from chemicals contained in crumb rubber, and adverse impacts on amenity. People living immediately adjacent to fields reported the need to close their homes when they might otherwise have windows and doors open to dissipate heat or enjoy the fresh air. Also reported were physical symptoms (headaches and nausea), particularly noticeable on very hot days. Some expressed concerns for players, noting however, that athletes may be exposed for more limited periods. A second issue raised is the lack of a clear pathway for managing odour complaints, this is discussed in Chapter 6.

Site visits by the Review team occurred predominantly in autumn and winter. In some fields, malodour was noticeable (although not dominant) even on cool days. There was no discernible pattern other than that when it was noticeable it appeared associated with fields with crumb rubber infill. Systematic data were not collected, but when asked, players and field managers responses ranged from ‘not noticeable’ to ‘definitely (on hot days)’.

Available literature indicates factors affecting the extent of impact include its intensity, quality, duration, and number of exposures, with repeated exposure events a strong predictor of complaints (Stuetz et al., Appendix 14).

Potential sources of odorants include desorption and in-situ production (Stuetz et al., Appendix 14). The first hypothesises that odorants are present as components (or impurities) in the materials and are released when the relative concentration between the material and the air above changes. Although not the only influencing factor, higher rate of desorption at elevated temperatures may account for detection on hotter days. Another potential source of odours is production by reactions occurring in the turf materials itself.

Interactions between odorants, their emission mechanisms and the dispersion rate are highly complex. Influencing factors include but are not limited to temperature, wind speed and direction, terrain and layout. Fences, green belts and buildings can affect turbulence and therefore dispersion. As compounds disperse, they may be subjected to different chemical and photochemical reactions. The rate and nature of reactions may be influenced by temperature, humidity and solar radiation. The neuropsychological basis of olfaction for individuals is equally nuanced and complex.

Given the above, consideration should be given to using non-rubber infill or non-infill options for installation of synthetic fields in close proximity to homes. Future research efforts would be best directed on engaging individuals specifically and significantly affected to better understand causal agents. Research gaps include measurement for sulfurs and some acids, temperature effects on VOC emissions and local environmental factors that may interact with synthetic turf compounds.

Findings and insights:

- Gaseous chemicals are emitted from synthetic turf fields in low concentrations.
- Air pollutants from synthetic turf require more research to determine risks to vulnerable portions of the population such as children, and any potential long-term effects.
- Odorants may have adverse impacts on amenity.

4.7 Mental and social dimensions of health

The potential health benefits of green space (parks, sport spaces, trees, natural grasslands, wetlands, etc.) are well-documented, associated with improved mental health, heat exposure reduction and climate resilience. In an urban context, green space has been associated with improving individual physiological and psychological health due to an increase in physical activity opportunities and the stress-relieving effects of nature as well as improving social cohesion and positive social interactions. There is a growing body of evidence that shows a relationship between levels and proximity of green space in the local neighbourhood and people's perceived health and well-being, especially for low-income urban populations. Further, urban green space plays a role in promoting a community's 'culture of health', including social health.[86] What dosage (quantity, accessibility and quality) of green space is needed to incur benefits is not known.

The relationship between green space and health is complex and multidimensional. The replacement of natural turf fields with synthetic turf may decrease local communities' access to natural green space and amenities, which may have implications for community cohesion and mental health. Replacement of natural grass with a synthetic turf represents a loss of natural green space. However, if the outcome is beneficial (e.g. improved and functional playing field, well-maintained amenities such as lighting, footpaths, playing areas) or that provides thermal comfort via natural vegetation and shading, then a decrease in health benefits may not arise.

There are no studies to date that specifically examine whether replacing natural turf fields with synthetic turf has a negative effect on the health and wellbeing of individuals and communities associated with the loss of natural green space (NSW Health, Appendix 3). The social and environmental context of each playing field and its surrounds is different and the implications on the physical, mental and social dimensions of health cannot be drawn without research or surveying the community. From a public health perspective, equity considerations are also important and any barriers to community's access to amenities, including for specific groups who may be deprived of other access to green space, should be considered.

Although the evidence for a positive correlation between green space via natural sports fields and the mental and social dimensions of health within the community is strong, it is not conclusive. This can be understood through surveying the local community, assessing demographics, recreational needs and individual access and proximity to quality green spaces.

The Review examined council documents about community consultation and received feedback from community stakeholders. Relevant questions raised included whether:

- the replacement of natural fields with synthetic turf results in a partial or complete transition from public recreational use to private use (e.g. through lease arrangements with sports clubs and associations)
- a conversion from natural turf to synthetic turf surface creates more or less health disparities by encouraging/discouraging use by different groups within the community (e.g. older people, people with existing health conditions or disabilities and different cultural groups)
- the change erodes community contact with nature, more relevant in areas with limited green space.

[86] A "culture of health" has been broadly defined as a culture that supports health improvement by fostering healthy, equitable communities that enable everyone to make healthy lifestyle choices (Robert Wood Johnson Foundation, 2016), mindful of locality, race and ethnicity (Roe et al, 2016).

4.7.1 Community access

Community access is complex given the spatial and social diversity of communities. Accessibility of public open space can promote physical activity in all age groups. This became more apparent during the COVID-19 pandemic when people spent more time in their local communities due to restrictions and changes in work arrangements.[87] In many areas, the sporting field appeared to provide unifying and socially cohesive benefits beyond the physical activities involved.

Synthetic turf has the potential to improve individual and community health in relation to its accessibility for physical activity, particularly in a range of weather conditions. Regular exercise can increase muscle and bone strength, prevent and reduce risk of disease, promote healthy lifestyles, social cohesion and reduce stress and anxiety. Participation in organised sports can benefit the broader community as well as individuals where participants develop positive social norms and attitudes. This was affirmed on site visits, with sport providing leadership and development opportunities across a range of communities.

The benefits of synthetic turf in extended wet conditions were highlighted by sporting organisations and other stakeholders over the first half of 2022 when many natural fields were closed to organised sporting activities.

Negative access impacts for proximate residents– actual and perceived – appear more acute when a pre-existing field is changed to a synthetic surface, single field sites and where there is close proximity between field and residences. The following featured in feedback to the Review, especially in relation to single field sites:

- sporting fields are large and may dominate the space, even where there are green verges
- competition for field time may mean access for non-organised sport or other exercise is limited even when theoretically available, especially in peak periods
- limitations on community activities that may have been enjoyed previously. – e.g. carols by candlelight and similar due to fire risk, dog walking, picnic chairs etc.
- high density areas with low levels of open space or infrastructure that limits access to alternatives (major roads, rail lines etc)
- the nature of organised/club sports may have a bearing as people playing sport may not be from the immediate local area
- how well and how effectively community engagement was undertaken, including communication of likely changes and their management.

Council decisions about access vary widely between sites. One field that was visited by the Review was locked, most but not all are fenced. Most fenced fields allow open access to people but maintain gates – some to help manage pollutant ‘walk-off’, others to discourage vandalism. More restrictive access policies appear less of an issue when there are ample alternate grass fields or open areas.

Most synthetic fields have large signs listing rules of use, including the need for specific footwear. While this may help maintain a field, it may appear exclusionary. Again however, there is variability in whether this is enforced or not. With the exception of weights, some councils allow open access and/or regard it as a condition of installation, especially in high density areas with limited open space. The Review did not test this systematically, but greater public access does not appear to cause particular problems, a more frequent

[87] NSW DPIE. (2020). Sydneysiders take to green space during the COVID-19 pandemic. https://www.planning.nsw.gov.au/News/2020/Sydneysiders-take-to-green-space-during-the-COVID-19-pandemic#:~:text=Almost%20half%20the%20respondents%20(46,public%20spaces%20during%20the%20pandemic

observation being that failure to rotate use for team sports or moving goal mouths are the cause of field damage.

4.7.2 Consequences of field infrastructure on nearby residents

The predominant negative issues of sporting field infrastructure include noise, parking, lights and odour. Noise, lights and parking issues may be associated with either natural or synthetic fields. Generally speaking, greater community dissatisfaction with these factors appears mostly associated with single fields installed in predominantly residential areas where a synthetic field has replaced a formerly natural surface field.

Consultations suggest contributing factors include extended hours of use associated with synthetic fields. Demand for playing fields may have narrowed or eliminated quieter periods during weekdays and weeknights and 'off-season' periods. It may also be that fields not previously lit with sporting lights have them installed and use extends much later than previously occurred.

There are general provisions under the *NSW Local Government Act 1993* regarding impacts on residents from sporting fields. Sections 36F and 36G establish the management objectives for land categorised as sportsgrounds and parks, respectively. Under s 36F sports ground objectives are to encourage and promote recreational pursuits involving organised and informal sporting activities and games and to "*ensure that such activities are managed having regard to any adverse impacts on nearby residents*."

The Review team undertook site visits, including informal visits at different hours to observe activities and to test issues raised. Impacts on daily life raised specifically included high-intensity lights being intrusive and disturbing sleep for those needing to wake early. An inability to access parking or repeated illegal parking including blocked driveways was also raised, some residents reported being told to 'call the police' when unable to access their homes.

The Review observed illegal parking in access points into sports fields and across driveways in fields located in residential areas without dedicated parking. In places this appeared a safety issue, with the need to walk into roads to pass and would preclude anyone using a mobility aid. Appropriate council communication and measures of enforcement would assist these issues. Parking does not appear to be an issue where there is dedicated parking, including at multi-field centres.

4.7.3 Sports lighting

Light associated with sporting fields can be positive in terms of perceived increased physical safety and allowing increased hours for exercise. However, sporting lights are extremely powerful, and can be an intrusive and harmful cause of light pollution. The environmental impacts of are discussed in Section 5.3 and Appendix 16. This section focuses on human residential impacts.

Light pollution is not included in the NSW *Protection of the Environment Operations Act 1997*, although it features in other jurisdictions.[88] However, there are a number of Australian Standards including control of obtrusive effects from outdoor lighting as well as standards for different sporting codes.[89] Councils have varying outdoor lighting policies

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[88] See for example, the ACT *Environment Protection Act 1997* Schedule 3 "environmental nuisance means an unreasonable interference with the enjoyment by the public, a section of the public or a person of a place or area, if the interference caused or likely to be caused by— (a) dust, fumes, light, noise, odour or smoke; or (b) an unhealthy, unsightly or otherwise offensive condition because of pollution."
[89] AS/NZS 4282: 1997 Control of the obtrusive effects of outdoor lighting (guidelines); AS/ NZS 4282-2019 Control of the obtrusive effects of outdoor lighting (requirement specification); AS 2560.1: 2002 Sports lighting: General principles; AS 2560.2: 2018 Sports lighting: Specific applications

established under Part 3 of the *Local Government Act 1993*. Some identified by the Review specifically reference lighting upgrades to reduce spill from sporting grounds.[90]

Sporting codes set out standards for lighting of fields, including for example FIFA,[91] Rugby,[92] Hockey[93] and Tennis.[94] Sporting requirements vary in relation to lux levels, and encompass uniformity, colour temperature, glare and flicker. Associations between adverse human health impacts and exposure to light at night (LAN – also referred to as ALAN[95]) are increasingly well-documented, including exposure to LAN of 5 lux or more.[96,97,98,99]

The Review identified examples of light spill concerns in council reports and during site visits directly observed instances where sports lighting was spilling strong light directly into neighbouring residences at night. This appears to be a more substantive issue in residential areas where homes are in close proximity to fields. The Review was advised that it is possible to dim lights to a level still safe for play but less intrusive. Modern sports lighting should also be able to be set at angles and with appropriate shielding to address this issue.

Findings and insights:

- The replacement of natural turf with synthetic turf has complex mental, social and health influences on the local community depending on the social and environmental context of each playing field.
- Effects on accessibility, life quality, infrastructure access and amenity should be considered in community consultation and planning.

[90] For example, City of Ryde (2021) Open Space Lighting Policy https://www.ryde.nsw.gov.au/files/assets/public/council/policies/2021/open-space-lighting-policy.pdf
[91] FIFA. (2020). FIFA Lighting Guide: Standards, requirements and guidance for pitch illuminance systems at FIFA tournament stadiums and training sites. https://digitalhub.fifa.com/m/75486e34dc4aa39f/original/edawdowsmtr5fntxxwup-pdf.pdf
[92] Rugby AU. Sports Lighting- Australian Standard. https://d26phqdbpt0w91.cloudfront.net/NonVideo/e961ec99-886e-4177-84de-08d9467ea091.pdf
[93] International Hockey Federation. Facilities guidance sports lighting non-televised outdoor hockey: Performance and operational requirements Version 2.2. https://cdn.revolutionise.com.au/cups/hockeynsw/files/cq6qygheexcl0pbq.pdf
[94] Tennis Australia. Outdoor Court Lighting Information Sheet. https://www.tennis.com.au/wp-content/uploads/2013/02/Lighting-information-sheet-pdf.pdf
[95] Artificial Light at Night (ALAN)
[96] Obayashi, K., et al. (2018). Bedroom Light Exposure at Night and the Incidence of Depressive Symptoms: A Longitudinal Study of the HEIJO-KYO Cohort. *American Journal of Epidemiology*, 187(3), 427-434. Liu, J.A., et al. (2021). Disruptions of Circadian Rhythms and Thrombolytic Therapy During Ischemic Stroke Intervention. *Frontiers Neuroscience*. https://doi.org/10.3389/fnins.2021.675732
[97] Gaston, K.J., et al. (2014). Human alteration of natural light cycles: causes and ecological consequences. *Oecologia*,176, 917-931.
[98] Zhang, D., et al. (2020). A large prospective investigation of outdoor light at night and obesity in the NIH-AARP Diet and Health Study. *Environmental Health*, 19(74).
[99] Ticleanu, C. and LIttlefair, P. (2015). A summary of LED lighting impacts on health. *International Journal of Sustainable Lighting*, 17, 5-11.

5. Environmental impacts

Terms of Reference 2a, 2c and 2d asks for advice on potential water, environmental and ecological impacts. This Chapter discusses the evidence associated with these impacts, including:

- potential water pollution impacts and mitigation measures (Section 5.1)
- opportunities to maintain soils (Section 5.2)
- light and heat impacts (Section 5.3 and 5.4).

An area of environmental concern raised in the Term of Reference 2b was the potential water pollution impacts associated with use of different materials in the construction and installation of synthetic turf and from water runoff. Glamore et al. (Appendix 4) provided advice on hydrology, including stormwater infiltration and drainage implications of field design and risks associated with pollutant and contaminant runoff from synthetic turf into the surrounding environment and waterways. Further expert advice regarding plastics, weathering and release of chemicals and microplastics in the environment was provided by Palanisami (Appendix 19).

Similar concerns about toxicant and plastic pollution were raised regarding soil health. Pochron, with input from Vadakattu and the Review team provided advice on the importance of complex and healthy soil ecosystems, relevant research on potential environmental and ecological impacts of synthetic turf, and knowledge gaps (Appendix 17).

Term of Reference 2c sought advice on potential environmental and ecological impacts, including changes to fauna habitat and wildlife corridors. There are a range of potential impacts to biodiversity caused by replacing natural grass with synthetic surfaces. These impacts extend beyond the footprint of the field in question, including:

- tree canopy loss, through root removal or dieback
- biodiversity change
- biodiversity loss and health impacts for particular fauna (e.g. reported incidences of synthetic turf ingestion)
- habitat loss (e.g. insects and grass seeds)
- disruption of habitat corridors, increased edge effect potentially leading to population fragmentation.
- increased artificial light at night (ALAN)
- increased heat from the synthetic surface.

These impacts were discussed with experts during the Review. They are site specific in that they rely on understanding the flora and fauna present in the area. The potential impacts of light and heat were the subject of commissioned advice from Hochuli et al. (Appendix 16). Impacts of light and heat originating from synthetic turf sporting fields on the ecosystem is often not considered in planning processes. However, the impacts of artificial light and urban heat is the subject of a growing field of research.

Links to papers: Appendix 4, Appendix 16, Appendix 17, Appendix 19.

5.1 Potential water pollution impacts

Synthetic fields have high infiltration capacities and field design can have a positive or negative impact on the volume and timing of water entering the stormwater network. Under the field, infiltrated water is usually managed by one of three main drainage designs - horizontal drainage, vertical drainage through a gravel aggregate base with pipes, or vertical drainage through a gravel aggregate base without pipes. Vertically draining bases delay and store rainfall for longer, placing less stress on the stormwater network. In NSW, councils advise that horizontal systems have been used particularly when there are vertical height installation limits.

The hydrologic implications of synthetic fields on runoff and infiltration are not well documented. However, pollution through field infiltration is generally unlikely because of the use of sand infill and calcite rich base aggregate in the third-generation synthetic turf system. Sand is known to be an effective filter for many pollutants while calcite can reduce zinc levels through absorption. Research into hydrology and mitigation of environmental risk is detailed as a research priority in Chapter 9.

5.1.1 Stormwater management

The construction of synthetic turf fields can have positive or negative impacts on the volume and timing of water entering the stormwater network (Glamore et al., Appendix 4).

Short intense rainfall periods are most likely to affect the infiltration system of a synthetic turf field. However, generally it could be expected that surface runoff is unlikely to exceed the infiltration capacity of a well-designed field more than a couple of times over its lifetime. Although, this may be affected by increasing frequency of intense rainfall events under climate change. Pooling and other issues are more likely attributable to the drainage system under the field, particularly in the context of moderate, long-lasting rain events.

Synthetic fields can be intentionally designed to assist with stormwater management and/or recycling of the rainfall on the field surface. This can only be achieved in fields with vertically draining profiles and is done by storing rainfall which infiltrates through the field in the base and controls the rate of discharge. Natural turf fields can also be the collocated with underground stormwater storage infrastructure. However such underground water tanks are typically used to store water from other parts of the stormwater network, rather than rainwater infiltrating through the field. Both natural turf and synthetic fields have large variability in their response and retention of stormwater based on the infiltration and storage capacity of either the soil (for natural turf) or synthetic system.

5.1.2 Chemical toxicants, microplastics and leaching risk

Zinc is considered the toxicant most likely to pose a risk to aquatic ecosystems. Associated with vulcanisation of tyres used for crumb infill, quantities found in runoff from synthetic turf fields exceed the guideline values for freshwater ecosystems.

Virgin rubber infill options appear to release less zinc and total toxicants overall. PAHs, metals and other toxicants may be of concern in some fields. Zinc concentrations are found to be highest in SBR (the most common infill used in Australia). Leaching from other types of infill and from the different components of the synthetic field such as shock pads and turf fibres are less researched and may present a different risk profile.

Weathering, UV exposure and the association of microbes with plastic material influences chemical leaching into the environment. Research under Australian conditions has found mixed contaminants including heavy metals, such as zinc found in SBR crumb, have higher toxicity and bioavailability than those in isolation (Appendix 19). In marine environments it has been found that the surface of microplastics from synthetic fibres and other sources facilitates sorption of chemicals to the particle surface, increasing bioaccumulation of contaminants. There is evidence of trophic transfer and microplastics in marine food chains (Carbery et al., 2018 in Appendix 17 and 19).[100]

Special attention should be given to fields with high toxicant loads located near sensitive ecosystems. Mitigation measures to manage leaching and pollutant transport off-field should reduce the risk. Flooding risks that may impact on this are discussed in Section 3.2.1 of this Review. Comparative studies to test the effectiveness of mitigation measures are recommended as a research priority (Chapter 9).

5.1.3 Migration of plastic pollution

While the majority of reports focus on the pollution impact of infill.[101] Both turf fibre blades and rubber infill pose a risk of being transported to waterways as plastic pollution and threatening aquatic life. Both rubber and fibre loss – fragments and blades – were observed on site visits. Loss may be substantial, especially at end of life or if a field is poorly maintained. Variations in fields makes quantification of loss and mobility of synthetic turf blades and rubber difficult. Turf blades are less dense than water and therefore more mobile yet have been subject to less research or risk assessments. Although denser than water, rubber infill is highly mobile, even in slow moving runoff.

The dispersal routes of small fragments of turf fibres and disintegrated infills include 'walk-off' on players' shoes, clothing or skin, maintenance equipment, removal with leaves, 'splash' from play, wind and transport through runoff to waterways.

Glamore et al. suggest most of the fibres and microplastics transported by players, maintenance, splash or wind will either remain in the soil surrounding the field or be removed by maintenance crews while the rest will be transported into water networks by any sizable rainfall event. The extent of the material migration into the environment may be increased through the players washing their clothes at home. Anecdotal feedback from players indicates this may be sizeable. Research suggests further work is needed in relation to the efficacy of washing machine filters and testing methods.[102]

Glamore et al. reviewed literature on attempts to quantify loss of microplastics to waterways (Section 2.2 of this Review, Appendix 4). Concluding that 10 to 100 kg of infill per year per field is likely to be transported from a synthetic turf field with no strategies to reduce infill migration in place and loss of turf fibres is likely to be in the 100s of kilograms per year. Field design and studies to understand the extent and impact of pollutant migration and effectiveness of mitigation strategies are proposed in Chapter 9 and Appendix 4.

Relevant observations from Review site visits and consultations are as follows. These observations should not be taken as a reflection of field managers, who clearly make great efforts and take pride in maintaining fields to the highest quality possible.

- Although not quantified, significant quantities of rubber infill and turf blades were regularly observed around and near fields, including some 5-10 metres from the side of fields. This appeared the norm in sites visited, with some exceptions.
- A mix of age and integrity of field composition, ranging from newly installed to states of significant ageing and deterioration. Two fields had observed quantities of material seen running into unfiltered drains.

[100] Carbery, M., O'Connor, W., and Palanisami, T. (2018). Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environment international, 115, 400-409. https://pubmed.ncbi.nlm.nih.gov/29653694/

[101] Olshammar, M., et al. (2021). Microplastic from cast rubber granulate and granulate-free artificial grass surfaces. The Swedish Environmental Protection Agency. Report 7021.

[102] Browne, M.A., et al. (2020). Pore-size and polymer affect the ability of filters for washing-machines to reduce domestic emissions of fibres to sewage. https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0234248&type=printable

- Design features to limit transport of plastics observed in synthetic turf fields included: dropped level of the playing field relative to the surrounding area; installation of solid surrounding curb; installation of low-level wooden bunding around a field (although not fully extended to ground level).
- Fencing with boot grates sited at exit gate points were observed on many although not all fields. The effectiveness of grates is not known. Some did not appear to be cleaned out; the quantity of material removed is unclear; players were observed to step over them.
- Mixed reports of using leaf blowers to remove material (maintenance unobserved) – some councils reported being advised to use these tools to remove leaves and debris in between maintenance services (direction of field centre to sides of field); service providers advised practice of using towards direction of the field).

Findings and insights:

- The construction of synthetic turf fields affects the stormwater management, which can be managed by having vertical drainage allowing storage and controlled discharge.
- Zinc, PAHs and other chemical leachate pose risks to aquatic ecosystem.
- Poor field maintenance and lack of infill and turf blades capture strategy contribute to microplastics pollution.

5.2 Soil health

There is increasing recognition and interest in Australia in understanding and protecting soil health and the ecosystems it supports.

Healthy soils are identified as Australia's most valuable natural asset and the value of soil greatly exceeds the value of land itself. This is reflected in the National Soil Strategy,[103] Interim Action Plan,[104] establishment of the role of Soil Advocate[105] and the soil science Challenge outcomes.[106]

Beyond the agricultural sector, soil health is recognised as central to delivering resilience to climate change and natural disasters, human health disease prevention and supporting ecological systems. Avoiding and mitigating physical impacts of compaction and degradation are an important part of the national strategy.

The incorporation of soil health in urban environments is a nascent field but is recognised as underpinning green infrastructure. It is anticipated that soil health indicators may play a role in decision-making, similar to the way canopy cover has been used as a metric in urban planning.

Healthy soil supports a lot of living organisms, particularly at the microscopic level of the soil microbiome. Generally the greater the complexity and diversity in the soil microbiome, the more resilient the environment. Applied research on the soil environment and microbiome indicates poor soil health outcomes in the footprint of a synthetic field. In isolation, a single field may appear minor. However, cumulative impacts of multiple fields are unknown, and may become increasingly relevant, particularly in urbanised areas with

[103] DAWE. (2021). National Soil Strategy. https://www.agriculture.gov.au/sites/default/files/documents/national-soil-strategy.pdf
[104] DAWE. (2021). Commonwealth Interim Action Plan: National Soil Strategy. https://www.agriculture.gov.au/sites/default/files/documents/commonwealth-interim-action-plan-national-soil-strategy.pdf
[105] DAFF. (2022). National Soils Advocate. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils/national-soils-advocate
[106] DAFF. (2022). National Soil Package. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils

low canopy and high average temperatures (Appendix 17). There is growing interest and research on the relationship between human health and soil, including in urban environments.[107]

The main impacts of installing a synthetic turf surface would likely be compaction and contamination. While the impact of installation directly on the soil ecosystem below it has not been studied. Research examining soil under impermeable surfaces has found an anerobic environment, which may lead to an increase in pathogens harmful to human health. Contamination from crumb rubber and other materials and additives used in synthetic turf have potential to adversely impact surrounding environments as particles and leachate travel through the soil and impact other environments. The impact of crumb rubber and its leachate is poorly studied in terrestrial systems but negative impacts on indicator species in laboratory experiments have been found (Appendix 17).

In order to understand the impact of surface changes such as the installation of synthetic turf, research partnerships and collection of soil health assessment and monitoring data is encouraged. The Australian Microbiome initiative is creating a continental-wide microbial genomic resource and has has established sampling methods and protocols.[108]

5.3 Artificial light at night (ALAN)

The impact of ALAN is not specific to turf type and would apply to both natural and synthetic turf surfaces that have artificial overhead lighting. Evidence suggests there are ecological impacts of ALAN, influencing the breeding and feeding behaviour of light-intolerant species. The most vulnerable species to ALAN are nocturnal animals that use light as cues for navigation and foraging activities. This includes insects, bats, turtles, birds and marine invertebrates.

There is limited literature examining the specific impact of ALAN on fauna in the context of sporting fields and current knowledge is heavily informed by faunal response to light in general. Light colour has been a particular area of focus with blue lights, the main colour of white LED lights, scatter more easily, increasing light pollution. A shift from sodium and mercury vapour lights to LED lights may be increasing the extent of light pollution.

The International Union for the Conservation of Nature (IUCN) gives broad advice on mitigating potential impacts of sporting fields on biodiversity, suggesting limiting lights and exploring new light technology. Emerging technology includes the use of different colours of light. There is some evidence that suggests red lights reduce impacts for bats and insects, but negatively impact migratory birds. Similarly yellow lights have shown little effect on turtles and insects, but negatively impacts amphibians.

There are significant knowledge gaps on the impacts on ALAN on Australian fauna, with most work examining Northern American and European species. Studies of the effect of ALAN on Australia fauna in terrestrial and marine systems are summarised by Hochuli et al. in Appendix 16 (Table 2). The Australian National Light Pollution Guidelines for Wildlife offer a good starting point for understanding mitigation measures for light pollution and sky glow on fauna, however, are limited in the suite of fauna examined (focusing on marine turtles, seabirds, and migratory shorebirds).

To fully understand the potential of light-related impacts to biodiversity associated with sports fields, place-based assessments that consider likely fauna that might be impacted

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[107] Li, G., et al. (2018). Urban soil and human health: a review. European Journal of Soil Science, 69(1), 196-215. Hazelton P. and Murphy, B. (2021). Understanding Soils in Urban Environments. https://ebooks.publish.csiro.au/content/understanding-soils-urban-environments-9781486314027#tab-info.

[108] CSIRO. (2019). Australia's microbiome on the map. https://blog.csiro.au/australias-microbiome-on-the-map/

specifically to that area are required. Targeted, species-specific local surveys in the region of the sports fields, including before and after (installation of lighting) would advance knowledge of faunal response; this is of particular importance given the different response to light, and the type of light, across species. Information about the time of year sky glow might be most detrimental would also be useful given some species in the region may be more sensitive with seasonal variability such as at breeding time (Appendix 16).

Experimental work on the light spectra, as well as installation variation such as the position of lights, angle, height and fauna response for light sensitive species such as bats and birds are also needed. There is currently little evidence of how these actions might impact biodiversity, especially in an Australian sporting field context.

There is global agreement on the need to limit ALAN to support biodiversity health. To date, solutions have largely centred on reduction in lighting levels. However, advances in lighting technology and understanding of colour and intensity would be useful to explore. Similarly, new approaches to light angles, use of filters and tree boundaries, although these remain largely untested. Guidelines for sporting organisations, which currently focus primarily on field performance and safety, should encompass impacts of light pollution on biodiversity. Good practice frameworks for managing and mitigating adverse impacts of lights from sports fields on fauna and research priorities are included in Appendix 16 and Chapter 9 of this Review.

5.4 Heat related impacts

There is incontrovertible evidence demonstrating the impacts of increased heat on biota. Most studies focus primarily on at-scale impacts of climate change. Evidence includes modelling species distribution, lab experiments and mesocosm temperature manipulation experiments. There is an emerging body of evidence from work examining potential impacts on species from increased heat, such as changed foraging and reproductive behaviours. These impacts are recognised to be relatively localised around the synthetic turf field (Hochuli et al., Appendix 16).

A study on Australian magpies found that heat stress had a significant negative effect on their performance.[109] Similarly, it was found that exposure to high mean daily maximum temperatures during early development in the cooperative breeding species, the Southern pied babbler (*Turdoides bicolor*) was associated with reduced survival probabilities of young in all three developmental stages.[110] The Urban Bird Conservation Action Plan (CAP), led by Birdlife Australia is currently underway with an aim to provide a framework for the coordination and collaboration of urban bird conservation across Australia, and identifies both light pollution and heat island effect as key threats faced by urban birds.[111]

Care must be taken to recognise the scale of synthetic turf relative to other factors and infrastructure contributing to urban temperatures and loss of green space. However, given the heat-related impact of synthetic surfaces, decision-makers need to consider this potential impact and undertake assessments that include the mix of field types, strategic tree planting and addition of other green features to reduce the overall heat on the surrounding environment.

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[109] Blackburn, G., et al. (2022). Heat stress inhibits cognitive performance in wild Western Australian magpies, *Cracticus tibicen dorsalis*. *Animal Behaviour*, 188, 1-11.

[110] Bourne, A.R., et al. (2020). High temperatures drive offspring mortality in a cooperatively breeding bird. *Proceedings of the Royal Society B*, *287*(1931), 20201140.

[111] BirdLife Australia. Urban Bird Conservation Action Plan. https://birdlife.org.au/projects/urban-birds/urban-bird-conservation-action-plan

Findings and insights:

- Incorporation of soil health in urban environmental planning is necessary as it underpins all other important environmental assets.
- The main concern is the potential impact of poor soil health on environments surrounding synthetic turf fields.
- Effects of light and heat from the construction and use of synthetic turf fields across different species are not well understood although there is evidence of some negative impacts.
- Strategic planting of vegetation around sites with synthetic turf installed will ameliorate some impacts of habitat loss, heat effects on fauna and light spill.

6. Recommendation Group 1: Planning and approvals

Planning is essential to balance meeting the requirements of the public now and into the future, encompassing sustainability and intergenerational equity. The requirement of the Review to address heat impacts on immediate users in public spaces, and on proximate residential areas is outlined in the second Term of Reference. The increasing recognition regarding the importance of reducing heat impacts is seen in the Premier's Priorities, which include increasing access to greenspace[112] and increasing tree canopy cover[113].

Objectives for planning in the Greater Sydney region include the commitment to 40 percent canopy cover under the Greening our City Program. Planning initiatives through the Greener Neighbourhoods[114] program seek to incorporate green infrastructure[115] into strategic planning. Examples include the Macquarie Park Strategic Infrastructure and Services Assessment (SISA),[116] Place-based Infrastructure Compacts (PICs)[117] and the Valuation Framework.[118]

Spatial data is critical in understanding and managing the relationship between urbanisation, surface cover, heat and related environmental and human health considerations. Planning in the Greater Sydney region is assisted by the spatial data layers for greenspaces, canopy cover and heat vulnerability, as well as analysis of the urban environment.

Analysis of surfaces across the Greater Sydney region has identified the Cooks River, Sydney Harbour, Parramatta River, Curl Curl Lagoon and Dee Why Lagoon catchments as having a high level of urbanisation with more than one-third impermeable surface area.[119] Some of the surrounding catchments have much lower proportions of impermeable surfaces with higher extents of tree canopy cover and greenspaces. A spatial layer identifying canopy cover for the Greater Sydney region has been captured by a 2019 dataset. The planned repeat collection of canopy cover datasets in 2022, 2024 and 2026 will enable measurement of change over time so that canopy cover can be used as a quantifiable metric for planning. With the aim of establishing and maintaining the commitment to 40 percent canopy cover.

Replacement of existing natural fields in residential areas with a synthetic field appears associated with the highest level of concern and dissatisfaction for nearby residents. Malodour commonly associated with higher temperatures is reported as a significant factor for some residents in close proximity to fields. Loss of ability to undertake activities previously enjoyed on a natural field (community events, dog walking) are also factors. With some issues ameliorated by: mitigation measures (such as screens for noise and privacy), control of off-field amenity factors (irrespective of field type), prompt management of complaints (such as increased traffic, parking, noise, lights) and early community engagement. Dedicated multi-field sports centres and hubs with parking and/or located in areas already associated with similar activities, traffic, light or noise were identified as more appropriate by many stakeholders.

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112 Greener Public Spaces: to increase the proportion of homes in urban areas within 10 minutes' walk of quality green, open and public space by 10% by 2023. https://www.nsw.gov.au/premiers-priorities/greener-public-spaces
113 Greening our city: Increase the tree canopy and green cover across Greater Sydney by planting 1 million trees by 2022. https://www.nsw.gov.au/premiers-priorities/greening-our-city
114 Greener neighbourhoods. https://www.dpie.nsw.gov.au/premiers-priorities/greening-our-city/greener-neighbourhoods
115 Green infrastructure: Network of green spaces, natural systems and semi-natural systems in urban environments. Government Architect NSW. Greener Places. https://www.governmentarchitect.nsw.gov.au/policies/greener-places
116 Greater Cities Commission. Innovation Districts. https://greatercities.au/innovation-districts/districts
117 Greater Cities Commission. Western Sydney PIC Program. https://greatercities.au/project/western-sydney-pic-program
118 DPE. Valuing green infrastructure and public spaces. https://www.dpie.nsw.gov.au/premiers-priorities/valuing-green-infrastructure-and-public-spaces
119 The Pulse of Greater Sydney 2020. https://greatercities.au/pulse-of-greater-sydney-2020/pi-4-addressing-urban-heat

While providing a safe and high-quality environment for sport and recreation, light pollution may adversely affect proximate residents. This may be in synthetic or natural turf fields. An increase in the number of lights, their intensity, the angle and spill of overhead lighting in sports grounds also have potential to impact fauna in a number of ways, including effects on reproductive and feeding behaviour. There is a lack of guidance for options to limit the impacts of light pollution on fauna in the vicinity, while managing positive amenity outcomes.

6.1 Participation needs analysis and future demand assessment

The Office of Sport has worked with organisations and individuals to develop Regional Sport and Active Recreational Plans.[120] The regional models are based on data sources that define the current situation in terms of participation and facilities, and also future demand assessment and needs analysis.[121] Stakeholders such as sporting associations, state sporting organisations (SSOs) and councils provide information on sporting demand and strategic direction.

Previously, participation in sport and recreation data was collected at a federal level via the Australian Bureau of Statistics (Exercise, Recreation and Sport Survey, ERASS 2001-10; ABS 2013-14[122] or through the Committee of Australian Sport and Recreation Officials (CASRO 2011-14). Since 2015, Sport Australia has conducted the AusPlay survey, a national survey to track sport and physical recreation participation in Australia.[123] AusPlay data is collected continuously throughout the year. Predominately through randomly selected computer assisted telephone interviews of approximately 20,000 adults and 3,600 children annually, with quotas for surveys set for each state and territory.[124]

AusPlay data is used to generate insights into participation rates and trends in organised sport and physical activity. Examples of analysis from AusPlay data include: AusPlay NSW Report,[125] Sport in Rural and Regional Australia,[126] and the NSW Office of Sport: Participation in sport and active recreation.[127]

Councils and some sporting clubs have information on sports field use through their own data management systems that record detail about bookings of particular sporting facilities. SSOs also collect sports participation data through the administrative processes of registering members. A number of companies in NSW and Victoria have produced interfaces to provide services to SSOs and councils to manage this data. Desensitised data of registered members from the SSOs is provided to the Office of Sport. Together with relevant sporting associations, the Office of Sport has conducted analysis of participation and projections of use. This analysis uses the Department of Planning and Environment population projection data to estimate number of participants by 2036.[128]

Planning for non-formal sport and passive recreation needs is also important, however, it is more difficult to identify its main data sources. A number of councils have used localised

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[120] OOS. Regional Sport and Active Recreation Plans. https://www.sport.nsw.gov.au/regional-delivery/regional-sport-and-active-recreation-plans

[121] OOS. (2017) Regional Sports Hub Model, Draft Report. https://www.sport.nsw.gov.au/sites/default/files/2021-04/oos-regional-sports-hubs-feb18.pdf

[122] ABS. (2015). Participation in Sport and Physical Recreation, Australia. https://www.abs.gov.au/statistics/people/people-and-communities/participation-sport-and-physical-recreation-australia/latest-release

[123] Clearinghouse for Sport. AusPlay Background. https://www.clearinghouseforsport.gov.au/research/ausplay/background

[124] Australian Sports Commission (now Sport Australia). History of participation data for sport and physical recreation in Australia. PSA History of participation data (clearinghouseforsport.gov.au)

[125] Owen, K., et al. (2021) AusPlay NSW: Participation in organised sport and physical activity amongst children aged 0-14 years. https://www.sport.nsw.gov.au/sites/default/files/2021-04/ausplay_nsw_kids_final_website.pdf

[126] Clearinghouse for Sport. (2021). Sport in Rural and Regional Australia. https://www.clearinghouseforsport.gov.au/kb/sport-in-rural-and-regional-australia#statistics

[127] OOS. Participation in sport and active recreation. https://www.sport.nsw.gov.au/participation-sport-and-active-recreation

[128] NSW DPE. Population projections. https://www.planning.nsw.gov.au/Research-and-Demography/Population-projections

surveys or other forms of community feedback to assess needs and future demand. Other recreation needs may be incorporated into metrices for liveability and greenspaces.[129]

6.2 Planning approval process

Excepting major stadia, local councils have primary responsibility for development and maintenance of sporting fields. In a context of constrained resources and climate futures, councils have the challenging task of managing competing values and interests, including availability and application of open space.

Council planning identifies recreation area zoning (RE1 and RE2[130]) in Local Environment Plans (LEPs). It is noted that the implementation in LEPs may differ across the state, and there is overlap with environmental areas, particularly in foreshores and waterway/creek corridors where zones may be a mixture of recreation and environmental.[131] NSW Government has recognised that the category of environment zones is too broad, and that land of environmental value based on ecological evidence will be referred to as 'conservation zones'.[132]

The majority of synthetic turf installations in NSW are the development of recreation areas and facilities carried out by a determining authority such as a government agency or council. In these cases, development consent is not required where the proponent is the determining authority for the proposed works[133], and the installation can be assessed by a Review of Environmental Factors (REF) under Division 5.1 of the *Environmental Planning and Assessment Act 1979* (EP&A Act).

A REF must address the requirements of s171 of the *Environmental Planning and Assessment Regulation 2021*[134], outlined in the Guidelines for Division 5.1 assessments (Table 4 of Appendix 2).[135] Although additional guidelines and resources may be developed.[136] REFs also consider relevant Environmental Planning Instruments such as LEPs and state environmental planning policies (SEPPs).

Analysis of a sample of REFs for synthetic turf installation showed gaps in consideration of environmental impacts, these are included in Table 3.

It has also been noted by the Review that the pathways for community consultation and complaint management is not always clear, such as the management of malodours. The *Environmental Planning and Assessment Act 1979* must comply with the common format and content outlined in the Standard Instrument (Local Environmental Plans) Order 2006 (Standard Instrument).[137] However, odour control works are included for sewage reticulation systems and waste disposal facilities only. Section 125 of *the Local Government Act 1993* gives councils the power to deal with public nuisance, defined as interference with the enjoyment of public or private rights. A nuisance is 'public' if it

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[129] Australian Urban Observatory. Scorecard for Sydney. https://auo.org.au/measure/scorecards/ (summarised in Australia State of the Environment Report)

[130] RE1: Public Recreation, including all land which is to be used for public open space or recreation purposes (including local, and regional, and future); RE2: Private Recreation. Taken from DPE (2007). Standard instrument for LEPs – Frequently asked questions. https://www.planning.nsw.gov.au/Plans-for-your-area/Local-Planning-and-Zoning/~/media/BFB0AD30FBAB4F9482A1F31D8CE80646.ashx

[131] Midcoast Council. (2019). Recreation Zone Review – Draft for exhibition. https://www.midcoast.nsw.gov.au/files/assets/public/document-resources/have-your-say/know-your-zone/recreation-zones-review-for-exhibition.pdf

[132] NSW DPE. (2022). Environment Zones. https://www.planning.nsw.gov.au/Policy-and-Legislation/Environment-and-Heritage/Environmental-zones

[133] Under the *State Environmental Planning Policy (Transport and Infrastructure) 2021*

[134] Environmental Planning and Assessment Regulation 2021. https://legislation.nsw.gov.au/view/html/inforce/current/sl-2021-0759

[135] DPE, June 2022, Guidelines for Division 5.1 Assessments. https://www.planning.nsw.gov.au/-/media/Files/DPE/Guidelines/Policy-and-legislation/SSI-Guidelines/Guidelines-for-Division-51-assessments.pdf?la=en

[136] For example: Local Government NSW. Council Roadside Reserves Project. https://lgnsw.org.au/Public/Public/Policy/REM-pages/CRR_Project.aspx

[137] https://legislation.nsw.gov.au/view/html/inforce/current/epi-2006-0155

materially affects the reasonable comfort and convenience of a sufficient class of people to constitute the public or a section of the public. Clear pathways to provide feedback at all stages of planning would assist identification and management of issues of concern.

Although decisions are made at a local level, there are benefits for more regularly assessing regional level impacts and opportunities as part of the planning process for synthetic fields (Table 3). Feedback to the Review indicates councils will often check with adjoining Local Government Associations (LGAs) to assess spill-over impacts or opportunities for shared infrastructure.

Consistently embedding regional level trends would not appear to add an additional impost given the Regional Infrastructure Planning approach established by the Office of Sport. It also appears consistent with the regional and district approach adopted by major sporting codes. Appendix 2 sets out information sources available at Local and Regional scales and available information sources on participation and user experience.

Table 3: Identification of apparent gaps and important environmental and human health considerations in the Review of Environmental Factors (REF) for synthetic turf sites

Factor	Coverage	Gaps and important considerations
Climate change	Climate change is sometimes included in a REF where the contribution of a synthetic surface to increased heat is acknowledged. Suggestions for mitigation of surface heat include using particular infill, mixing organic components or liquid to the surface and use/retention of shade where possible.	Expected impact from climate change or contribution of the synthetic turf installation to greenhouse gases does not appear to be quantified in REFs.
Soil characteristics and health	Soil testing data is collected as part of a REF.[138] Typically Environmental Protection Authority (EPA) standards are used for soils collection with a focus on contamination assessment.	The impact of installation and increasing the extent of impermeable surface is generally only considered in terms of flood liability in a REF, and soil health is not considered in the process. Soil testing data is generally not collated from REFs or other processes and is not used to inform future planning decisions. Collation of this data would contribute to larger-scale research and understanding of soil health and requirements in urban planning.
Waste and EOL	Waste disposal is generally only considered for the construction phase of an installation.	REFs typically do not address end of life plans for synthetic turf and associated products that are installed.
Contamination	Micro and nano plastic contamination: The *Protection of the Environment Operations Act 1997 (POEO Act)* definition of waste and water pollution encompasses micro- and nano-plastics, and synthetic fibre wastes are recognised in the EPA Waste Classification Guidelines.[139]	Micro and nano plastic contamination are generally not considered in REFs, and an Environmental Protection Licence (EPL) or mitigation measures are not required.
Impact on fauna	Some councils have a policy for lighting in the public domain. Lighting might be considered in an REF to ensure it is within the range expected for the location of the synthetic turf installation.	Impact on fauna outside the development footprint is generally not considered in a REF. Although increased heat, lighting, noise is expected through the installation process and afterwards in the surrounding area, fauna will be influenced in different ways. Increased light and heat can affect reproductive and feeding behaviour of some fauna; impacts cannot be understood as occurrence data of the nearby fauna

[138] Soil samples collected during a REF are typically analysed at a NATA accredited lab who summarise the results
[139] NSW EPA. Waste classification guidelines. https://www.epa.nsw.gov.au/your-environment/waste/classifying-waste/waste-classification-guidelines

		community is generally not collected in a REF.
Community consultation	Potentially not required for installations of synthetic turf.	Early community engagement that continues through the planning period enables discussion and representation of all stakeholders
Environmental impact on the community or reduction in range of beneficial uses	Potential for odour impacting nearby residents is not always considered.	Unpleasant odours may not be a health risk but impact the quality of life for some nearby residents and users of the field, resulting in a restriction of their use and habits. Legal pathways for managing odour complaints is not clear.
Participation and user experience	Councils, SSOs and associations and the OOS use participants information from registrations, AusPlay and other surveys to analyse the current situation, needs analysis and future requirements of sports participants. Technology using sensors, data analytics and machine learning is used in some sports fields to obtain reports on cumulative player hours, use hours, maintenance hours and EUH.	Data on user experience and on non-formal sport including passive recreation use of sites is generally lacking. Under the Smart Places Strategy, there is potential to electronically collect feedback on: experience of the site, damage or maintenance needed, injury details and location (potentially linking data collection such as the AIHW National Injury Database).
Spatial Data and metrices	Planning in the Greater Sydney region is assisted by the spatial data layers for greenspaces, canopy cover and heat vulnerability as well as analysis of the urban environment. Some spatial datasets such canopy cover have provision for future data collection in the Greater Sydney region, allowing canopy cover to become a trackable environmental metric.	If these spatial data layers were extended to include other areas of NSW, including measurement of impermeable surfaces, planning for the incorporation of synthetic turf installation and potential cumulative impacts at different scales (e.g. regional, LGA, Statistical Area Level 1 (SA1) and microclimate) could be better understood. Support for datasets of other essential factors such as soil health would generate other useful metrices.

6.3 Recommendations

Given longer-term climate and heat projections, attention should be given to mitigating environmental risk in existing and planned synthetic turf installations, implementing best practice natural turf management, advancing materials research into new alternative materials. A set of requirements for approval and funding of synthetic turf fields is needed to assist with the management of identified environmental issues, and the identified data gaps that currently limit decision-making and innovation.

Specific recommendations have been developed to allow NSW to reduce potential human health and environmental impact of synthetic turf through planning, design, and mitigation measures. These focus initially on managing pollutant ‘runoff’ and ‘walk-off’ risks and exploring the potential of best-practice design and maintenance of natural turf fields to meet increasing use requirements.

Approval conditions	
R1.1	NSW councils and other bodies approving the installation of new synthetic turf fields or replacement of existing fields adopt standard conditions of approval. As relevant, additional actions may be required for specific developments. A range of mitigation strategies should be implemented to manage pollutant ‘runoff’ and ‘walk-off’ risks. Approval standards include:

	a. Assessment of the cumulative impacts (including heat, extent of impenetrable surfaces, light, soil and water health) at a regional as well as local scale, from the addition of fields b. Fields are constructed with: i. a surrounding solid curb to prevent microplastic loss, as well as overland runoff entering or exiting the field ii. a drainage system which collects all water from the field surrounds to local drains iii. 200 micron filters, or biofilms as technology becomes available, within these drains to collect microplastics which leave the field and are mobilised by runoff. c. Stormwater treatment devices are fitted into drainage systems. Device performance is independently tested and verified, both in controlled conditions and in the field, such testing undertaken by an appropriately experienced, equipped and independent organisation. d. Fields located in proximity to or draining into a sensitive ecosystem are independently assessed. Runoff should be sampled, with testing outcomes reported on and remediation action taken to bring testing within acceptable scientific standards. e. A financial plan for (i) maintenance costs across the life of the field, and (ii) replacement, including a confirmed funding strategy f. An EOL management plan.
R1.2	DPE work with relevant agencies such as NSW Environment Protection Authority (EPA) and the Office of Local Government to provide specific advice regarding preparation of a Review of Environmental Factors (REF) for synthetic turf installations. This advice would supplement existing environmental factors guidelines such as the DPE Guidelines for Division 5.1 Assessments (2022), and build the capacity of councils and other proponents to address environmental and human health considerations for potential synthetic turf sites.
Funding conditions	
R1.3	NSW Government establish a requirement that grants or funding for synthetic or hybrid turf sporting fields comply with standard conditions of approval for receipt of NSW Government funds, being compliance with minimum data standards (Recommendation Group 3), approval standards and implementation of outcomes of the whole of life cycle management project.
Flood and fire risk	
R1.4	Risk assessments are undertaken, and synthetic turf fields are not approved in areas of high environmental risk. This includes bushfire prone areas and areas with a higher likelihood of flooding. Assessments and testing should be informed by relevant NSW Government emergency response agencies as well as independent expert advice, including advice contained in this report.
R1.5	Standards Australia, together with relevant state fire agencies (including Fire and Rescue NSW, the NSW Rural Fire Service) and research experts (including the NSW Bushfire Risk Management Research Hub, ARC Research Hub for Fire Resilience Infrastructure, Assets and Safety Advancements, Natural Hazards Research Australia and the CSIRO) review ignition and fire testing standards for synthetic turf sports fields in bushfire prone areas and provide advice to the NSW Department of Planning and Environment and the NSW Office of Sport on standards that should be used for approvals.
Management models	
R1.6	NSW Government commission an independent review and provide advice on the types, strengths and weaknesses of leasing and management models, and financial and governance arrangements between local government and other entities in relation to

	synthetic turf fields. The term ‘other entities’ includes sporting codes and bodies, schools and universities and other public, private and not for profit bodies. Findings should inform good practice guidance and future funding requirements. Drawing on data, experience and examples in NSW and comparable jurisdictions, advice should include: • The financial and access impacts of these arrangements as they pertain to both individual fields and sporting hubs. ‘Access impacts’ includes impacts on other sporting codes as well as informal sport and general community access. • The extent to which these arrangements are designed to recover (in part or whole) maintenance and replacement costs, and associated considerations and challenges.

7. Recommendation Group 2: Sustainability and end of life

Given the use of synthetic turf in public and private settings is increasing across NSW, a staged plan across government and non-government settings and sectors is required in order to develop appropriate standards and end of life solutions. A starting point is understanding the volumes, composition and fate of products used.

The process should draw on the considerable expertise in mapping systems and material flows to support the NSW Government's net zero target and circularity policies that has been undertaken in recent years. A recent successful example of ecosystems analysis and collaboration in NSW that may be useful is the Materials and Embodied Carbon Leadership Alliance (MECLA).[140]

The benefit of such an approach is the opportunity to design out and begin identifying substitutes for chemicals or compounds of concern used in production or installation at an industry-wide scale. The process should help inform future standards and certification of materials. Existing sporting certifications should also consider a more thorough approach to environmental assessment.

A standard on minimising infill dispersion developed in Europe has been adopted in Australia.[141] In Australia, the *Recycling and Waste Reduction Act 2020* provides a framework to manage the environmental health and safety of products across their lifecycle. With voluntary, co-regulatory and mandatory product stewardship arrangements. In NSW, the *NSW Plastic Reduction and Circular Economy Act 2021* makes provision for design standards and managing regulated products. The NSW Waste and Sustainable Materials Strategy 2041 and NSW Net Zero Plan Stage 1: 2020-2030 establish targets for resource recovery, waste reduction and decarbonisation.[142]

Best practice natural turf guidance assessed by the Review, such as the Lower Hunter guidelines, typically include information on water management, soil health and cultivar selection. Analysis in the guidelines reported that when both lifecycle costs and carrying capacity were considered, natural turf fields built to best practice were more cost effective than alternative options including synthetic turf.[143] Financial and resilience indicators can be used to compare construction, maintenance and lifecycle costs for decision-makers. Communicating evolving thinking on natural turf requirements and transitioning from standard/current to best practice appear equally important in optimising the capacity and longevity of natural playing fields.

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[140] Established with the support of NSW Government, the alliance has engaged all major industry stakeholders to reduce embodied carbon in the building and construction industry Details at https://www.wwf.org.au/what-we-do/climate/mecla#gs.axq850. A range of resources have been developed including case studies and tools relevant to specific sub-sectors and materials. https://www.supplychainschool.org.au/mecla/

[141] SA TR CEN 17519:2021. https://www.techstreet.com/standards/sa-tr-cen-17519-2021?product_id=2216625. Adopts CEN/TR 17519:2020. Draft CEN technical report https://www.estc.info/wp-content/uploads/2020/03/FprCENTR-17519-Public.pdf

[142] See https://www.environment.nsw.gov.au/topics/climate-change/net-zero-plan and https://www.dpie.nsw.gov.au/__data/assets/pdf_file/0006/385683/NSW-Waste-and-Sustainable-Materials-Strategy-2041.pdf

[143] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter.

7.1 Recommendations

The responsibility for sustainability and end of life solutions is greater than a single NSW Government agency or land manager and requires industry engagement. Consideration of emerging science and new materials is required, as well as alternatives such as natural turf. The adoption of best practice guidelines and benchmarks for natural turf in open spaces will support the capacity of natural turf sporting fields to meet demands for use.

Given the observed risk of deteriorating fields, synthetic turf installation should be subject to a set of requirements to ensure best practice use during the product lifespan and appropriate end of life planning and disposal to avoid stranded assets.

End of life management plan	
R2.1	A requirement of approval for the use of synthetic turf is an end of life (EOL) management plan that is consistent with the intent and provisions of the NSW Waste and Sustainable Materials Strategy and the *NSW Plastic Reduction and Circular Economy Act 2021*. If the preferred EOL option is unconfirmed, a contingency plan should be developed.
R2.2	The practice of cutting up EOL sporting fields for use in other settings should not be approved as an acceptable EOL plan
Best practice for improving management and decisions based on whole of life cycle	
R2.3	The DPE and the NSW Office of Sport work with Hunter Water, Sydney Water, local councils and sporting codes to support adoption and take up of best practice guidelines and benchmarks for natural turf in open spaces. An expert technical advisory group should be established to support development of priorities and a staged implementation plan. This includes advice on the nature and extent of the 'gap' between best and current practices and condition assessment of fields.
R2.4	The EPA and the Office of Energy and Climate Change (OECC) coordinate a cross-government and cross-sector review on the use of synthetic turf in both public and private spaces in NSW and make recommendations on the whole of life cycle management of synthetic turf materials. The review should address issues identified in this Review and include but not be confined to: • quantification of and trends in the types and flows of all materials used in the manufacture, installation and recovery of synthetic turf in different sectors (including sport, recreation, education, residential, other public/private infrastructure) • composition and traceability of materials • relevant standards and certifications • design and potential to substitute components to reduce or eliminate materials or chemicals of concern • producer responsibilities • appropriate EOL strategies • alignment with the waste hierarchy and relevant NSW sustainability and net zero policies and targets • provisions under the NSW *Plastic Reduction and Circular Economy Act 2021*.

8. Recommendation Group 3: Data

8.1 Minimum open data requirements

A large amount of data is already collected about natural and synthetic turf sporting field installation and maintenance. However, it is not currently collated and made openly accessible. Table 4 sets out open data requirements to make this possible. While the parameters listed in the following tables are relevant to sporting fields, the majority can be applied to natural and synthetic turf applied in other settings. Table 5 sets out minimum data requirements, presented in three parts – site characteristics, installation data and maintenance data.

An extended data set that would build on minimum data requirements over time is set out in Tables 6 and 7. Table 6 includes data commonly collected but may not be routinely collected at all sites. Table 6 includes finance data that is currently accessible from different sources, but to aid decision-making could be collated. In this process it could be de-identified and possibly presented in ranges.

Table 7 encompasses two aspects of data not previously collected in NSW - life cycle analysis and injury. Sports relevant data collected on injury and the site details may be shared with the National Sports Injury Data Reporting Tool[144] (currently in development) in-line with the NSW Information Management Framework and relevant standards, including the Smart Places Data Protection Policy.[145]

Data parameters proposed could be tested as part of the guidance on synthetic turf sporting fields for councils being developed by DPE. Consultation on the guidance represents an opportunity to test also how readily elements from existing data sets from different sources (e.g. from maintenance reports, participation in sporting organisations, audits and environmental assessments) might be incorporated into an existing open data platform.

Table 4: Open data requirements for synthetic turf and natural turf data

Open data	Is publicly available and supports robust decision-making, including infrastructure decisions. It is findable and readily accessible, is high quality (dependable), and is in a usable format that can be integrated with other data and information. Open data is transparent and open to scrutiny
Infrastructure	Includes above- and below- ground works (drainage, irrigation, surface) for synthetic, hybrid and natural turf fields
Transparency	Includes clarity about the source of data, how it is collected and analysed, by whom and details of data gaps and limitations. Transparency encompasses information about how data is processed and if modelled, parameter and model assumptions. Where relevant, the assessment and management of risk and uncertainty is well described, A glossary and definition of terms used is included, building on the NSW Government Data Glossary[146]
Use	Includes use by organised sport through sporting codes, and where possible, casual sport and recreational users. Use data includes demographics, sports injury data and the type of field on which the injury occurred and feedback from end users about the fields, including type and location of the field. Demographic use data, injury data and end-user feedback data should be appropriately de-identified and managed in accordance with NSW privacy provisions

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[144] National Sport Injury Data Collection Survey Preview. https://survey.websurveycreator.com/s.aspx?t=0093ba5c-d871-4fee-8154-9cf45937c539&lang=en
[145] Smart Places Data Protection Policy (Draft) https://data.nsw.gov.au/data-protection-policy
[146] NSW Government Data Glossary. https://data.nsw.gov.au/nsw-government-data-glossary

Data management	Accords with the NSW Government Data Strategy, including but not confined to the Information Management Framework,[147] the Infrastructure Data Management Framework (IDMF)[148] and the Data Quality Reporting Tool[149]
Accessibility	Data is made available through NSW Government Open Data Portals such as the Spatial Collaboration Portal[150] and the SEED portal[151]
Minimum data standards	Standardised collection and analysis and metrices, applying Australian and New Zealand Environment and Conservation Council (ANZECC) or industry standards where applicable/ agreed. Includes required minimum data with options for additional data to be stored / appended to the online platform/

[147] Informational Management Framework. https://data.nsw.gov.au/information-management-framework
[148] Infrastructure Data Management Framework. https://data.nsw.gov.au/IDMF
[149] Data Quality Reporting Tool. https://data.nsw.gov.au/data-quality-reporting-tool
[150] Spatial Collaboration Portal. https://portal.spatial.nsw.gov.au/portal/apps/sites/#/home/
[151] SEED: The Central Resource for Sharing and Enabling Environmental Data in NSW. https://www.seed.nsw.gov.au/

Table 5: Minimum data requirements (public open spaces) synthetic turf and natural turf
Some data parameters are specific to either natural or synthetic turf, while others are common to both

<table>
<tr><th>Natural turf</th><th>Synthetic turf</th></tr>
<tr><td colspan="2"><u>Part 1: Site Characteristics</u></td></tr>
<tr><td colspan="2">Geolocation, street address and site name</td></tr>
<tr><td colspan="2">Surface type (categorised list: synthetic, hybrid, soil profile, natural turf sand profile, natural turf soil profile)</td></tr>
<tr><td colspan="2">Replacement year/s (if turf is partially or completely replaced)</td></tr>
<tr><td colspan="2">Total area of surface (spatial polygon, ha)</td></tr>
<tr><td colspan="2">Total area of sports playing surfaces (spatial polygon, area, if applicable)</td></tr>
<tr><td colspan="2">Number of sporting fields (categorised list to include full and small sized fields by sport activity)</td></tr>
<tr><td colspan="2">Cricket pitches and batting cages (number, in oval/practice nets and surface type)</td></tr>
<tr><td colspan="2">Microclimate modifiers (categorised list including: natural windbreak, canopy with summer shade/winter shade)</td></tr>
<tr><td colspan="2">Presence of stormwater flows from surrounding areas: buildings, car parks, embankments etc</td></tr>
<tr><td colspan="2">Stormwater discharge point/s (geolocated)</td></tr>
<tr><td colspan="2"><u>Part 2: Installation and asset renewal for new, full or partial replacement of surface</u></td></tr>
<tr><td colspan="2">Type of installation (e.g.: new synthetic turf, full/partial replacement synthetic turf, natural turf to synthetic turf)</td></tr>
<tr><td colspan="2">Year of installation</td></tr>
<tr><td colspan="2">Design use (e.g. high foot traffic, playground, sport field etc.)</td></tr>
<tr><td colspan="2">Sports line markings (categorised list of sports)</td></tr>
<tr><td colspan="2">Surface type, manufacturer/installer</td></tr>
<tr><td colspan="2">Drainage layer present, manufacturer/installer</td></tr>
<tr><td colspan="2">Irrigation system present</td></tr>
<tr><td colspan="2">Soil tests undertaken</td></tr>
<tr><td colspan="2">Depth of underlying gravel layer if present</td></tr>
<tr><td colspan="2">Standards testing results and date (if applicable, data results from experts can be uploaded)</td></tr>
<tr><td colspan="2">Stormwater treatment</td></tr>
</table>

	Infill and microplastic control devices installed and storage capacity of each
	Pile type/ height
	Infill type, manufacturer/installer, volume on installation
	Base layer, manufacturer/installer
Part 3: Maintenance Practice, for each maintenance entry, associated occurrence data includes a record of: date, time in, time out, difficulty accessing the field, person/organisation inspecting the field	
Irrigation (water use and system check)	
Drainage system check and cleaning	
Minor repairs to small high wear areas, depressions etc	
Type of damage/ repair requirement and remediation action	
Hours/days closed due to damage	
Evidence of field rotation, status of goal box, penalty box	
Presence of any pests/weeds, pest/weed control, wetting agent (date, type, amount)	
Presence of mottling or anaerobic activity	
Surface slope (cross fall) and slope length	
Oversowing with ryegrass over winter (date, rate of application)	Cleaning and grooming, field debris, stain removal (date and type)
Top dressing (date, type [e.g. sand/soil] and amount)	Deep cleaning
Presence of wear spots (categorised list describing surface evenness)	Presence of wear spots (categorised list describing surface evenness); Infill depth and variation across the site, volume of any top-up
Surface hardness and traction (according to standard/typical measures)	Presence of seam breaks/degradation
Turf visual quality, health and density	Pile direction and condition
Turf coverage (percent cover of turf species, weeds and bare ground) and variation across the site	Evidence of infill or surface blade migration
Mowing (date/frequency, height of cut)	Microplastic and infill controls (brush grate, walk-off mats, extraction devices in drains) checked and the amount extracted (volume) and destination (e.g. reused on site, recycled, landfill)
Physical treatment (date and type e.g. aeration, dethatching, etc)	Moss, algae and anti-microbial treatment, Power brushing, join and seam maintenance (date and type)

Table 6: Extended data set to be developed over time: currently not routinely collected
Data parameters are the same for natural and synthetic turf. All parameters would be linked to the data collected in Part 1-3 (Table 5)

Part 4: Soil characteristics, Soil testing is conducted for synthetic turf surfaces prior to installation, testing of natural turf may be conducted annually
Number of locations assessed within the site, date assessed
Description of soil physical characteristics
Topsoil texture classification, texture, depth and variation across the site
Topsoil infiltration rate (field measurements)
Subsoil texture classification and variation across the site
Presence, extent and location of water repellency
Presence and location of tree roots from surrounding areas
Visible root depth
Infiltration rate of other layers including subsoil (field measurements)
Readily Available Water (RAW): from laboratory tests and/or field measurements
Volumetric Soil moisture content
Soil chemistry test results can be uploaded (and date)
If turf on sand profile: depth of profile, particle size and shape characteristics, depth of thatch, thatch and black layer management, height of perched water table
Part 5: Irrigation, drainage and stormwater systems (where applicable)
Field drainage system type: e.g. sub-surface, sand slit
Irrigation system type (categorised list including: manual watering, sub-surface, sprinklers, sand slit)
Irrigation Water Source(s) and Quantities Used
Irrigation system maintenance activities (routine and reactive)
Irrigation system performance: evenness of coverage (Distribution Uniformity, Scheduling Coefficient), application rate, pressure and spacing variation, amount of under and overspray
Drainage system type
Field drainage system parameters: pipe sizes, slopes, spacing, discharge rate
Drainage maintenance activities (e.g. sand grooving, inspections, testing)

Discharge capacity of stormwater system and design event (e.g. 10% AEP)
Part 6: Use and wear, restrictions on use – specific to sites where the design use is a sport field
Winter sport played (from a categorised list)
Summer sport played (from a categorised list)
Level(s) of competition (categorised list: community, development, representative, elite)
Competition age brackets (categorised list: children [< 12 years old], juniors [12-16 years old], open age)
Number of registered players in each sport, age bracket and competition level
Regular School use: Age and number of students
Number of matches and training sessions each week for each sport, age bracket and competition level
Casual and training use: date, activity and number of participants
Seasonal break between summer and winter (categorised list to select months)
Number of cancellations/days lost and reason (e.g. adverse weather conditions, hazardous weather, damage)
Part 7: Finance data (de-identified collated data, possibly presented in ranges)
Construction cost
Replacement cost
Asset renewal (or partial replacement) cost and timeframes
Annual routine maintenance cost
Reactive maintenance cost (e.g. vandalism damage)

Table 7: Data not currently collected for natural and synthetic turf sites but would contribute to better decision making
Data parameters are the same for natural and synthetic turf. All parameters would be linked to the data collected in Part 1-3 (Table 5)

Part 8: LCA to include but not be limited to the following parameters
LCA (details to be addressed), including energy and water efficiency, environmental controls, greenhouse gas impacts, waste disposal, end of life for all materials
Energy and water use and efficiency measures
Greenhouse gas impacts
Lifecycle cost

Expected asset life (years)
On-site environmental controls and mitigation measures
Waste (extent and type) and fate of waste generated during construction, routine maintenance, asset renewal and end of life disposal
Part 9: Injury
Age bracket
Role of injured person (categorised list: player, coach, ref, spectator, other)
Sport being played, level of competition, cause of injury, activity at time of injury (e.g. playing, training, cooling down etc.)
Injury body parts/tissues (categorised list)
Injury onset (categorised lists: sudden/gradual, new/ previous)
If medical attention sought (categorised list: yes, no, yes and plan to seek further)

8.2 Recommendations

A more accessible and reliable source of verified information is required. To enable informed investment decisions about surfaces installed in public open space, specific recommendations have been made to allow for the establishment of minimum open data standards for sporting fields, with the aim to broaden data capture to include other applications of synthetic turf across NSW.

This could be integrated with other data sets to support forward planning and investments, test assumptions and, over time, ground-truth observations, support transparency and accelerate innovation.

Data collection and accessibility	
R3.1	The NSW Office of Sport and the Office of Local Government, with the support of peak bodies such as Local Government NSW (LGNSW) and Sport NSW, work with the NSW Chief Data Scientist and the Data Analytics Centre to ensure (a) an integrated 'whole' of system' approach to sporting infrastructure data (b) implementation of minimum data standards and (c) development of an action plan to drive the maturity of sport and recreation data collection and use. This includes technologies and tools to support collection, analysis and reporting. The expertise of existing entities should be drawn on, such as the NSW Data Champions Network and the NSW Sharing and Enabling Environmental Data (SEED) Board.
R3.2	NSW and local Government agencies work with industry (including maintenance suppliers) to expedite the development of an app for real time collection and reporting of maintenance data from synthetic, hybrid and natural turf fields. The initiative might benefit from a technology challenge approach. Given broader interest, engagement of other Australian jurisdictions should be explored. Data collection should be in accordance with the minimum data standards.
R3.3	Data to assist the development of best practice guidelines and benchmarks for synthetic turf in open spaces to minimise environmental and human health impacts. To address best practice maintenance practices that the Review has identified due to improper use in some cases, including the use of leaf blowers on synthetic turf surfaces with rubber crumb infill.
Smart technology	
R3.4	The NSW Smart Sensing Network (NSSN) convene an industry - local government forum to progress options for a pilot data collection about the comparative carrying capacity of synthetic and natural turf fields under NSW conditions. As possible, the study should include different types of synthetic fields. The forum should draw on NSW expertise in sensing, data analytics, artificial intelligence and machine learning.
R3.5	As part of the Smart Places strategy, the NSW Department of Planning and Environment facilitate development of an app to gather real time feedback on user experience of the use of synthetic turf in public open spaces. Pilot testing should include sporting fields, local parks and playgrounds. Outcomes should be analysed and published to drive innovation and improvement in all surface types.

9. Recommendation Group 4: Research program

During the process of the Review, commissioned experts were asked to identify the most impactful and critical research priorities for future work. These research recommendations are summarised in Table 8 (with more detail in relevant Appendices).

Research priorities fall into main themes. These themes are inter-related and often recommend product innovation to meet environmental sustainability demands. The research program recommended in this section and the development of a strategic direction and decision-making framework in NSW (Recommendation Group 1 and 2) all require a foundation of accessible data (identified in Recommendation Group 3). Involvement of stakeholders in information collection and communication of research results is essential.

9.1 Chemical constituents of synthetic turf

Many of the commissioned experts, from diverse research areas, identified a singular major knowledge gap - that chemical constituents of synthetic turf components, and their associated human and environmental health impacts are not fully known.

There is a need for laboratory and on-site studies conducted under Australian climatic and environmental conditions, and human health assessments across age and demographic categories. The development of a chemicals and materials library for synthetic turf components could inform leachate toxicant and pollutant identification and identify the impacts of synthetic surfaces on ecological and human health. Including chemicals and additives used during production, and materials such as SBR rubber that have a high variability. Data collection should occur through a research and knowledge hub to encourage collaboration from interdisciplinary academic communities, local councils and sport associations. Shared platforms through Cooperative Research Centres (CRC), ARC linkage programs, or other networks that are co-funded by government and other agencies should be considered.

Table 8: Summary of research priorities from experts commissioned by the Review
Note: Further details on each are contained in the relevant appendix

Theme	Priority research actions
Chemical constituents of synthetic turf: multiple appendices	Analyse the components of synthetic turf to identify chemicals and understand potential toxicity in isolation and as mixed contaminants
Human health: Appendix 3, 12, 19	• Epidemiological studies or health risk assessments to provide a more accurate understanding on how outdoor synthetic turf fields may behave under local climatic conditions and the potential health risks involved in Australia. • Survey local communities to determine the implications on the physical, mental and social dimensions of health in that community • Injury: Data capture, starting from existing data collected by sporting organisations and sport insurers (will be reported through National Sport Injury Project, if available)
Heat impacts, thermal comfort and heat-related health risks: Appendix 7, 8, 9	Heat impacts: • Measure the key environmental parameters influencing heat: ambient temperature, mean radiant temperature, absolute humidity and wind velocity on synthetic grass surfaces in a range of environmental conditions and geographical locations. Model and predict the rate of heat exchange to explore whether synthetic grass surfaces can affect heat gain • Examine influences of different environmental parameters, including solar irradiance on surface temperatures and the resultant warming ambient near-surface air above and around synthetic turf surfaces. Test whether the increased solar reflectance elevates the radiant heat load around the surface, and whether this increases heat gain by radiation. Examine the influence of area and type of synthetic turf technology used • Quantify the effectiveness of mitigation and avoidance of extreme surface heat of synthetic turf surface: Quantify the cooling magnitude, cooling duration and cooling distance of a range of applicable interventions that differ in scale and complexity Thermal comfort and heat-related health risks: • Does synthetic grass surfaces affect markers of heat stress and thermoregulation in humans. Examine the impacts of radiant heat from unshaded synthetic turf surfaces on human thermal comfort, including that of young children • Identify thermal indices based on user profile and activity: Heat balance models/ thermal indices to be applied appropriately to specified users (i.e. children, active individuals with different metabolic output, clothing ensembles and activity speed) • Develop holistic suitability evaluation of thermal conditions through in-situ and ex-situ studies, apply findings to sport heat policies to determine whether modifications are required for synthetic grass surfaces
Smart sensing technology to measure field	Low cost pilot study using infrared or radar gate counters to track people entering and exiting fields to determine usage. To initially be tested on a single synthetic and natural turf field in the same locality, and include an examination of comparative carrying capacity

use: Appendix 11	
Contaminants and the environment: Appendix 4, 5, 19	Stormwater and wastewater: • Measure the discharge of several synthetic turf fields with the different three drainage designs (horizontal, vertical through a gravel aggregate base with pipes and vertical through a gravel aggregate base without pipes). Vertical drainage systems are not widespread in Australia and less understood • Collect discharge data by logging water levels at the drainage levels and analyse with reference to rainfall measurements, hydraulic modelling data and other data from industry • Immediate measures to treat stormwater and surface water drains to capture 99% of microplastics • Establish standard protocol for extracting microplastics from stormwater that could accurately differentiate turf plastics from the other suspended materials • Treatment solutions for micro and nano plastics in waste and grey water using advanced treatment technologies that extract more than filtration can Leaching: To investigate the effect of chemical leaching coming from a field located close to a sensitive ecosystem sample and test synthetic turf runoff from the location where runoff enters the ecosystem, examine whether zinc and other toxicant levels are within acceptable levels Microplastic transport and weathering from synthetic turf fields: • Perform laboratory study to test the transportability of different infill types and turf fibres on surfaces found around the synthetic turf fields, including concrete, grass and in pipes • Conduct field surveys to assess the loss of microplastics from synthetic turf fields of different ages and with different mitigation strategies to assess the variability in loss between fields and to allow quantification of the effectiveness of mitigation strategies • Measure synthetic turf microplastics found in waterways, the surrounding environment (i.e. grass and soil) and in the stormwater systems with the fields tested have or do not have curbs and surrounding drainage • Note the effects of maintenance regimes on infill loss • Assess the effectiveness of filters within drains surrounding synthetic turf fields (especially if specific proprietary devices are used) by searching microplastics downstream of the filter • In-situ and laboratory weathering studies incorporating chemical mixture and microbial interactions, seasonal and climate effects on the microplastics and chemical release.
Soil health: Appendix 17	In-situ research on the environments surrounding synthetic turf fields. Examine spatial relationship of surface type and use, soil variables, soil organisms and surface biota using spatial design distances out from identified synthetic turf surfaces
Odorant monitoring: Appendix 14	• Measure the odorants coming from synthetic turf through in-situ experiments using dynamic flux member measurements or through lab analysis, studying the effect of temperature on the odorant release • Involve the community to capture essential factors involved in perceiving environmental odours (i.e., characteristics and qualities of the odours)

Air pollutant and exposure risk: Appendix 15	• Conduct epidemiological study and biomonitoring of PAHs, VOCs and other contaminants on larger population to understand population variability • Conduct further research on the impact of chemicals released by turf to children while playing on synthetic turf surface. • Conduct longitudinal studies on exposure to turf-associated chemicals amongst sports players to gauge the long-term health outcomes from chemical exposure from synthetic turf pitches
Impacts of artificial lights at night: Appendix 16	• Before and after surveys to understand the local species composition and potential effects after light installation. There is an urgent need to undertake experimental approaches at new developments to test the predictions from work. Local surveys are required as species-specific responses are varied. These surveys should include a wide range of taxa, and include species listed in State and Commonwealth threatened species legislation, and examine the light spectra and intensity used in different installations • Study the effects of installation position of lights, such as angle and height, to be more efficient and minimise the effect of spill light in dark areas, although this may be of benefit to humans in reducing light pollution, it is not clear if there are benefits to fauna • Address knowledge gaps to enable lighting guidelines that incorporate the range of potential impacts to different fauna, as well as providing safe and high-quality environments for sport and recreation, and significant guidance for options to limit the impacts of light pollution
Bushfire risk: Appendix 10	• New testing methodology that includes high temperatures and wind conditions as experienced in bushfire prone areas • Develop alternative infill materials optimised for high flammability resistance while meeting other physical/ chemical/ environmental/ economic/ aesthetic requirements • Improve the flame retardancy of the blades and infill materials by incorporating flame retardant fillers that are non-toxic and suited for extreme outdoor conditions. The fillers can be of hydrophobic nature to improve the durability of the flame-retardant fillers
Development of new materials: Appendix 5, 19	Incorporate environmental and social aspects during the development and explore options for bio-based materials.
Life Cycle Analysis: Appendix 6	Relevant NSW Government agencies to collect data from local councils and sports organisations to determine an appropriate LCA

9.2 Recommendations

This Review identified significant knowledge gaps in key areas of concern, which hinders effective decision-making. Data collection should be complemented by the research program to address key knowledge gaps in human health and environmental impacts.

Research collaboration	
R4.1	The NSW Department of Planning and Environment (DPE) work with relevant agencies at state and local levels to co-convene an industry-research Roundtable series. To assess research initiatives identified by this Review and identify pathways for implementation to address key knowledge gaps. Given broader application and interest it would be advisable to invite Commonwealth and inter-jurisdictional participation.
R4.2	A research priority is addressing the knowledge gaps regarding characteristics and composition, including the chemical composition, of materials used in synthetic turf and associated layers.

10. Appendices list

Appendix 1	Review Engagement
Appendix 2	Data
Appendix 3	Health Impact of Synthetic Turf (Artificial Grass) Surveillance and Risk Unit, Environmental Health Branch, Health Protection NSW, NSW Health
Appendix 4	Independent review into the design and use of synthetic turf in public space – WRL Technical Review Water Research Lab, University of New South Wales (UNSW) Sydney Associate Professor William Glamore, Dr Francois Flocard, Ms Margot Mason
Appendix 5	Synthetic Turf in Public Spaces – Chemical composition of materials University of Technology Sydney Institute for Sustainable Futures Associate Professor Nick Florin, Dr Melita Jazbec
Appendix 6	Environmental Impact of Synthetic Turf: A Life Cycle Analysis (LCA) Review and Circular Economy Perspective Waste Transformation Research Hub, School of Chemical and Bimolecular Engineering, The University of Sydney Professor Ali Abbas, Mr Eric Sanjaya, Dr Gustavo Fimbres Weihs
Appendix 7	Synthetic turf in public spaces - systematic assessment of heat and environmental impacts Urban Planning and Management, Western Sydney University Associate Professor Sebastian Pfautsch, Dr Agnieszka Wujeska-Klause
Appendix 8	Synthetic Turf in Public Spaces: Thermal Comfort, Heat Strain, and Heat-related Health Risks UNSW Built Environment, UNSW Sydney Dr Negin Nazarian, Mr Pooriya Mohseni
Appendix 9	Limitations and future directions for research on environmental measurements on synthetic grass sports surfaces Faculty of Health, Southern Cross University Mr Gurpreet Singh, Dr Christopher Stevens
Appendix 10	Use of Synthetic Turf in Bushfire Prone Areas ARC Training Centre for Fire Retardant Materials and Safety Technologies, UNSW Sydney Professor Guan Yeoh, Dr Cheng Wang
Appendix 11	Smart sensing technology review: Measuring the usage of synthetic and natural turf in public places NSW Smart Sensing Network Dr Tomonori Hu, Ms Kimi Izzo, Dr Ayu Saraswati
Appendix 12	National Sports Injury Data Strategy Australian Institute of Health and Welfare Dr Sonia Glasson

Appendix 13 Per- and Poly-fluoroalkyl Substances (PFAS)
Request for advice to and response from the NSW PFAS Technical Advisory Group

Appendix 14 Odour of synthetic turf and its relationship with local communities
UNSW Odour Group, UNSW Sydney
Professor Richard Stuetz, Dr James Hayes, Dr Ademir Prata, Dr Ruth Fisher

Appendix 15 Artificial turf and air quality in sporting fields: Review
School of Pharmacy, The University of Queensland
Dr Shamshad Karatela

Appendix 16 Environmental lighting and heat impacts
School of Life and Environmental Sciences, The University of Sydney
Professor Dieter Hochuli, Dr Caragh Threlfall
School of Biological, Earth and Environmental Sciences, UNSW Sydney
Dr Mariana Mayer Pinto

Appendix 17 Soil Health
School of Marine and Atmospheric Sciences, Stony Brook University
Associate Professor Sharon Pochron
CSIRO
Dr Gupta Vadakattu
Synthetic Turf Review team, Office of the Chief Scientist & Engineer

Appendix 18 Natural turf sporting surfaces
Synthetic Turf Review team, Office of the Chief Scientist & Engineer

Appendix 19 Environmental Plastics
Environmental Plastics Innovation Cluster, The University of Newcastle
Associate Professor Thava Palanisami

Appendix 1
Review Engagement

DPE had established a working group of 30 plus urban and regional councils that had expressed an interest in providing advice on the synthetic turf guidance being developed. The Review presented to this group, then followed up with a detailed request for advice.

The information sought included fields established or planned, including the number of fields in the LGAs, whether they are existing or planned, year of installation, area, use design, description of materials used, history of land on which the fields are located, records of damage, maintenance and repair, replacement, sports or recreational use, type of surfaces and environment adjacent to the fields, and whether the fields have been used for studies or sampling work. The list of councils initially contacted is at Table 1.

Table 1: Initial request for information to NSW local councils

Bayside Council	Hunters Hill Council	Port Macquarie Hastings Council
Bega Valley Shire Council	Inner West Council	Randwick City Council
Blacktown City Council	Ku-ring-gai Council	City of Ryde
Camden Council	Lake Macquarie City Council	Snowy Valleys Council
City of Canada Bay Council	Lane Cove Council	Tamworth Regional Council
City of Canterbury Bankstown	Liverpool City Council	Tenterfield Shire Council
Cumberland City Council	City of Newcastle	The Hills Shire Council
Fairfield City Council	Murray River Council	Waverley Council
Georges River Council	Northern Beaches Council	Wollondilly Shire Council
Gunnedah Shire Council	Penrith City Council	Wollongong City Council
Hornsby Shire Council		

Additional advice and information were also requested and provided by Bathurst Regional Council, City of Sydney and Greater Sydney Parklands.

The Review team worked with relevant councils to arrange a number of formal site visits. The purpose of the site visits was to have a close inspection of various fields and surfaces, obtain additional information from council staff and local communities relevant to the Review Terms of Reverence, including technical issues related to the field installation, maintenance, any records held by council related to field planning, management plan and regulatory approval process regarding field replacement or upgrade. Meetings were held with staff and officials from the following councils, with a list of fields viewed both formally and informally over the course of the Review at Table 2.

- Blacktown City Council
- City of Canada Bay Council
- City of Sydney Council
- Northern Sydney Council
- Ku-ring-gai Council
- Penrith City Council
- Waverley Council
- Wollongong Council

Site visits were undertaken at different times of the day and during the week (mornings, afternoons, evenings, weekdays and weekends), with some fields visited two or three times. from morning until evening.

Table 2: Site visits

LGA	Fields
Bayside Council	Gardiners Park, Hensley Athletic Field,
Blacktown City Council	Fyfe Road Rugby League Field, Kellyville Ridge, Blacktown Football Park (Blacktown International Sports Park)
City of Canada Bay Council	Majors Bay, Cintra Hockey Complex
City of Sydney	Alan Davidson Oval, Getiela, Gunyama Park, Moore Park synthetic field, Perry Park, Turruwul Park
City of Wollongong	Kooloobong Oval, Sir Ian McLennan Oval
Inner West Council	Arlington Recreation Area, Henson Park, Leichardt #2, Leichhardt #3, Tempe Reserve fields
Ku-ring-gai Council	Barra Brui sports ground, Karuah Park, Norman Griffiths Oval, Rofe Park
Mosman council	Middle Head Oval
North Sydney Council	Cameray Park, North Sydney Oval
Northern Beaches Council	Brookvale Oval, Cromer Park, Melwood Oval
Penrith City Council	Jamison Park
Randwick City Council	Coogee Oval, Heffron Park, Latham Park, Pioneers Park, David Phillips Sports Field
Sutherland Shire Council	Kareela Oval
Waverley Council	Waverley Oval

In addition to commissioned experts, the Review team met with or requested advice from government agencies, other research experts, industry representatives, the community and representatives from sporting bodies (Tables 3 to 7). Most meetings were followed by subsequent email exchanges and questions, with submission of articles, reports, policies, plans and data, some of which were provided in confidence.

Table 3: **Government representatives**

Name	Title	Affiliation
Jessica Aceski	Program Support Officer	Sustainability Victoria
Dr Merched Azzi	Atmospheric Research	NSW DPE
Sarah Balmanno	Manager Air Policy	NSW DPE
Janina Beyer	Contaminants and Risk -Science, Economics & Insights Division	NSW DPE
Jennifer Bräunig	Senior Scientist - Contaminants and Risk -Science, Economics & Insights Division	NSW DPE
Dr Pip Brock	Science Standards Officer	NSW DPI
Kent Burton	Facilities Consultant	WA Department of Sport and Recreation
Julie Cattle	Principal Technical Officer	NSW EPA
Derek Elmes	Acting Director Environment Protection Science - Science, Economics & Insights Division	NSW DPE
Anil Gautam	Senior Scientist	NSW DPE
Deborah Hailstones	Manager Science Strategy, Chief Scientist Branch	NSW DPI

Steve Hartley	Executive Director Green and Resilient Places	NSW DPE
Karen Jones	Chief Executive	OOS
Ruby Kan	A/Unit Head, Air Policy	NSW DPE
Louise Kristensen	Technical Policy Advisor-Air	NSW EPA
Maria Kwiatkowska	Director, Greener City	NSW DPE
Kishen Lachireddy	Principal Advisor at Health Protection NSW	NSW Health
Grace Lee		NSW Health
Adam Littman	Principal, Open Space Strategy	NSW DPE
Richard Loudon		NSW DPE
Fiona MacColl	Principal Advisor, Facilities, Strategy and Planning	OOS
Fiona Morrison	Commissioner Open Space and Parklands	NSW DPE
Celia Murphy	Executive Director - Policy and Planning	OOS
Dr Wayne O'Connor	Senior Principal Research Scientist at the Port Stephens Fisheries Institute	NSW DPI
Lucinda Pike	Senior Manager Open Strategy and Policy	NSW DPE
Ann Quinlan		VIC EPA
Susan Read	Manager, Circular Economy Policy	NSW DPE
Cheryl Robertson	Program Manager	NSW DPE
Yvonne Scorgie	Senior Manager	NSW DPE
Hanna Shalbaf	Director, Infrastructure, Grants & Delivery	NSW DPE
Jeff Standen	A/ Director Environmental Health	NSW Health
Prof Mark Taylor	Chief Environmental Scientist	VIC EPA
Nathan Vincent	Principal Policy Analyst	Resilience NSW
Emily Yip	Director Circular Economy Policy and Markets, Climate Change & Sustainability	OECC

Table 4: Research experts

Name	Title	Affiliation
Prof Ali Abbas	Professor of Chemical Engineering	University of Sydney
Dr Mark Browne	Senior Lecturer	University of New South Wales
Dr Elizabeth Carter	Facility Manager, Vibrational Spectroscopy, Sydney Analytical	University of Sydney
Ana Porta Cubas	Knowledge and Translation Broker, Centre for Air pollution, energy and health research	Woolcock Institute of Medical Research
Professor Paul Dastoor	Professor of Physics	University of Newcastle
Assoc Prof Melanie Davern	Director Australian Urban Observatory	RMIT University
Professor David Eager	Professor, Centre for Audio, Acoustics and Vibration	University of Technology Sydney
Dr Ruth Fisher	Lecturer in Environmental Engineering and Sustainability	University of New South Wales

Name	Title	Affiliation
Dr Francois Flocard	Principal Engineer, Water Research Laboratory	University of New South Wales
Dr Emma George	Senior Lecturer in the School of Science and Health	Western Sydney University
Assoc Prof William Glamore	Water Research Laboratory	University of New South Wales
Sonya Glasson	Project Manager, Injury and Systems Surveillance Unit	Australian Institute of Health and Welfare
Nicholas Haskins	Chief Operating Officer	NSW Smart Sensing Network
Dr James Hayes	Research Associate	University of New South Wales
Prof Dieter Hochuli	Professor, Integrative Ecology Group	University of Sydney
Dr Tomonori Hu	Research Theme Leader	NSW Smart Sensing Network
Dr Cynthia Isley	Postdoctoral Research Fellow	University of Adelaide
Kimi Izzo	Electronics and development Engineer	NSW Smart Sensing Network
Professor Ollie Jay	Professor of Heat and Health, Director – Thermal Ergonomics Laboratory	University of Sydney
Stuart John	Project Officer	Australian Institute of Health and Welfare
Dr Shamsad Karatela	Environmental epidemiologist	University of Queensland
Prof Peter A Lay	Professor of Chemistry	University of Sydney
Prof Guy Marks	Professor of Respiratory Medicine	University of New South Wales
Margot Mason	Hydrology Masters Student	University of New South Wales
Prof Lidia Morawska	Distinguished Professor in the School of Earth and Atmospheric Sciences	Queensland University of Technology
Dr Negin Nazarian	Scientia Senior Lecturer, School of Built Environment	University of New South Wales
Dr Thava Palanisami	Associate Professor in School of Engineering	University of Newcastle
Dr Riccardo Paolini	Senior Lecturer	University of New South Wales
Prof Ian Paulsen	Distinguished Professor in School of Natural Sciences	Macquarie University
Assoc Prof Neil Perry	Associate Professor in Corporate Social Responsibility and Sustainability	Western Sydney University
Prof Christopher Pettit	Director of City Futures Research Centre	University of New South Wales
Assoc Prof Sebastian Pfautsch	Associate Professor in Urban Studies	Western Sydney University
Dr Mariana Mayer Pinto	Scientia Senior Lecturer, School of Biological, Earth and Environmental Science	University of New South Wales
Assoc Prof Sharon Pochron	Adjunct Professor	Stony Brook University
Prof Jeff Powell	Professor, Hawkesbury Institute for the Environment	Western Sydney University
Dr Ademir Prata	Research Associate	University of New South Wales
Prof William S. Price	Professor of Medical Imaging Physics	Western Sydney University
Prof Ataur Rahman	Professor in Water Engineering	Western Sydney University
Dr Jason Reynolds	Senior Lecturer in School of Science	Western Sydney University

Name	Title	Affiliation
Dr Ayu Saraswati	Senior machine Learning and data engineer	NSW Smart Sensing Network
Prof Sathaa Arumugam Sathasivan	Professor of Environmental Engineering	Western Sydney University
Dr Neda Sharifi-Soltani	Research Fellow	Macquarie University
Prof Jason Sharples	Professor of Bushfire Dynamics in the School of Science	University of New South Wales
Gurpreet Singh	PhD Candidate	Southern Cross University
Scientia Professor Martina Stenzel	Professor, Department of Chemistry	University of New South Wales
Dr Christopher Stevens	Senior Lecturer (Sport and Exercise Science)	Southern Cross University
Prof Richard Stuetz	Professor, School of Civil and Environmental Engineering	University of New South Wales
Dr Caragh Threlfall	DECRA Fellow, School of Life and Environmental Sciences	University of Sydney
Dr James Turner	Ecophysiologist	Charles Sturt University
Dr Gupta Vadakattu	Senior Researcher	CSIRO
Dr Cheng Wang	Research Associate	University of New South Wales
Dr Scott Wilson	Chief Scientist	Earthwatch Institute
Prof Guan Yeoh	Professor, School of Mechanical and Manufacturing Engineering	University of New South Wales

Table 5: **Industry representatives**

Name	Title	Affiliation
Dr Mick Battam	Principal Soil and Irrigation Scientist	AgEnviro Solutions
Carolyn Campbell	Chief Executive Officer	Scouts NSW
David Carpenter	General Manager	Advanced Polymer Technology Asia Pacific
Alastair Cox	ESTC Technical Director	EMEA Synthetic Turf Council
Trent Cummings		Tuff Group
Toni DeClase	Business Development Manager - Partners	TigerTurf Australia
Celine Ducher	Product & Marketing Manager	FieldTurf Australia
Mark Edmonson	SAPIA President and General Manager of All Grass Sport Surfaces	SAPIA/ All Grass Sports Surfaces
James Ellender	Chief Executive Officer	ActiveXchange
Fraser Gehrig	Managing Director	Tuff Group
Lina Goodman	Chief Executive Officer	Tyre Stewardship Australia
Samantha Grant-Vest	Resource Recovery Manager	SESL Australia
Andres Grigaliunas	Principal Environmental Scientist/ NSW Environment Manager	SESL Australia
Simon Haire	Director - SportsEye	ActiveXchange
Jarrod Hill	Chief Executive Officer	SPORTENG
Grant Humphreys	SAPIA Board Member and Director of Acousto-scan	SAPIA/ Acousto-scan
Paul Kamphuis	General Manager	Polytan Asia Pacific

Name	Title	Affiliation
Nick Kerr	National Sales & Marketing Manager	TigerTurf Australia
Dr Paul Lamble	Principal Consultant	Peak Water Consulting
Kate Luffman	Managing Director	Sports Clean
Dr Keith McAuliffe	Managing Director	Labosport Australia
Alex Mednis	Managing Director	Revolutionise
Dr Linda Mitchell	Science and Innovation Advisor	Tyre Stewardship Australia
Emily Moore	Chief of Staff	Revolutionise
Andrew Morrow	Commercial manager	SPORTENG
John Neylan	Turfgrass Agronomist	SPORTENG
Malcom Parkes	SAPIA Vice President	SAPIA
Dr Kellie Pendoley	Director	Pendoley Environmental
Matt Roche	Director and Principal Turf Consultant	Australian Sports Turf Consultants
Persephone Rougellis	Strategy Manager	Sydney Water
Martin Sheppard	SAPIA Member/ Director of Smart Connection Consultancy	SAPIA/ Smart Connection Consultancy
Lucas Skelton	Field of Play Team Leader	SPORTENG
Dr Peter Somerville	Senior Victoria Soil Scientist	SESL Australia
Ian Tittershill	SAPIA Member and Vice-President International of FieldTurf	SAPIA/ GrassMaster Solutions
James Tritt	Chief Operating Officer	Sport Group Asia Pacific
Mark Unwin	Chief Executive Officer	Australian Sports Turf Managers Association
Dr Christian Urich		Hydrology and Risk Consulting (HARC)
Christian Urriola	Engineer	Atlantis
Humberto Urriola	Founder and Chief Executive Officer	Atlantis
Robyn Wilcox	National Secretary	Sports & Play Industry Association

Table 6: Community members

LGA	Number of community members met
Bayside Council	26
Blacktown City Council	1
Georges River Council	1
Hunters Hill Council	1
Inner West Council	2
Ku-ring-gai Council Council	5
Northern Beaches Council	1
Randwick City Council	1

Table 7: Sporting associations and bodies

Name	Title	Affiliation
Ross Bidencope	Chief Executive Officer	Sport NSW
Anthony Brooks	Facilities & Government Manager NSW ACT	AFL
David Eland	Chief Executive Officer	Northern NSW Football
Gavin Lawrence		NSW Rugby League
David Lawson	Project Manager & Facilities Specialist- NSW & QLD	AFL
Kean Marshall	Venue manager - Lake Macquarie Regional Football Facility	Northern NSW Football
Brett Pettersen	Manager Infrastructure & Planning	Tennis NSW
Daniel Ristic	Manager - Government Relations, Funding and Infrastructure	Football NSW
David Thompson	Senior Manager - National Strategic Projects	Hockey Australia

Appendix 2
Data

2.1 The data about synthetic turf in NSW

A single sports field may have a variety of line markings and be used to play various sport activities (Figure 1). In the analysis conducted by NSW Office of Sport, fields are categorised by the sport activity that is played on them requiring the largest field marking, the other sports activities played on them are listed separately. Each field, even if it is part of a larger facility, is counted separately and once only. Efforts have been made to count each field once only, regardless of the number of different sports played on them and to check these numbers with the relevant sporting associations. As sporting associations may report fields slightly differently, numbers are displayed for both NSW Office of Sport and those provided by sporting associations (Table 1, summarised by sport in Table 2).

The analysis only includes public outdoor sporting areas that are accessible to the broader community in some form (even if this might require payment or limited access). Facilities on school grounds are not included although it is recognised that some allow access to the wider community. Sporting areas in universities and those that only allow restricted access to the public and are owned by clubs or associations are included. Other outdoor sports facilities with synthetic turf surfaces that are not listed here due to insufficient information or difficulty distinguishing between synthetic turf and other synthetic surfaces, include: miniature golf, lawn bowls/petanque/boule, playgrounds and leisure areas, shooting ranges, tennis, netball, volleyball, horse/harness racing and other horse-riding arenas.

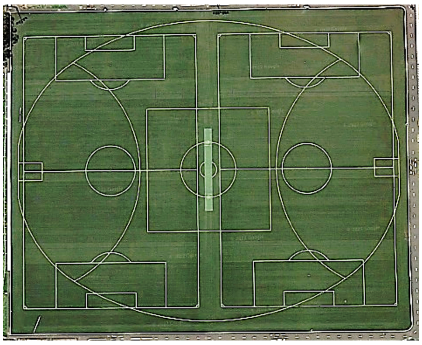


Figure 1: Example of a multi-use synthetic turf field

Table 1: **What sports are played on synthetic turf fields in NSW, as reported by the NSW Office of Sport in a collated dataset for sport in NSW**

Fields that are categorised under the sport (Number of outdoor synthetic fields in NSW) and the synthetic fields that are categorised under different sports (Approximate number of other outdoor synthetic fields that the sport is played on in NSW), figures have been checked with relevant sporting associations.

Sport activity	Number of outdoor synthetic sports fields in NSW	Approximate number of other outdoor synthetic fields that the sport is played on in NSW
Hockey	77[1]	0
Football (soccer)	64 (including 10 junior)[2]	16 (including 2 junior)[3]
Futsal/five-a-side	24	0
Cricket	7	0
AFL	5[4]	2[5]
Rugby league	2	2
Rugby union	2	1
Oztag/ touch	0	2
Softball	0	2
TOTAL	**181**	

[1] Number of synthetic fields used for hockey in NSW confirmed by Hockey Australia

[2] Football NSW reports 75 full size synthetic fields in NSW, which would make the total number of synthetic fields in NSW 192

[3] Football NSW reports 22 other synthetic fields that are used for Football (Soccer) in NSW

[4] Number of synthetic fields used for AFL in NSW confirmed by AFL NSW

[5] Number of other synthetic fields that are also used for AFL in NSW confirmed by AFL NSW

Table 2: Number of fields and area synthetic turf and natural turf in outdoor sporting facilities in NSW

Numbers as reported by the NSW Office of Sport in a collated dataset for all sport in NSW, this dataset was updated with information from various councils and sporting bodies. Where relevant sporting associations report different figures, these are shown in brackets. The NSW Office of Sport numbers are used to generate a conservative approximate total surface area of synthetic turf playing surfaces in NSW with reference to the area of natural turf playing surfaces

Region	Sport activity requiring largest field marking[1]	Natural Turf: Number of playing fields	Approximate area (m^2)[2]	Synthetic Turf: Number of playing fields	Approximate area (m^2)[2]
Sydney Metropolitan	AFL[3]	82 (77)	1,434,590	5	87,475
	Baseball diamond[4]	232	174,232	0	0
	Cricket oval[5]	855	18,060,165	7	147,861
	Football (Soccer) – junior[6]	185	444,000	11	26,400
	Football (Soccer) – senior[7]	614	4,383,960	49	349,860
	Futsal/Five-a-side[8]	0	0	5	5,250
	Hockey[9]	13	65,351	22	110,594
	Oztag/Touch[10]	14	63,000	0	0

	Rugby League – junior[11]	41	157,440	0	0
	Rugby League – senior[12]	224	1,675,520	2	14,960
	Rugby Union[13]	133	931,000	2	14,000
	Softball diamond[14]	108	42,336	0	0
	Total fields	**2,501**	**27,431,594**	**103**	**756,400**
	Cricket pitch in oval[15]	131		731	56,472
	Cricket pitches, practice nets[16]	108	8,424	672	52,416
	Total cricket pitches	**239**	8,424	**1,403**	**108,888**
Hunter	AFL	7 (16)	122,465	0	0
	Baseball diamond	7	5,257	0	0
	Cricket oval	231	4,879,413	0	0
	Football (Soccer) – junior	(76)	0	0	0
	Football (Soccer) – senior	126 (198)	899,640	2	14,280
	Futsal/Five-a-side	0	0	14	14,700
	Hockey	6	30,162	8	40,216
	Oztag/Touch	18	81,000	0	0
	Rugby League – senior	57	426,360	0	0
	Rugby Union	19	133,000	0	0
	Softball diamond	0	0	0	0
	Total fields	**471**	**6,577,297**	**24**	**69,196**
	Cricket pitch in oval	231		0	0
	Cricket pitches, practice nets	36	2,808	140	10,920
	Total cricket pitches	267	2,808	140	10,920
Central West and Orana	AFL	9	157,455	0	0
	Cricket oval	148	3,126,204	0	0
	Football (Soccer) – junior	(47)	0	0	0
	Football (Soccer) – senior	2 (62)	14,280	0	0
	Hockey	8	40,216	11	55,297
	Rugby League – senior	5	37,400	0	0
	Total fields	**172**	**3,375,555**	**11**	**55,297**
	Cricket pitch in oval	145		3	234
	Cricket pitches, practice nets	12	936	48	3,744
	Total cricket pitches	157	936	51	3,978
North Coast	AFL	14 (13)	244,930	0	0
	Baseball diamond	11	8,261	0	0
	Cricket oval	157	3,316,311	0	0
	Football (Soccer) – junior	46 (31)	110,400	0	0
	Football (Soccer) – senior	93 (140)	664,020	0	0
	Hockey	3	15,081	10	50,270

	Oztag/Touch	25	112,500	0	0
	Rugby League – junior	14	53,760	0	0
	Rugby League – senior	39	291,720	0	0
	Rugby Union	47	329,000	0	0
	Softball diamond	2	784	0	0
	Total fields	**451**	**5,146,767**	**10**	**50,270**
	Baseball batting cage	0	0	1	92
	Cricket pitch in oval	147		10	780
	Cricket pitches, practice nets	17	1,326	159	12,402
	Total pitches and cages	**164**	1,326	**170**	**13,274**
Illawarra Shoalhaven	AFL	5 (12)	87,475	0	0
	Baseball diamond	2	1,502	0	0
	Cricket oval	114	2,408,022	0	0
	Football (Soccer) – junior	22 (42)	52,800	0	0
	Football (Soccer) – senior	100 (120)	714,000	2 (1)	14,280
	Hockey	0	0	6	30,162
	Oztag/Touch	20	90,000	0	0
	Rugby League – junior	1	3,840	0	0
	Rugby League – senior	29	216,920	0	0
	Rugby Union	6	42,000	0	0
	Softball diamond	2	784	0	0
	Total fields	**301**	**3,617,343**	**8**	**44,442**
	Cricket pitch in oval	112		2	156
	Cricket pitches, practice nets	35	2,730	61	4,758
	Total cricket pitches	**147**	**2,730**	**63**	**4,914**
Central Coast	AFL	2 (11)	34,990	0	0
	Baseball diamond	4	3,004	0	0
	Cricket oval	61	1,288,503	0	0
	Football (Soccer) – junior	6 (11)	14,400	0	0
	Football (Soccer) – senior	47 (55)	335,580	0	0
	Futsal/Five-a-side	0	0	5 (13)	5,250
	Hockey	3	15,081	2	10,054
	Oztag/Touch	1	4,500	0	0
	Rugby League – senior	1	7,480	0	0
	Rugby Union	2	14,000	0	0
	Softball diamond	5	1,960	0	0
	Total fields	**132**	**1,719,498**	**7**	**15,304**
	Cricket pitch in oval	61		0	0
	Cricket pitches, practice nets	3	234	50	3,900
	Total cricket pitches	**64**	234	**50**	**3,900**

New England and North West	AFL	6 (8)	104,970	0	0
	Baseball diamond	17	12,767	0	0
	Cricket Oval	100	2,112,300	0	0
	Football (Soccer) – junior	(36)	0	0	0
	Football (Soccer) – senior	(47)	0	0	0
	Hockey	2	10,054	7	35,189
	Total fields	**125**	**2,240,091**	**7**	**35,189**
	Cricket pitch in oval	97		3	234
	Cricket pitches, practice nets	8	624	34	2,652
	Total cricket pitches	105	624	37	2,886
South East and Tablelands	AFL	8	139,960	0	0
	Cricket oval	94	1,985,562	0	0
	Football (Soccer) – junior	(20)	0	0	0
	Football (Soccer) – senior	19 (60)	135,660	0	0
	Hockey	3	15,081	6	30,162
	Oztag/Touch	0	0	0	0
	Rugby League – senior	13	97,240	0	0
	Rugby Union	2	14,000	0	0
	Softball diamond	0	0	0	0
	Total fields	**139**	**2,387,503**	**6**	**30,162**
	Cricket pitch in oval	74		20	1,560
	Cricket pitches, practice nets	1	78	28	2,184
	Total cricket pitches	**75**	**78**	**48**	**3,744**
Riverina Murray	AFL	18 (80)	314,910	0	0
	Baseball diamond	1	751	0	0
	Cricket oval	180	3,802,140	0	0
	Football (Soccer) – junior	(23)	0	0	0
	Football (Soccer) – senior	28 (58)	199,920	0	0
	Futsal/Five-a-side	0	0	0	0
	Hockey	5	25,135	5	25,135
	Oztag/Touch	16	72,000	0	0
	Rugby League – senior	29	216,920	0	0
	Rugby Union	7	49,000	0	0
	Softball diamond	1	392	0	0
	Total fields	**285**	**4,681,168**	**5**	**25,135**
	Baseball batting cage[17]	0	0	1	92
	Cricket pitch in oval	149		31	2,418
	Cricket pitches, practice nets	36	2,808	143	11,154
	Total pitches and cages	**185**	**2,808**	**175**	**13,664**

Far West	AFL	14 (3)	244,930	0	0
	Baseball diamond	1	751	0	0
	Cricket oval	41	866,043	0	0
	Football (Soccer) – junior	1	2,400	0	0
	Football (Soccer) – senior	11 (3)	78,540	0	0
	Hockey	0	0	0	0
	Oztag/Touch	6	27,000	0	0
	Rugby League – senior	11	82,280	0	0
	Rugby Union	6	42,000	0	0
	Softball diamond	1	392	0	0
	Total fields	**92**	**1,344,336**	**0**	**0**
	Cricket pitch in oval	41		0	0
	Cricket pitches, practice nets	0	0	12	936
	Total cricket pitches	**41**	**0**	**12**	**936**
Grand Total Fields		4,669	58,521,152	181	1,081,395
Grand Total Cricket Pitches and Cages[15]		1,444	19,968	2,149	167,104
Grand Total Area (m^2)			**58,541,120**		**1,248,499**

[1] A large number of sports are played on a single natural or synthetic turf field with markings for multi-sport. To avoid double-counting, each field in this table is categorised by the sports activity with the largest playing area

[2] Playing surface area based on standard/ best practice dimensions, not including run-off or penalty areas, if a standard is not given then maximum size is used as listed in the Sports Dimensions Guide or as advised from the appropriate sports association in NSW

[3] AFL senior and junior (under 11 & 12) standard field calculated as an oval with axes of 165 and 135 m: **17,495 m^2**

[4] Baseball diamond surface area, given the sides are 27.4 m: **751 m^2**

[5] Cricket playing area boundary, calculated for single pitch field assuming the field is the ideal circle with maximum distance between the pitch and boundary, including the outfield, of 82 m: **21,123 m^2**

[6] Football (Soccer) – junior (under 10) surface area given best practice sides are 60 m by 40 m: **2400 m^2**

[7] Football (Soccer) – senior surface area, given recommended side dimensions are 105 m by 68 m: **7140 m^2**

[8] Futsal/Five-a-side surface area, given the sides are a maximum of 42 m by 25 m: **1050 m^2**

[9] Hockey surface area given the sides are 91.4 m by 55 m: **5027 m^2**

[10] Oztag/Touch surface area, given the sides are 70 m by 50 m with a maximum touchdown zone of 10 m at each end: **4500 m^2**

[11] Rugby League – junior (under 10) surface area: **3840 m^2**

[12] Rugby League – senior surface area, given recommended side dimensions are 110 m by 68 m: **7480 m^2**

[13] Rugby Union senior surface area, given maximum side dimensions are 100 m by 70 m: **7000 m^2**

[14] Softball diamond – co-ed surface area, given the sides are 19.81 m: **392 m^2**

[15] Cricket pitch in cricket oval, given maximum dimensions are 28 m by 2.8 m: **78 m^2**. Note that to avoid double counting, the area of the pitch is not included in total calculations for area if the oval is the same surface (natural or synthetic)

[16] Cricket pitches in practice nets **78 m^2**

[17]Baseball batting cage **92 m^2**

2.2 Potential for a semi-automated approach to spatially detect synthetic turf

A trial was done attempting to identify synthetic turf sporting fields using 10 m resolution imagery from Sentinel 2, which is publicly available at the Sentinel Australasia Regional Access Hub. The imagery was filtered, isolating pixels which fell within the ranges shown in Table 3, and removing identified areas below 1,500 m^2. These filters identified most (but not all) synthetic turf fields, thus the need to further develop the imagery analysis algorithm. This approach also identifies many non synthetic turf pixels – mainly pixels partially containing vegetation. Verges in suburbs and alongside highways were common false positives. Moreover, some natural turf fields with heavily worn grass were falsely identified as synthetic turf fields. See Figures 2a-d for examples. Sorting by area to perimeter ratio further improved results, as identified synthetic turf fields tend to be more rounded (higher ratio) while false positives tended to be elongated (lower ratio). Nevertheless, manual sorting to remove false negatives was still required.

Table 3: Reflectance values for filtering Sentinel 2 imagery to identify synthetic turf fields

Band	Minimum	Maximum
B2 (Red)	1200	1500
B3 (Green)	1500	1850
B4 (Blue)	1300	1800
NDVI	0.097	0.27

While this approach clearly needs to be refined, it is suggested as a potential basis for identifying synthetic turf fields from satellite imagery, which could then be spatially joined to the existing Office of Sport database. For a large area (e.g. all of NSW) this would be computationally demanding, and manual sorting of outputs would likely still be required, so this approach may not prove more efficient than manually checking the 1,170 fields with no surface specified.

Figure 2a: Correctly identified synthetic turf fields on Sentinel 2 imagery (left) and higher resolution satellite imagery (right)

Figure 2b: False negative - synthetic turf field not identified by algorithm on Sentinel 2 imagery (left) and higher resolution satellite imagery (right)

Figure 2c: False positive - highway verge identified as synthetic turf on Sentinel 2 imagery (left) and higher resolution satellite imagery (right)

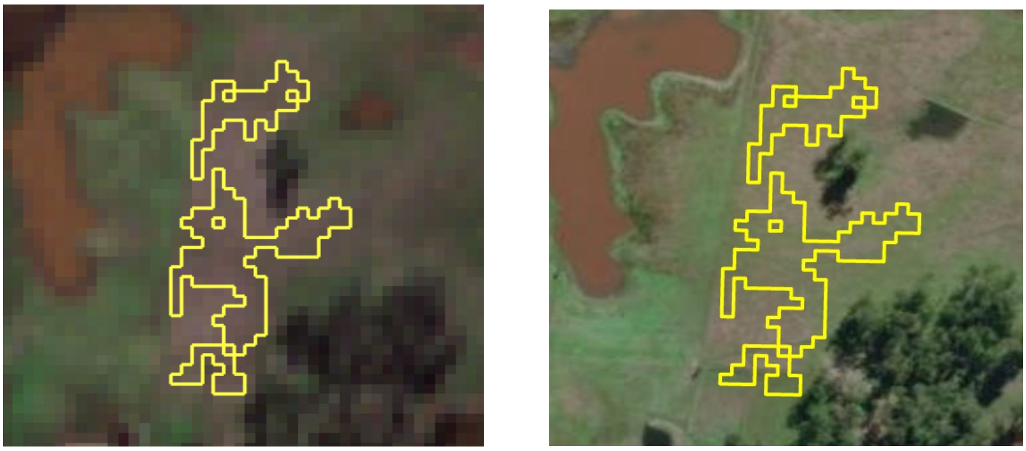


Figure 2d: False positive - sparse grass identified as synthetic turf on Sentinel 2 imagery (left) and higher resolution satellite imagery (right)

2.3 Consideration of environmental factors

Synthetic turf field installation in NSW is commonly assessed by a Review of Environmental Factors (REF) under Division 5.1 of the *Environmental Planning and Assessment Act 1979.* A REF must address the requirements of section 170 and 171 of the *Environmental Planning and Assessment Regulation 2021* outlined in Guidelines for Division 5.1 assessments (reproduced in Table 4).

Table 4: Environmental factors the proponent and determining authority must take into account in a REF, as listed in s 171(2) of the *Environmental Planning and Assessment Regulation 2021*
Source: Reproduced from Guidelines for Division 5.1 assessments

Environmental factor	Example
Environmental impact on the community	Social, economic and cultural impacts
Transformation of the locality	Human and non-human environment
The environmental impact on the ecosystems of the locality	Flora, fauna, ecological integrity, biological diversity, connectivity/fragmentation, air, water including hydrology, soil
Reduction of the aesthetic, recreational, scientific or other environmental quality or value of the locality	Visual, recreational, scientific and other
Effects on any locality, place or building that has: • aesthetic, anthropological, archaeological, architectural, cultural, historical, scientific or social significance, or • other special value for present or future generations	Aboriginal heritage (including intangible cultural significance), architectural heritage, social/community values and identity, scenic values and other
Impact on the habitat of protected animals, within the meaning of the *Biodiversity Conservation Act 2016*	Listed species and habitat requirements/ critical habitat
Endangering of a species of animal, plant or other form of life, whether living on land, in water or in the air	Listed species, non-listed species and key threatening processes
Long-term effects on the environment	Ecological, social and economic
Degradation of the quality of the environment	Ecological, social and economic
Risk to the safety of the environment	Public health, contamination, bushfire, sea level rise, flood, storm surge, wind speeds, extreme heat, urban heat and climate change adaptation
Reduction in the range of beneficial uses of the environment	Natural resources, community resources and existing uses
Pollution of the environment	Air (including odours and greenhouse gases); water (including runoff patterns, flooding/tidal regimes, water quality health); soil (including contamination, erosion, instability risks); noise and vibration (including consideration of sensitive receptors); or light pollution
Environmental problems associated with the disposal of waste	Transportation, disposal and contamination
Increased demands on natural or other resources that are, or are likely to become, in short supply	Land, soil, water, air, minerals and energy
Cumulative environmental effect with other existing or likely future activities	Existing activities or future activities
Impact on coastal processes and coastal hazards, including those under projected climate change conditions	Coastal processes and hazards (impacts arising from the proposed activity on coastal processes and hazards and impacts on the proposed activity from coastal processes and hazards), climate scenarios
Applicable local strategic planning statements, regional strategic plans or district strategic plans made under the Act, Division 3.1	Issues, objectives, policies and actions identified in local, district and regional plans
Other relevant environmental factors	Any other factors relevant in assessing impacts on the environment to the fullest extent

2.4 Information sources available at regional and localised scales for consideration when planning synthetic turf installations

Regional scale

Flora and fauna
- DPE, BioNet Atlas
- DPE, Biodiversity Values Map and Threshold tool
- DPE, NSW Koala Habitat Information Base
- DPE,NSW State Vegetation Type Map
- DPI, Key Fish Habitat
- DCCEEW (Cwth), Protected Matters Search Tool

Cultural
- Heritage NSW, Aboriginal Heritage Information Management System (AHIMS)
- Heritage NSW, State Heritage Inventory

Regional Cultural Mapping Projects (e.g. Jackson et al. 2018)

Protected areas
- DPE, Protected areas
- DPI, Marine Protected areas
- DCCEEW (Cwth), CAPAD: protected area data

Planning

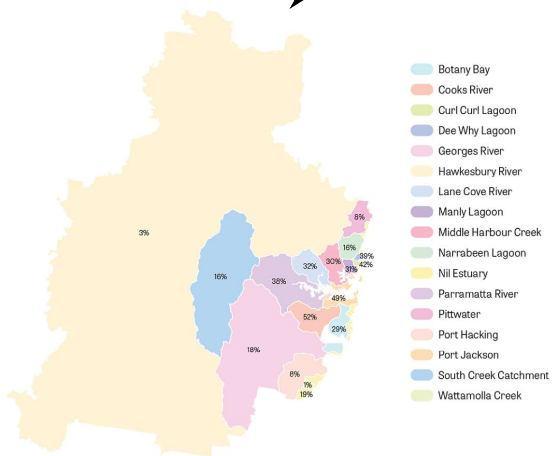
DPE, Environmental Planning Instruments - Local Environmental Plans (LEPs), State Environmental Planning Policies (SEPPs), and Regional Environmental Plans (REPs), including:
- Riparian lands watercourses
- Groundwater vulnerability
- Environmentally sensitive land
- Scenic protection
- Native Vegetation Protection
- Drinking Water Catchment
- Flood and Land Slide Risk

- DPE, Coastal Wetlands
- DPE, Greater Sydney tree canopy (2019 data to be updated in 2022, 2024 and 2026); Urban vegetation cover
- DPE, Regional Plans; Land Zoning
- DPE, Local Provisions: including cultural areas and landscape, wildlife corridors, significant native vegetation and urban areas
- Councils, LEP conservation zones
- Councils, tree inventory - e.g. Lane Cove Council

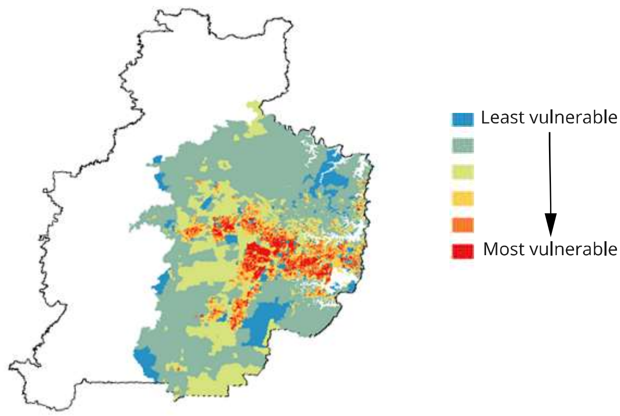
Livability metrices
- Australian Urban Observatory, Scorecard for Sydney (summarised in Australia State of the Environment Report 2021)

Topography
- Geoscience Australia, Topographic maps
- Spatial Services (DCS), DPE, Topographic Maps; NSW Landcover; NSW Physiography; NSW Features of Interest
- Surface features data e.g. Geoscape

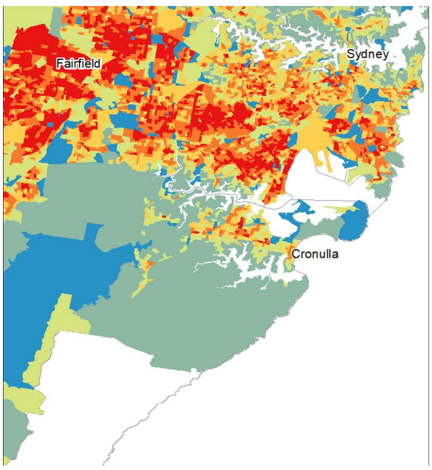
Urban environment and heat
- DPE, Heat vulnerability index (Greater Sydney)
- DPE, Urban heat island (Greater Sydney)
- DPE: Green-grid: existing green assets; and green corridor (Sydney)
- Greater Sydney Commission, Proportion of impermeable surface area 2020



Sydney catchments proportion of impermeable surface area (Greater Sydney Commission 2000)

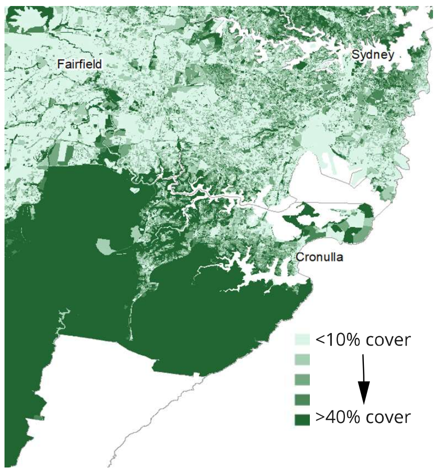


Urban heat vulnerability index for the Sydney Metropolitan area (DPE)



Heat vulnerability index, Southern Sydney (DPE)

Existing green assets, Southern Sydney (DPE)



Percent tree canopy cover, Southern Sydney (DPE)

Water
Including location and distances to surface water/ water receptor, groundwater drainage, flood information and water infrastructure
• Spatial Services (DCS), NSW Hydrography, includes land subject to inundation
• DPE, Estuary Drainage Catchments
• WaterNSW 509 water quality monitoring sites in NSW (internal water quality database)
• WaterNSW and Sydney Water, Stormwater and wastewater, treated water for fields, other water infrastructure
• BOM, National performance reports: Water Information, wastewater assets
• EPA, Sensitive zone maps
• Spatial Services (DCS), NSW Water Theme multiCRS
• CRC for Water Sensitive Cities, Scenario Tool
• DPI, High Ecological Value Waterways and Water Dependent Ecosystems: LGA maps, using 39 indicators (blue grid, SEED)
• Councils, DPI, MHL, others, Drainage/flood catchment boundaries, flood studies, model stormwater, daily water flow series and run-off from catchments (collated in NSW Flood Data Portal)

Flood risk
Various sources, SES Flood data portal

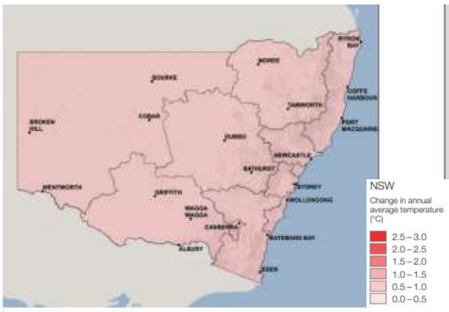
Bushfire
• RFS (NSW), Bushfire prone Land
• RFS (NSW), Neighbourhood safer places
• DPE, Fire Extent and Severity Mapping

Soil
• DPE, eSPADE; Great Soil Group (GSG) Soil Type map of NSW; NSW soil profiles
• CSIRO, Soil and Landscape Grid of Australia
• The Australian Microbiome Initiative, Biomes of Australian Soil Environments
• Regional NSW, Geology

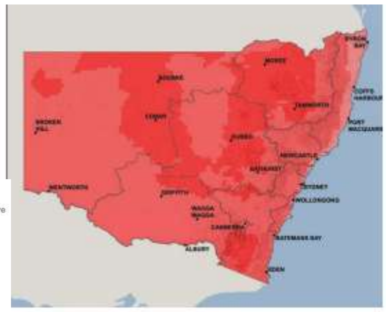
Air quality
DPE, Air Quality NSW; Air quality concentration data

Imagery
• Geoscience Australia, Elvis Aerial imagery and LiDAR
• USGS, Landsat, Surface temperature data
• Spatial Services (DCS), NSW Imagery

Climate change projections
• DPE, Adapt NSW, Climate change projections map



Near future (2020-2039) change in annual mean maximum temperature, compared to the baseline period (1990-2009) AdaptNSW



Far future (2060-2079) change in annual mean maximum temperature, compared to the baseline period (1990-2009) AdaptNSW

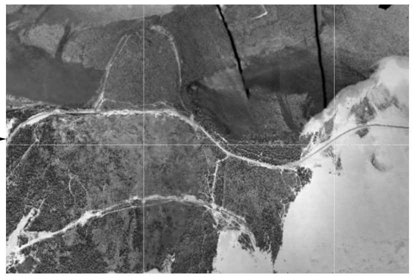
Participation demand at regional and local scale
• OoS, DAC, Active Kids Casestudy
• SSO / SSOD - State Sporting Organistions / State Sporting Organisation for people with Disability, Participation data. This may be managed by a third party e.g. Revolutionise Sport, ActiveXchange who also model demand forecast

Demand forecast
• ABS, Estimated Resident Population (ERP)
• ABS, Population projections
• DPE, NSW Population Projections, DPE (methods use assumptions approved by the NSW Government Common Planning Assumptions Group)

Transport, access and inclusivity
• ABS, Socio-Economic Indexes for Areas (SEIFA)
[Includes: The Index of Relative Socio-economic Disadvantage (IRSD); The Index of Relative Socio-economic Advantage and Disadvantage (IRSAD); The Index of Education and Occupation (IEO); The Index of Economic Resources (IER). Includes data on income, education, employment, occupation, housing]
• Department of Education: NSW Government school locations and size; NSW university locations
• Transport NSW, Transport Planning Zones (TPZ); Transport Services; Passenger Travel; Cycleway Finder; Household Travel Survey (Sydney Greater Metropolitan Area)
• Walking analysis e.g. Tract Consultants, Walking catchments (10mins) for Penrith Green Grid Strategy
• Spatial Services (DCS), Roads and Transport
• Movement data providers e.g. Google; Mapbox

Field scale

Historical land use
• State Archives & Records, Land history use
• Australian Land Title Search
• NSW Land Registry Services, Historical Records
• Spatial Services (DCS), Historical, Aerial and Satellite Imagery
• Geoscience Australia, Historical aerial photos



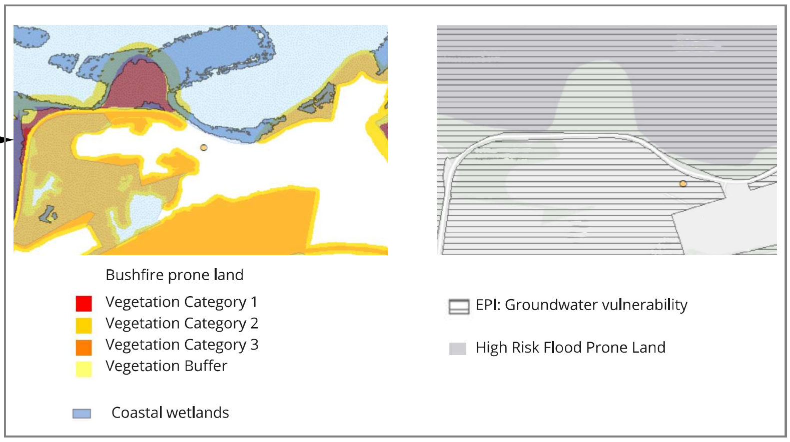
Historical imagery from 1955

Imagery from 2015

Imagery from 2022

Bushfire
• RFS (NSW), Bushfire prone Land
• RFS (NSW), Neighbourhood safer places
• DPE, Fire Extent and Severity Mapping

Flood risk
• Flood inundation and flood impact assessment study: including predict direction, velocity and amounts of run-off / vertical flow, peak flood depths)
• BOM, Meterological history, Flood Knowledge Centre
• Various sources, SES Flood data portal



Planning
• DPE, Environmental Planning Instruments - Local Environmental Plans (LEPs), State Environmental Planning Policies (SEPPs), and Regional Environmental Plans (REPs)
• DPE, Public Spaces, NSW Public Spaces Charter; Greener public spaces; Valuing green infrastructure
• Requirements of a Review of Environmental Factors
• DPE, Greater Sydney tree canopy (2019 data to be updated in 2022, 2024 and 2026); Urban vegetation cover; Coastal Wetlands; Regional Plans; Land Zoning; Local Provisions; Hazards including Flood and Land Slide Risk
• Councils, LEP conservation zones, tree inventory e.g. Lane Cove Council

Transport access
• Transport NSW, Transport Services; Passenger Travel; Cycleway Finder; Household Travel Survey
• Movement analysis e.g. Tract Consultants, Walking catchments (10mins) for Penrith Green Grid Strategy; data providers e.g. Google; Mapbox
• Spatial Services (DCS), Roads and Transport

Inclusivity considerations, including:
• Parking, dedicated pathway from parking to facilities (toilet, seating etc)
• How much of the facility is accessible (e.g. City of Sydney; NPWS, Access Friendly Experiences
• Toilet and seating areas wheelchair, pram accessible

Relevant design use standards, including:
• Relevant Australian Standards, including AS 1428 Design for Access and Mobility; AS 2560:2007 Sports Lighting; AS 4282 Control of the obtrusive effects of outdoor lighting
• National Construction Code 2019 (NCC)
• Asset Standards Authority (ASA) standards
• International (e.g. FIFA), national and state sporting associations facilities standards
• Council, Local Environmental Plan; Development Control Plan; Civil Infrastructure Design
• Crime Prevention Through Environmental Design (CPTED) e.g. NSW Police
• OoS, Outdoor Design
• DJPR (Victoria), Sport and Recreation Design Principles

Infrastructure including:
• DPE, Planning Portal ePlanning Spatial Viewer
• Spatial Services (DCS), Survey Control Information Management System
• Underground services and overhead power lines (electrical lighting link surrounding the park), easements
• Stormwater drainage pipes

Regional scale analysis relevant at a site

Soil and Geology

- Soil assessment; Soil testing results; Geotechnical assessment
- DPE, eSPADE; Great Soil Group (GSG) Soil Type map of NSW; NSW soil profiles
- CSIRO, Soil and Landscape Grid of Australia
- The Australian Microbiome Initiative, Biomes of Australian Soil Environments
- Regional NSW, Geology

Contamination risk

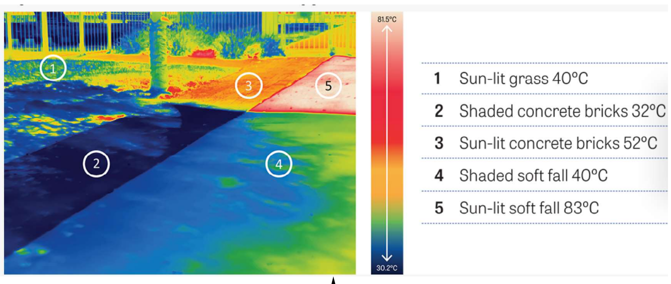
- DPE, Acid sulphate soil risk; Salinity potential
- EPA, POEO Register; Contaminated land register
- CSIRO, Australian Collaborative Land Evaluation Program ASRIS Atlas of Australian Acid Sulphate Soils
- Safework NSW, Hazardous Chemicals Notifications
- DAWE (Cwth), National Waste Management Database

Topography and imagery

- Spatial Services (DCS), Elevation (2m contour); NSW Imagery
- Geoscience Australia, Topographic maps
- Spatial Services, DPE, Topographic Maps; NSW Landcover; NSW Physiography; NSW Features of Interest
- Surface features data e.g. Geoscape
- Geoscience Australia, Elvis Aerial imagery and LiDAR
- USGS, Landsat, Surface temperature data

Flora and fauna

- DPE, BioNet Atlas
- DPE, Biodiversity Values Map and Threshold tool
- DPE, NSW Koala Habitat Information Base
- DPE, NSW State Vegetation Type Map
- DCCEEW (Cwth), Protected Matters Search Tool
- DPI, Key Fish Habitat



Local urban heat measurements and assessment: extent and type of impermeable surface, ensuring canopy cover to manage contributions of wind and solar radiation on heat

e.g. Greater Sydney Commission, Proportion of impermeable surface area 2020; Pfautsch et al. 2020, Penrith City Council; WSROC, Cool Suburbs

Cultural

- Heritage NSW, Aboriginal Heritage Information Management System (AHIMS); State Heritage Inventory and Register

Protected areas

- DPE, Protected areas
- DPI, Marine Protected areas
- DCCEEW (Cwth), CAPAD: protected area data

Data to inform on-going needs and new installations

Sustainability planning data

- Life cycle analysis (LCA), including energy and water efficiency, environmental controls and mitigation, greenhouse gas impacts, waste disposal and end of life for materials in a way that is comparable between synthetic turf (e.g. Russo et al. 2022) and natural turf (e.g. Infotech Research 2020)
- EU Product Environmental Footprint Category Rules (PEF-CR), Synthetic Turf Industry PEFCR
- Dutch industry association BSNC, LCA analysis tool for sports surfaces using DuboCalc
- Dutch National Environmental Database (NMD)
- NSW Net Zero Emissions Dashboard; Net Zero Plan

Collection of maintenance data

- Cleaning
- Grooming
- Moss, algae and anti-microbial treatment
- Stain removal
- Join and seam maintenance
- Infill top up
- Power brushing
- Deep cleaning
- Microplastic controls monitoring and maintenance
- Irrigation (depending on type, some synthetic turf is irrigated)
- Drainage system check and cleaning
- Rotating goal positions
- Condition, damage and replacement

Use design data

- Purpose: playground, playing field; type and extent of use
- Standards compliance required: e.g. FIH, FIFA, IRB
- Current base/ soil
- Drainage: number of drains, location, outlet type
- Edging requirements
- Fire rating requirements
- Fall height requirements
- Shock pads required & type
- Bases and liners

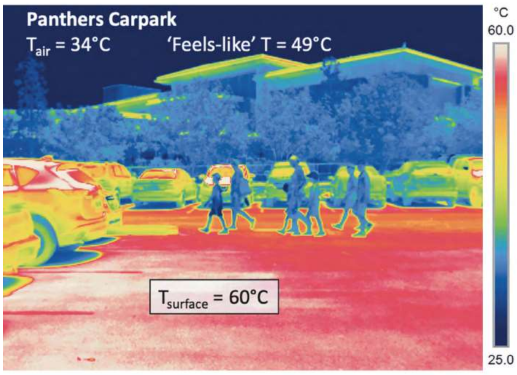
Materials used data

- Feedstock materials and which types of plastic/rubber/waste are recycled
- Location where feedstock materials sourced from
- Variability of the feedstock received and used
- Chemicals and additives used during production (e.g. processing aids such as lubricants, binders, and chemicals to increase fire protection or UV stabilisation) e.g. if SBR crumb infill used, the country and facility the tyres for recycled rubber crumb are from, and the standards and testing used to determine composition

Facility data

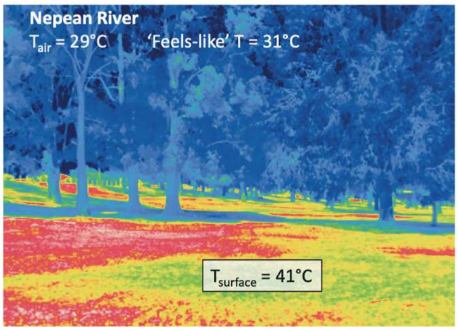
- Surface type
- Installation: year, layers and materials, new/replacement
- Drainage, containment devices
- Lighting
- Estimated life-span
- Life Cycle Analysis
- Site monitoring details

People's experience



Heat

Heat recording
e.g. [Penrith City Council] recorded air temperature and people's experience of temperature



Main activity types
- Sports match
- Organised sport training
- Non-formal sports use
- Passive recreation use

Some data on use

Little/ no data on use

Sports use
- Type of sport played
- Level of sport placed
- Age of players
- Match duration
- Number of participants
- Type of use (training or match)
- Injury

Non-formal sport, recreation and passive use
Number of people, frequency and type of use e.g. walking, running, cycling, non-organised team sports, picnicking and playing

How is the site used?

Conditions - weather and environment
- How does the synthetic surface change the use of the site, and how is this influenced by extreme weather such as intense rainfall, floods, drought and heatwaves
- Of the four climate factors influencing thermal comfort, wind and radiation are the most affected by immediate environment, how have these factors been influenced by the design or management of the immediate environment e.g. retention and planting of canopy trees, nearby natural vegetation

Infill 'walk-off'
Athletes report infill such as SBR crumb getting caught in clothing and footwear then into washing machines.

Infill materials can be transported from synthetic turf in different ways (Standard CENTR-17519) including:
- carried by maintenance equipment
- inappropriate maintenance procedures
- inappropriate installation
- surface run-off or wind dispersion from the field

Thermal comfort: How hot does it feel?

Climate factors effecting thermal comfort
- Air temperature
- Relative and absolute humidity
- Radiant heat / strength of the sun (cloud opacity may also be measured)
- Wind speed

On-ground measurement methods

The Wet bulb globe thermometer (WBGT) measures the integrated effects of air temperature, radiation, wind and humidity

ABC News

BOM measures climate factors and models an approximation of the WBGT and Apparent Temperature indices, producing Thermal Comfort Observations.

On-ground units with sensors can now be used to make accurate measures of microclimate, providing real time data

Heat policies
- Tennis Australia and Sydney University, Australian Open Heat stress scale
- Sports Medicine Australia (SMA), Extreme heat policy includes temperature and humidity and recommendations for each sport risk classification. While data on cancellations under the policy is not collected, some sports authorities (e.g. Cricket Australia) collect their own data on cancellations
- Community Cricket Heat Stress Risk Index (HSRI)

Effect on individual's physiology, perception, and performance
Current research by Singh, Stevens and Bennett, Southern Cross University examining the potential heat effects of exercising on synthetic grass surfaces:
- Physiological measurements include: evaporative, convective and radiative heat in individuals (core body temperature, skin temperature, sweat rate and heart rate, perceptual and performance responses)

Variability in experience of heat stress
- Some people may be more vulnerable: influenced by age, heart or kidney disorders, certain medications, recent illness
- Proximity to hot ground surface influenced by age, height, people in wheelchairs or type of exercise
- Other factors such as hydration and clothing

Inclusivity considerations, including:
• Parking, dedicated pathway from parking to facilities (toilet, seating etc)
• How much of the facility is accessible (e.g. City of Sydney; NPWS, Access Friendly Experiences
• Toilet and seating areas wheelchair, pram accessible

Booking and using sporting facilities
How does access and user experience vary:
• Open accessibility verses restricted access based on club contributions to cost of synthetic installation
• Does multi-use design (i.e. with markings for different sports) increase access for all sports or do certain sports have priority use
• If the facility is the home ground for a particular sport or a neutral ground
• What are the differences in user experience and paid/volunteer facilitators in regional hubs verses areas with many smaller community clubs

Who is using the site?

Participation and use data sources
• Sports member data records
• Sport Australia (Cwth), AusPlay
• Gate/turnstile data for stadiums
• Sensor data e.g. Intelligent Play
• Facility booking data e.g. Councils

Sports Member data records:
collected by State Sporting Organisations (de-identified and provided to OoS, might also be managed by private companies paid to do so)
• Member Number/ID
• Association/ Club
• Home ground / facility address
• Council or LGA of facility
• Type (length of season, membership category
• Age/ date of birth
• Competition age category
• Home suburb
• Home postcode
• Activity, facility type and sub-type
• Local (level of competition, complexity)

Injury data
Australian Institute of Health and Welfare (AIHW) is working on a National Sport Injury Data Strategy with a Draft reporting tool, recording:
• Who is completing the form, date, gender, age
• Role of injured person (player, coach, ref, spectator, other)
• Sport being played, level, cause of injury, activity at time of injury (playing, training, cooling down etc.)
• State/territory, suburb, club, playing home/ away, indoors/ outdoors, location while completing form
• Body parts injured, tissues injured, sudden/gradual, new/ previous
• If medical attention sought, and if plan to seek further
• There is also provision for a question about indoor/outdoor surface with a drop-down list specific to type of sport (in NSI Data Strategy)

Other injury and sports participation data sources:
• AIS, Athlete Management System Injury Form, records: *date, details, onset, injury classification, diagnostic codes, surgery required, expected return to training, injury activity, treatment date, general location, sport specific information may include inputs on the 'sport surface'*
• Councils
• Hospitals (although diagnostic codes do not record information about surface injury occurred on)
• GPs and allied health
• Community sports
• State Sporting bodies
• Schools
• HeadCheck
• Sport insurance (private healthcare)
• Longitudinal study of Australia's children (AIFS)
National Health Survey & National Aboriginal & Torres Strait Islander Health Survey 2012-13: *'Injured while playing sport' was recorded*

Our understanding of other complex health issues
Research and evidence for the following interactions with human health is growing:
• Long-term exposure to particular materials and chemicals
• Soil health including increased pathogen load in anerobic conditions due to impact on the soil microbiome
• Mental health including stress, anxiety and depression levels and their contributing factors

Community, neighbours and spectators
• Positive interactions including: mental and physical health benefits of easy access to sport and recreation areas; greater community involvement
• Negative interactions including: odour from synthetic turf/infill; decreased access to natural greenspace; disturbance from lights or noise; concern about environmental impacts of microplastic or increased heat

User feedback
Potential for use of electronic feedback on specific sites e.g. QR code, NFC Tag, SnapTag

• Feedback on experience of the public open space
• Report damage or maintenance needed
• Report injury or link location into the AIHW National Injury Database reporting tool (under development)

Appendix 3

Health Impact of Synthetic Turf (Artificial Grass)

Health Impact of Synthetic Turf (Artificial Grass)

June 2022

NSW
GOVERNMENT

Authors: Grace W Lee and Neil Hime

Suggested citation: NSW Ministry of Health. (2022*). Health impact of synthetic turf (artificial grass)*.

Acknowledgements: The author acknowledges input from colleagues at the Environmental Health Branch, NSW Health Protection, and greatly appreciates valuable guidance and feedback from Catherine Bateman-Steel and Kishen Lachireddy. Many thanks to Jen Novak, Corporate library services, NSW Health.

CONTENTS

EXECUTIVE SUMMARY

Project overview

This project reviews the current scientific literature on the potential health impacts of synthetic turf use in public open space. Synthetic turf is designed to mimic natural grass and is typically made of plastic pile blades and recycled tyre crumb rubber infill. An increasing trend in the replacement of natural grass with synthetic turf fields has attracted community concern about potential health, environmental and social implications. In Australia, synthetic turf is used for community or elite level soccer, cricket, touch football and hockey.

This Report presents five health themes and a summary of scientific evidence of the potential direct health impacts associated with synthetic turf use and wider implications for population health.

This literature review was requested by the Office of the NSW Chief Scientist and Engineer (OCSE) to complement their ongoing research activities and the development of synthetic turf in public open space guidelines.

Method

Through discussions with the Project Control Group, five health themes were identified. A literature search strategy supported the identification of relevant peer reviewed scientific journal articles and grey literature for each health theme for analysis.

Health implications

The summary of available evidence is outlined below across the five health themes. There is a lack of evidence from Australia with most studies conducted in Europe and North America.

Theme 1: Lower body, head or abrasion injury

- Synthetic turf can generate greater stress on the players' feet.
- Inconsistent evidence to link higher rates of head or lower body injury or skin abrasion to synthetic turf over natural turf surfaces.
- Synthetic turf surfaces may heat to very high temperatures capable of causing dermal injury.

Theme 2: Heat-related illness, thermal comfort and the Urban Heat Island (UHI) effect

- Lack of studies investigated whether the ground heating of synthetic turf surfaces is capable of increasing heat-related illnesses amongst field users, although available evidence suggests that the rates of heat-related illnesses amongst field sports athletes in general are very low.
- Natural turf may offer greater thermal comfort than synthetic turf.
- Lack of studies investigated the heat contribution of synthetic turf fields to the wider UHI effect.

Theme 3: Chemical, microplastic & microbiological health risks

- The excess lifetime cancer risk of exposure to polyaromatic hydrocarbons (PAHs) in crumb rubber by inhalation, ingestion and dermal contact has been shown to fall within acceptable limits.
- The excess lifetime cancer risk and non-cancer risk of exposure to heavy metals in crumb rubber by ingestion, dermal contact or inhalation have generally been shown to fall within acceptable limits and hazard guidelines.
- The health risks of other synthetic turf chemicals including Volatile Organic Compounds (VOCs), plasticizers, antioxidants and additives were less well studied, but their levels of detection were generally low and unlikely to pose appreciable health effects.
- Preliminary studies suggest that microplastics from synthetic turf fields may contaminate surrounding soil or drainage systems, with the health impacts unknown.
- Evidence does not support synthetic turf as a source of methicillin-resistant *Staphylococcus aureus* infection.

Theme 4: Chemical leachate runoff

- Although the leaching dynamics of synthetic turf field chemicals are not well studied, preliminary studies indicate that leachates containing metals and PAHs are low and generally below regulatory standards.

Theme 5: Physical, mental and the social dimensions of health

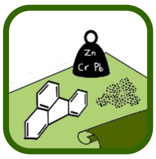
- Lack of evidence that the replacement of natural turf fields with synthetic turf has effects on health and wellbeing associated with the loss of natural green space.

Key findings

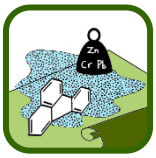
Sports-related injury may occur on both synthetic and natural turf fields at comparable levels and a good maintenance regime is required to ensure player safety.

The heat retaining property of synthetic turf surfaces is a characteristic that can impact health during hot conditions and their use should only be recommended during suitable weather for users on or around the field, particularly for children and exercising individuals who are susceptible to heat exhaustion.

The contribution of synthetic turf fields to the UHI effect at scale is likely small, but the cumulative depletion of natural grass over time undermines the role of green space on cooling down the city's land surfaces.



Even though the health risks of chemicals in synthetic turf are likely to be very low, progressive restrictive measures to limit potentially harmful chemicals in synthetic turf components may reduce unforeseen consequences to health.



Although leachate and microplastic runoff from synthetic turf fields are likely to be very low, measures to reduce chemical and microplastic pollution serve to reduce potential cumulative harm to aquatic and soil life, the environment and ultimately human health.

The social and environmental context of each playing field is different and the implications on the physical, mental and social dimensions of health cannot be drawn without research or surveying the community.

Conclusion

This Report did not identify major health risks associated with synthetic turf use, however, knowledge gaps remain, particularly for the potential indirect and longer-term cumulative health impacts of synthetic turf. Internationally, momentum is gathering to adopt a more precautionary approach. The banning of crumb rubber use on synthetic turf fields has been proposed in Europe to minimise any unforeseen and potentially harmful consequences for both health and the environment. Establishing local evidence will be an important step to inform policy development on synthetic turf use relevant to the Australian context.

INTRODUCTION

Background

NSW Health was invited by the Office of the NSW Chief Scientist and Engineer (OCSE) to provide input into evolving policies around the use of synthetic turf in public open space. In order to better understand health impacts, NSW Health was engaged to provide a rapid review of the potential human health impacts of using synthetic turf sport fields in outdoor open spaces. The increasing trend in the replacement of natural grass sport fields with synthetic turf by local councils across NSW has attracted community concern. Based on preliminary community consultations commissioned by the NSW Department of Planning, Industry and Environment (DPIE) in 2021, the health and safety of synthetic turf use, along with potential environmental and social impacts such as loss of green space and public amenities, were key concerns raised (Ethos Urban & Otium Planning Group, 2021). As a result, the NSW Department of Planning and Environment (DPE) is developing consistent state-wide guidelines to assist with the decision-making process by local Government authorities and agencies on the replacement of natural turf by synthetic turf materials.

This Report details NSW Health's review of the scientific literature on the potential physical, chemical and biological risks of synthetic turf on human health and the wider implications on population health. The Report contributes to the ongoing and longer-term development of guidelines and complement research activities commissioned by the OCSE for the purposes of mitigating potential environmental and health risks associated with synthetic turf use in open spaces. This Report focuses on 'third generation' synthetic turf, which is the most commonly adopted technology in Australia in recent decades (Ethos Urban & Otium Planning Group, 2021). We recognise that the synthetic turf technology is constantly evolving with new component materials and structures that have varying implications on their health risk profiles. However, given that synthetic turfs are durable substances that have over 10 – 20 years lifespan of use, the potential health and environmental risks identified from the current literature for third-generation synthetic turf materials will serve to be relevant and informative.

Research questions

The key health implications and findings of the Report are guided by the following key research questions:

1. What are the potential physical, chemical and biological health risks associated with exposure to synthetic turf?
2. What are the wider population health implications of synthetic turf use at the neighbourhood or city-scale?

Synthetic turf structure and material

Synthetic turf is a surfacing material first developed in the 1950's in America to mimic the appearance and sports performance of natural grass playing fields (Serensits et al., 2013). The intent was to provide a surface that could withstand heavy use without compromising playing characteristics and be easily maintained all year-round (Cheng et al., 2014; Serensits et al., 2013). Since its first installation at a major sporting venue at the Astrodome in Houston in 1966 as Astroturf, the technology has evolved to resemble closer and closer to the look and feel of natural grass with improved playability (Serensits et al., 2013). Figure 1 shows the evolution of the synthetic turf technology over the past decades, with the first generation of synthetic turf from the 60s made of short pile plastic nylon fibres with limited cushioning; to the slightly taller and less abrasive polypropylene fibres stabilised by sand infill of the second-generation products. The early generations of synthetic turf had higher levels of abrasiveness and hardness and were associated with more injury complaints from professional athletes (Serensits et al., 2013). Synthetic turf surfaces were also liable to heat up to dangerously high temperatures under mild to hot sunny conditions (Buskirk et al., 1971).

In response to these shortfalls, the third-generation technology, the most widely used today, was developed to provide less abrasion, more shock absorption and better athlete- and ball-surface interactions. Third-generation synthetic turf from the late 1990s featured an infill layer that combined a lower layer of sand and an upper layer of crumb rubber or organic material (Serensits et al., 2013). This layer provides shock absorption and upright stability for the longer polyethylene pile fibres. The pile fibres are sewn or glued to a polyester or polypropylene backing carpet which may be laid on an extra shock pad and/or drainage pipe network on a gravel bed.

However, whilst the physical property of third-generation synthetic turf is improved, concerns over its thermal and chemical attributes remained. In particularly, the introduction of crumb rubber infill (granules of 2 – 3 mm) and the shock pads typically made from granular styrene-butadiene (SBR) do little to reduce solar heat absorption and release (Petrass et al., 2014). Crumb rubber was primarily sourced from recycled end-of-life tyres (ELTs), which may contain hazardous levels of toxic metals such as zinc and lead and carcinogenic polyaromatic hydrocarbons (PAHs) (Cheng et al., 2014; Diekmann et al., 2019; Gomes et al., 2021; Perkins et al., 2019). Globally, an estimated 95% of third-generation synthetic turf contains SBR infill derived from end-of-life car and truck tyres (United States Environmental Protection Agency [U.S. EPA] & Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry [CDC/ATSDR], 2019). Crumb rubber granules and degraded plastic pile fibres are also classified as microplastics, which are contaminants of emerging health and environmental concern (Vethaak & Legler, 2021).

Beyond third-generation technology, the synthetic turf industry is beginning to introduce products to replace crumb rubber infill with organic alternatives such as cork and coconut fibre, which are naturally more cooling (Shaw Turf Sports, n.d.-b). A hybrid technology that grows natural grass in between the plastic pile fibres is also being developed (Shaw Turf Sports, n.d.-a).

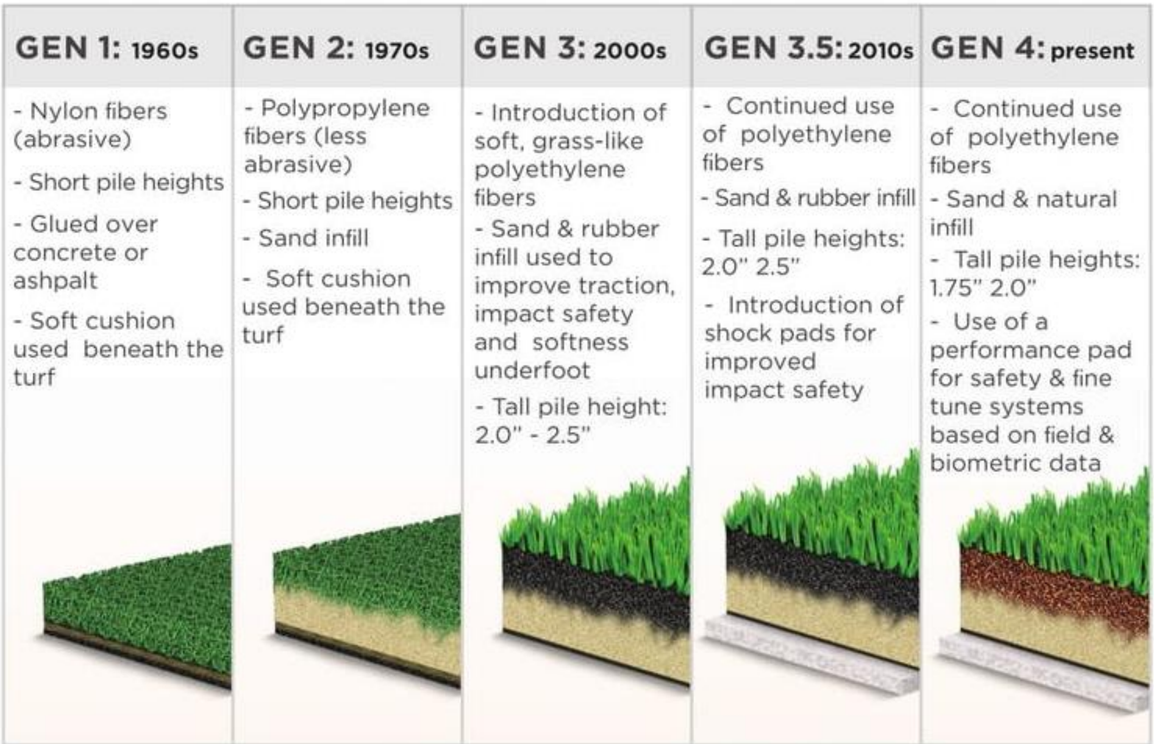


Figure 1. The evolution of synthetic turf.

Source: Shaw Turf Sports (Palubicki, 2019, April 23).

Current use and human health risk concerns

Given the public concern over the use of synthetic materials in the natural environmental, their increasing use for sports and recreational activities have been widely contested especially in Europe and North America, where their use is extensive. The use of synthetic turf has sparked debates over the exposure to potential health hazards, costs and benefits of the different play surfaces, and social and environmental consequences (Watterson, 2017). These debates have advanced investigations into the various aspects by local governments, agencies, industry groups, concerned communities and environmentalists against a shifting backdrop of advancing synthetic turf technologies, tightening environmental regulations, emerging exposure evidence, and market demands. Beyond the concern of health, Table 1 outlines some of the common conceptions around the use of synthetic and natural turf surfaces.

In Australia, the trends in synthetic turf conversions are expected to grow as local governments and sport clubs are facing pressures to provide more opportunities for communities to play sports and provide high-quality, low-maintenance sport surfaces to meet those playing capacities (Football NSW, 2021). Within the past five years, over 35 synthetic turf fields were installed across NSW (Football NSW, 2021). Some of those sites were already triggering strong community oppositions and igniting the debate around their impacts on the environment and health[1]. The decision to install synthetic turf or to replace natural turf with synthetic turf fields is therefore complex. Whilst it is not possible to weigh the pros and cons of all contested issues adequately within this Report, we acknowledge their relevance within the public health policy discourse for synthetic turf and health. This Report endeavours to evaluate the health-related implication of synthetic turf use based on scientific evidence and to draw considerations for the human health perspective. However, the ultimate decision should be guided by the balance of facts and values on the various practical, social and environmental dimensions.

Table 1. Synthetic vs. natural turf fields

	Synthetic turf fields	Natural turf fields
Maintenance	• Require brooming, decompaction and the removal of organic contaminates such as blood, saliva and animal droppings (Serensits et al., 2013; Simon, 2010). • Require periodic refilling of crumb rubber to compensate for loss from degradation from sunlight, compaction, and agitation by players (Verschoor et al., 2021).	• Require regular maintenance such as mowing, fertilising, topsoil dressing, decompaction, irrigating and resurfacing (Western Australia. Department of Local Government Sport and Cultural Industries, 2011b).
Playtime	• Current industry estimation suggested 60 hours of playtime per week with stable surface performance (Football NSW, 2021) with no waiting periods required between play (Simon, 2010). • When more playtime can be scheduled on synthetic turf than on natural turf, more physical activities are encouraged with potentially greater health benefits.	• Current industry estimation suggested 20 – 25 hours of playtime per week (Football NSW, 2021). • Degrade by intense play sessions and wet conditions and require more resting and recovery time. A council estimated that beyond 30 hours of utilisation per week would produce an unacceptable surface by the end of a regular football season (City of Ryde, 2017).
Appearance	• Stay green in all conditions but the crumb rubber component may release an unpleasant odour under hot conditions (Cheng et al., 2014).	• Appealing smell and visual appearance with proper maintenance but hot and dry summers may erode aesthetic qualities in addition to the loss of playability and safety (Cheng et al., 2014).
Water consumption	• Do not technically require irrigation.	• Require an irrigation schedule according to the demands of the local climate, the species of grass and professional level of sport (WADLGSC, 2011b).
Environmental	• May require chemicals to control weeds, moss and algae on a regular basis depending on location and environmental conditions (Serensits et al., 2013). • Preliminary studies indicated that synthetic turf has a larger carbon footprint	• Properly maintained and correctly fertilised natural turf contributes very little to nutrient and sediment runoff, as the dense plant structure provides less channelised pathways for water movement (Stier et al., 2013). Pesticide runoff from natural turf is also relatively

[1] Various million-dollar synthetic turf installation projects were opposed by local residents and environmental groups in the Lane Cover, Hunters Hill, Ku-ring-gai and Hornsby LGAs; a local advocacy group took the Bayside council to the Land and Environment Court to try stop work on the installation of an approved synthetic turf (STEP Inc. (2021, May 4). Opposition to Synthetic Turf is Growing. https://www.step.org.au/index.php/item/487-opposition-to-synthetic-turf-is-growing).

	than natural turf when considering the whole product lifecycle from manufacturing, transporting, installing, maintaining and to final disposal (Meil & Bushi, 2007). This is made worse if they cannot be recycled at disposal (Meil & Bushi, 2007). • The industry advocates that recycling ELTs for use in synthetic turf is beneficial to the environment as the alternative is disposal by incineration, stockpiling or illegal dumping. However, the disposal of end-of-life synthetic turfs with their component microplastics and crumb rubber remain a key environmental issue. The default disposal option for end-of-life synthetic turf is landfill as the technologies to deal with their reuse and recycling are yet to be fully developed (Eunomia Research & Consulting, 2017).	minor and poses more of a concern if irrigation occurs immediately after pesticide application (Stier et al., 2013). • Self-renewing and do not have the disposal issues of synthetic turf. Natural turf may provide a range of ecosystem services, including regulating the water cycle, support soil organisms, remediate contaminated soil and reduce atmospheric pollutants in urban environments (Stier et al., 2013). However, heavily trampled and barren natural turf surfaces would reverse the many ecosystem benefits a healthy natural turf surface can provide. • Provide cooler microclimates and ameliorate heat island effects through evapotranspiration (Stier et al., 2013). • Natural fields are carbon sinks, however, mowing and other maintenance activities may offset the benefits of carbon sequestration (Cheng et al., 2014)
Community perception	• Sport groups and synthetic turf users may favour synthetic turfs due to their consistent play surface and reduced disruption on playtime due to climate challenges. However, perception also depends on the various sports, with higher acceptance in soccer and less so for football, cricket and rugby (WADLGSC, 2011a).	• Local residents were often not consulted when councils were proposing the conversion of natural turf to synthetic turf fields (Ethos Urban & Otium Planning Group, 2021). This further implicates on equity concerns, as public natural open space becomes increasingly eroded for community use. Informal and passive activities on public space may also be diminished by the high intensity, privatised use by sports clubs on what should be a shared public good.

METHODS

Overall research process

Given the complexity of the topic, the breadth of the literature, the wide range of different interactions users can have with synthetic turf, and the potential environmental impacts, we undertook a two-stage process for the literature review. Figure 2 shows the key steps undertaken in the preparation of this Report, which includes the identification of health themes, conducting the literature review based on a search strategy, synthesising the evidence and discussing the key implications for each of the health themes.

Research Step	Activity
Identification of health themes	Working group consultation to identify health themes (see Table 2)
Literature review	Peer reviewed journal articles using Medline, Embase and Scopus databases according to the search strategy (see Table 3) Grey literature using Google according to the search strategy (see Table 3) Remove duplicates Exclude records based on title and abstract screening and relevance to each of the health themes Include additional relevant literature from the reference lists of publications found in the database searches
Summary of evidence	Full-text analysis and provide summary of evidence for each of the health themes
Discussion	Key implications for each health theme in the Australian context
Conclusion	Summary of key findings

Figure 2. Research processes and structural analysis of the literature review.

Identification of health themes

We began by holding a theme generation workshop with experts from the Project Control Group, including academic researchers and policy makers from the OCSE, DPE and NSW Health, to identify a set of themes from which to structure a deeper investigation of health concerns. Five health themes were identified based on the direct and indirect exposure pathways by which synthetic turf may affect human health (see Table 2). These themes broadly capture the range of health risks potentially associated with synthetic turf use, from direct effects to the wider implications of their use on population health.

Table 2. Rationales for the study's health themes.

Health Themes	Rationale for the health concerns	Health impact
Theme 1: Lower body, head or abrasion injury	The hardness and abrasiveness of synthetic turf surfaces may contribute to more bodily injury than natural grass surfaces. Synthetic turf surfaces, in particularly the crumb rubber infill, may heat to dangerous levels to cause burns.	Direct
Theme 2: Heat related illness, thermal comfort and the Urban Heat Island (UHI) effect	The elevated temperature of synthetic turf surfaces may cause thermal discomfort within its proximity as well as contributing to the UHI effect.	Direct and indirect
Theme 3: Chemical, microplastic and microbiological health risks	The chemical signature of synthetic turf components, particularly the crumb rubber infill, could potentially pose cancer or non-cancer health risks. Synthetic turf may be a source of microplastics with health implications. Also of concern is the potential for synthetic turf surfaces to harbour pathogens and cause bacterial infections.	Direct
Theme 4: Chemical leachate runoff	Chemicals from synthetic turf components may leach into drinking water resources with implications on population health.	Indirect
Theme 5: Physical, mental and social dimensions of health	The replacement of natural turf fields with synthetic turf may decrease local communities' access to natural green space and amenities, which may implicate on community cohesion and mental health.	Indirect

Literature review

Research questions

We formulated a search strategy guided by two key research questions to conduct a literature review for each of the health themes identified in Table 2:

1. What are the potential physical, chemical and biological health risks associated with exposure to synthetic turf?
2. What are the wider population health implications of synthetic turf use at the neighbourhood or city-scale?

Search strategy

The search strategy was conducted using the Medline (accessed 1 March 2022), Embase (accessed 1 March 2022) and Scopus (accessed 2 March 2022) databases for peer review journal articles. For grey literature, we used Google to search government and agency websites including the European Chemicals Agency, the European Union, the United States Environmental Protection Agency, the World Health Organisation, New South Wales Government agencies and selected local councils and other state jurisdictions. Table 3 outlines the search term keywords we used to explore each of the health themes.

Table 3. Search strategy.

Health Themes	Search Terms
Themes 1, 3 and 4: Direct health effects including injury and chemical, microplastic and microbiological health risks. Wider health implications include leachate runoff	On Medline and Embase databases, we included all research articles on synthetic turf: ("synthetic turf" or "artificial turf" or "synthetic grass" or "artificial grass").mp. On Scopus, we applied more targeted keywords to the search string as follows: (TITLE-ABS-KEY ("synthetic turf" OR "synthetic grass" OR "artificial turf" OR "artificial grass") AND TITLE-ABS-KEY(health OR injur* OR heat).
Theme 2: Heat-related illness, thermal comfort and the Urban Heat Island effect	On Medline and Embase: ("green space" or grass or turf or "heat island").mp. and ("thermal comfort" or "heat-related" or cool*).mp. On Scopus: TITLE-ABS-KEY("green space" OR grass OR turf OR lawn) AND TITLE-ABS-KEY("heat island" OR heat* OR cool* OR "thermal comfort").
Theme 5: Physical, mental and social dimensions of health	On Medline and Embase: ("green space" or turf or grass).mp. and Mental Health/ or ("social cohesion" or "mental health"). On Scopus: TITLE-ABS-KEY("green space" OR grass OR turf OR lawn) AND TITLE-ABS-KEY("mental" OR "social cohesion" OR "physical activity").

Additional relevant literature from the reference lists of publications found in the formal database searches were also included.

The literature search was limited to the past 20 years from 2002 to 2022. Third-generation synthetic turf technology was introduced in the 2000's and research studies investigating its properties would predominately arise from this time period. The articles were limited to full-text articles published in the English language. We did not limit by geographical location of the scientific studies.

Eligibility criteria and screening

The primary inclusion criterion was a clear statement of investigation of association between any of the synthetic turf components or green space with the health effects belonging to the five health themes. Study designs including exposure assessments, health risks assessments, modelling studies, epidemiological studies, systematic reviews or meta-analyses were eligible for inclusion where they presented quantitative data in relation to a comparator group. Studies that used natural grass (control) as a comparator group were prioritised, however, other studies using comparator groups such as background exposure, exposure threshold/guideline values or acceptable probability of risk were included.

The title, abstract or executive summaries of the search strategy outputs were reviewed by two individuals according to the eligibility criteria, with disagreements resolved by discussion.

Research limitations

Due to the breadth of health research themes covered by the review, the inclusion criteria needed to accommodate a diverse range of research methods or standards across different health themes where exposure risks were still being established. There is also a paucity of studies investigating the wider and more indirect implications of synthetic turf use in general. For example, the contribution of synthetic turf to heat island effects and possible heat-related health impacts is limited. As such we inferred findings from more tangential studies that considered the negative environmental impacts of impervious surfaces or the positive cooling effects of natural grass. Finally, this review does not attempt to provide an exhaustive summary of the literature but selected the most relevant, robust evidence available each health theme for critical analysis.

SUMMARY OF EVIDENCE

This review synthesised a diverse range of evidence to characterise the extent to which synthetic turf use may have an impact on human health. Diverse forms of evidence were identified across the different health themes. A large number of cohort and descriptive epidemiological studies, and some reviews and meta-analyses have explored the potential impact of synthetic turf compared to natural turf on bodily injury rates of college and professional level athletes engaged in different types of sports. There has been far less investigation of heat-related injuries caused by synthetic turf, where health risks were mostly conceptualised by modelling studies. Very few epidemiological studies explored methicillin-resistant *Staphylococcus aureus* (MRSA) infections on synthetic turf users, with a small number of field and lab studies investigated the microbiological profiles of synthetic and natural turfs. Human exposure to chemicals found in synthetic turf, particularly the crumb rubber component, was extensively explored in a number of large agency-led exposure assessments and health risk assessments, whilst many research studies explored the chemical compositions (and to a lesser extent, leachate compositions) of synthetic turf and their exposure risks. Microplastics stemming from synthetic turf is an emerging topic and their leaching dynamics into waterways and risk to health are largely unknown. There is also a paucity of studies investigating the contribution of synthetic turf to the UHI effect and heat exposure at the population level, or the mental and social dimensions of synthetic turf conversion form natural turf. Finally, there is a general lack of studies on synthetic turf and health in Australia, with most studies conducted in Europe and North America.

The following summarises the identified published evidence across five health themes.

Theme 1: Lower body, head, abrasion or dermal injury

As the use of synthetic turf has become more widespread, concerns have been raised regarding the impact of its play surface compared with natural turf with respect to injury types and severities. These concerns were more relevant to the harder and more abrasive first-generation ‘Astroturf’ which caused higher levels of knee injury and skin abrasion (Powell & Schootman, 1992; Taylor et al., 2013). More recently, third-generation synthetic turf was developed to mimic natural turf more closely and provide users with a more comfortable playable surface. The issue of heat remained problematic with the newer generations of technology. Under hot conditions, the surface temperature of synthetic turf could potentially heat to levels that cause burns (Denly et al., 2008). Injury caused by synthetic turf surfaces remain an important area of research as they are increasingly used across the different types of sports, levels of play and age groups. In Australia, synthetic turf is used for community and/or elite level soccer, cricket, touch football, hockey and more recently, rugby (WADLGSC, 2011b).

Synthetic turf can generate greater stress on players’ feet

Biomechanical studies suggested that players would experience greater rotational torque generated by the shoe-surface interface on synthetic turf compared to natural turf (Livesay et al., 2006; Villwock et al., 2009). Synthetic turf users could also experience impact from colliding with the field, where the hardness of the field can be influenced by the type and amount of infill, the extent of the infill’s compaction and the presence or absence of a shock pad (McNitt et al., 2003). However, many risk factors can influence player-surface interaction in practice, including the athlete’s build and style of play, type of footwear, the condition of the play surface and environmental factors such as moisture levels (Williams et al., 2013).

Inconsistent evidence to link higher rates of head or lower body injury or skin abrasion to synthetic turf over natural turf surfaces

The findings of cohort studies comparing the risks of injury to lower body extremities (i.e. knee, ankle and foot) between synthetic and natural turf have been mixed. A recent systematic review of 31 epidemiological studies showed that 51.6% of the studies found no significant differences in overall lower body injury rates amongst field sports players of any type of sports and level of competition between synthetic and natural turf, with 35.5% finding higher injury rates on synthetic turf and 12.9% finding higher injury rates on natural turf (Gould et al., 2022). However, stratified by foot and ankle injuries, 58.8% of studies reported higher injury rates on synthetic turf compared to 12.5% for natural turf (Gould et al., 2022). A meta-analysis of lower extremity injury incidence rates of soccer players from 8 cohort studies found an overall incidence rate ratio of 0.86 for synthetic compared to natural turf, suggesting lower injury risk with synthetic turf (Williams et al., 2013).

For head injury, a meta-analysis of 8 studies compared the rate of concussion on synthetic versus natural turf for competitive soccer, football and rugby (O'Leary et al., 2020). The study found a rate ratio of head injury and concussion to be 0.89, indicating a lower injury rate on synthetic turf over natural turf (O'Leary et al., 2020).

For abrasion injury, defined by damage to the epidermis or surface layer of the skin, a systematic review of 25 studies showed that whilst these injuries do occur on synthetic turf surfaces, the data were mixed on whether the risk was greater on synthetic turf or natural turf (Twomey et al., 2019). The review included studies investigating abrasion injury amongst professional soccer, American football, lacrosse and rugby athletes (Twomey et al., 2019). A key limitation to epidemiological studies investigating abrasion injury is the undercounting of the true incidence of abrasion, as medical attention is often not needed. Players' perception of whether synthetic turf causes more sports injury has also been investigated. Qualitative surveys reported that players preferred natural over synthetic turf as the latter was perceived to increase the risks of abrasion, muscle soreness and fatigue (Burillo et al., 2014; Roberts et al., 2020; Zanetti et al., 2013). This was also reflected in an Australian survey of football and cricket players who perceived synthetic turf to increase the risks of abrasion injury (Twomey, 2019). These negative perceptions may play a role in changing the playing style of athletes on the field, as observed in a study that correlated the avoidance of side tackles by football players with higher negative perception of synthetic turf (Andersson et al., 2008).

A review of the differences in injury risks associated with synthetic and natural turf for different types of sports found no difference between turf surfaces on the overall injury risk for soccer and rugby (Sivasundaram et al., 2021). However, when stratified by the location of injury, synthetic turf may be associated with greater foot and ankle injury rates in American football, whilst for the results among soccer players was less clear (Sivasundaram et al., 2021).

Regardless of the type of injury investigated, there are considerable variabilities between the outcomes of the studies. Studies are often difficult to compare because it is difficult to control for a range of confounding risk factors, partly due to the difficulties in accounting for them. These include the specification, condition and age of the turf surfaces; the different styles of play across the different field sports types and professional levels; the types of shoes worn by the athletes; and other environmental factors such as temperature or wet/dry field conditions (O'Leary et al., 2020; Taylor et al., 2013; Twomey et al., 2019; Williams et al., 2013). Studies also often classified the location and the types and severities of the injury inconsistently (Twomey et al., 2019; van den Eijnde et al., 2014; Williams et al., 2013). Furthermore, many epidemiological studies failed to categorise injury type to either player-to-player contact or player-surface contact, which is a limitation (Taylor et al., 2013; Williams et al., 2013). Player-to-player contact (e.g. collision during play) generally accounts for the majority of sport injuries (Fuller et al., 2007). Without the differentiation, the true effect of injury risks attributable to the player-surface interface (i.e. ankle or knee torque caused by stop or turn at the shoe-surface interface, concussions caused by the head coming into contact with the play surface, or abrasion caused by contact with the play surface) could be masked by injuries caused by player-to-player contact (O'Leary et al., 2020; van den Eijnde et al., 2014; Williams et al., 2013).

Synthetic turf surfaces may heat to very high temperatures capable of causing dermal injury

Synthetic turf may expose players to higher heat than natural turf via heat conduction from the ground to the soles of the shoes and by the convection of heated air near the ground surface (Jim, 2016, 2017). The thermal profile of synthetic turf is further discussed in Theme 2 of this section. Contact with very hot synthetic turf surfaces may cause burns depending on the exposure duration. Synthetic turf surfaces can reach beyond 70ºC on hot summer days (Devitt et al., 2007). Cutaneous thermal injury can occur when surface temperature is above 44ºC, where second-degree burns can occur with 35 seconds of exposure to a 77ºC surface (Harrington et al., 1995). There is very limited evidence documenting burns attributed to contact with synthetic turf. It has been reported that high temperatures of synthetic turf caused burns and blisters on athletes' feet through the soles of their shoes (Denly et al., 2008).

Theme 2: Heat-related illness, thermal comfort and the Urban Heat Island effect

The surface of synthetic turf can heat significantly higher than that of natural turf under the same ambient temperature and direct sunlight on hot days. The crumb rubber and plastic pile blades are the most heat-absorbent components of synthetic turf as they have low albedo[2], low specific heat[3] and can transform solar radiation to significant ground surface heating (Jim, 2016, 2017; Villacañas et al., 2017). On hot summer days with air temperatures reaching the mid-30s or higher, synthetic turf surface temperature can rise up to 38ºC more than that of natural turf, with maximum surface temperatures ranging from the 70s to above 90ºC (Devitt et al., 2007; Jim, 2016, 2017; Williams & Pulley, 2002). Even on milder days of 25ºC, synthetic turf surface temperatures can reach as high as 60ºC (Marsili et al., 2014). Natural turf, on the other hand, has a high specific heat and can keep surface temperatures close to that of ambient air temperatures (Jim, 2016). Environmental conditions especially solar radiation and ambient temperature, and the material composition of synthetic turf all influence surface temperature (Petrass et al., 2014; Villacañas et al., 2017). The thermal conditions of synthetic turf are expected to worsen over time with intense usage (Villacañas et al., 2017).

On the other hand, the air temperatures within the microenvironment of synthetic turf fields do not tend to rise as significantly nor correlate with synthetic turf surface temperatures. A study showed that the local air above a synthetic turf field rose to 42.7ºC at 15 cm and decreased to around 35ºC at the 50 cm and 1.5 m above the surface on a calm sunny day, where the maximum ambient temperature was 34.4ºC (Jim, 2016). The air above natural turf rose to 38.1ºC at 15 cm and then also decreased to around 35ºC at the 50 cm and 1.5 m marks (Jim, 2016). Whilst generally the microenvironment at the standing height is comparable for both turf surfaces, the air close to the ground is not, and players are potentially exposed to substantially hotter synthetic turf grounds on hot sunny days. Children, due to their shorter stature and lower heat tolerance, may be more susceptible to heat-related illnesses caused by heat emanating from synthetic turf fields (Bergeron et al., 2011; Jim, 2016). This is in addition to the heat they receive directly from the sun and from physical exertion.

At a wider intra-urban or city-scale, synthetic turf surfaces may contribute to the urban heat island (UHI) effect, as they can elevate temperatures surpassing that of common urban impervious surfaces such as asphalt and concrete (Devitt et al., 2007; Williams & Pulley, 2002). The UHI phenomenon can cause air temperatures in cities to reach 2 – 4ºC higher than that of the surrounding rural areas, with greater implications for night time temperatures which can reach 5 – 10ºC higher (Heaviside et al., 2017). A number of factors in the urban environment contribute to the UHI effect, including the reduction of natural landscapes and green spaces; the prevalence of heat retaining impervious surfaces; the increased obstruction of wind flow by building geometries; and the increased emissions of heat from vehicles and buildings (U.S. EPA, n.d.-c).The UHI effect is also intensified by climate change where higher frequencies of extreme temperatures and heatwaves are predicted (U.S. EPA, 2017; U.S. EPA, n.d.-a). The most direct impact of UHI effect on health is increased population exposure to higher ambient temperatures. The elderly, young children and people with underlying cardiovascular and respiratory conditions are physically more susceptible to excessive heat (Heaviside et al., 2017; U.S. EPA, n.d.-b).

Lack of studies investigated whether the ground heating of synthetic turf surfaces is capable of increasing heat-related illnesses amongst field users, although available evidence suggests that the rates of heat-related illnesses amongst field sports athletes in general are very low

No epidemiological studies were identified that specifically investigated whether synthetic turf could increase local ambient air temperatures to cause heat-related illnesses. There are broader studies from the US that investigated the types and rates of sports injury amongst college-level players who played field sports in general. Between 1988 – 1997, the aggregate rate of heat-related illness amongst 89,500 soccer players (equivalent to 290,344 player-hours of competition) was 2.8 per 1000 player-hours during the 'hot' years as compared to 0.6 cases per 1000 player-hours during 'normal' years. Increase in heat-related illnesses were observed to correlate with increase in mean temperatures (Elias, 2001). For heat-related fatalities, 0.16 per 100,000 football players or 1.9 cases annually occurred between 1990 – 2010 with the average maximum temperature of the fatal day and core body temperature identified to be 32ºC and 42ºC respectively (Boden et al., 2013). Although these epidemiological studies did not account for the different types of turf surfaces the games were played in, they showed that heat-related illnesses occurred during field sports were generally low.

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[2] Albedo is the amount of solar radiation (sunlight) reflected by surface, expressed as a ratio of reflected solar radiation to total direct solar radiation.
[3] Specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius.

Natural turf may offer greater thermal comfort than synthetic turf

Modelling studies are emerging to assess the level of heat stress that may be experienced by different population groups exposed to heat on synthetic turf fields (Jim, 2016; Liu & Jim, 2021). One of the more sensitive indices of heat stress is the Comfort Formula (COMFA) which accounts for a range of microclimatic and human physiological inputs (Coccolo et al., 2016). A model from subtropical Hong Kong investigated the potential heat stress levels experienced by children, young athletes and adults performing different physical activities under different weather conditions in summer on synthetic or natural turf (Liu & Jim, 2021). The differences in experiencing 'extremely dangerous' levels of heat stress on either surface are limited, regardless of weather conditions, if the physical activity undertaken is intense (i.e. playing soccer) (Liu & Jim, 2021). However, better thermal comfort is offered by natural turf under sunny or cloudy conditions if less intense physical activities are undertaken (i.e. walking), especially for children (Liu & Jim, 2021).

Lack of studies investigated the heat contribution of synthetic turf fields to the wider UHI effect

In the absence of studies that investigated how synthetic turf may contribute to the UHI effect, inferences may be drawn from field and landscape studies that investigated the heat profiles of comparable impervious surfaces to synthetic turf at different spatial scales. A Greek field study showed that air temperatures above grass and impervious surfaces such as concrete remained close to the ambient air temperature even though concrete reached significantly hotter surface temperature (46°C, compared to 35°C for grass) (Chatzidimitriou & Yannas, 2015). Globe temperatures[4], which are indicative of thermal comfort experienced by the human body, were also comparable for both surfaces. At a larger spatial scale, a UK study showed that larger expanses of concrete (42 x 25m) and grass (136 x 100m) had little effect on local air or globe temperatures (Armson et al., 2012). Other studies combined meteorological measurements and interview surveys to evaluate the thermal experience of people of different urban spaces. Thermal comfort is not solely measured objectively but can also be influenced by subjective judgements of thermal sensation, preference, comfort levels and acceptability (Lai et al., 2020). A Dutch study investigated the air temperatures, physiological equivalent temperatures (PET)[4], and people's opinions of grass and impervious areas around Amsterdam during hot summer afternoons. The study found that even though both air temperatures and PETs on grass were slightly lower than those of impervious surfaces, they were not perceived to be thermally more comfortable than impervious surfaces (Klok et al., 2019).

Although these studies did not directly investigate synthetic turf, they provided insight onto how synthetic turf would likely behave given similar heat absorbent properties compared to impervious surfaces such as concrete. It is likely that on hot sunny days, synthetic turf may locally increase air temperatures and PETs slightly. However, the contribution to the wider UHI effect at scale is likely very small given the proportionately small area occupied by such surfaces in the city.

Theme 3: Chemical, microplastic and micobiological health risks

The main components of a third-generation synthetic turf are the polyester or polypropylene backing, the crumb rubber infill layer and the polyethylene pile fibres. The chemical signature of crumb rubber, which reflects those of recycled tyres from cars and trucks of mixed origins, has raised the most health concern due to the toxic or carcinogenic potentials of some of the chemical components (Gomes et al., 2021). The potentially hazardous compounds found in crumb rubber include semi-volatile organic hydrocarbons (SVOCs) such as polycyclic aromatic hydrocarbons (PAHs), volatile organic hydrocarbons (VOCs), heavy metals and other antioxidants and additives (Armada et al., 2022; Cheng et al., 2014; Diekmann et al., 2019; European Chemicals Agency [ECHA], 2017; Gomes et al., 2021; Schneider, de Hoogd, Madsen, et al., 2020; U.S. EPA & CDC/ATSDR, 2019). Other

[4] Globe temperature takes into account microclimatic variables including humidity, wind speed, solar radiation and ambient temperature and is an indicator of thermal comfort experience by the human body. The globe temperature is indicative of thermal conditions experienced by pedestrians and can be used to calculate the Physiological Equivalent Temperature (PET) to assess the level of heat stress felt by pedestrians. Chatzidimitriou, A., & Yannas, S. (2015). Microclimate development in open urban spaces: The influence of form and materials. Energy and Buildings, 108, 156-174. https://doi.org/10.1016/j.enbuild.2015.08.048 .

components of synthetic turf such as the backing or plastic pile blades may also release chemicals of potential concern, however, the literature is limited on this topic (Cheng et al., 2014).

Despite the assumption that synthetic turf is extremely resistant to degradation; sunlight, heat, liquids, oxygen and ozone can breakdown synthetic turf during the lifetime of use (Cheng et al., 2014), which can be over 10 – 15 years. Potentially hazardous chemicals can volatilise into the air or leach into ground water and river catchments (Cheng et al., 2014). Humans may be directly exposed to these chemicals by ingesting the crumb rubber or leachates; inhaling gases or dust particles from the synthetic turf; or skin contact with crumb rubber or leachates (ECHA, 2017; U.S. EPA & CDC/ATSDR, 2019).

Crumb rubber particulates and broken pile fibres are classed as microplastics, being 1 – 5 mm granules with a 46% polymer content (Lassen et al., 2015). Microplastic pollution is an emerging environmental and health concern. Crumb rubber infill can transfer to the environment by players 'walking' it off the field in clothes and shoes which leads to transport to domestic wastewater. These microplastics can be washed away by rain and flow along the slope of the field terrain into stormwater drains, which may further reach river or marine environments (Li, 2019). It is outside of this review's scope to discuss the potential environmental impact of leachates or microplastics from synthetic turf, however, it is conceivable that they have harmful effects on soil biota and marine life (Armada et al., 2022; Cheng et al., 2014).

The excess lifetime cancer risk due to exposure to PAHs in crumb rubber by inhalation, ingestion and dermal contact has been shown to fall within acceptable limits

Polycyclic aromatic hydrocarbons (PAHs) are complex mixtures of organic compounds that exist naturally in rubber and in plasticizers used in the production of tyres (Gomes et al., 2021). Several PAHs are known genotoxic carcinogens to humans with non-threshold effects (International Agency for Research on Cancer, 2010). One of these PAHs, Benzo[a]pyrene (B[a]P), is used as an indicator of PAH contamination in crumb rubber due to its prevalence and high toxic potential (Diekmann et al., 2019). The US EPA designated 16 PAHs[5] as chemicals of concern in the 1970's based on their toxicity, carcinogenic potential and prevalence in the environment (Keith, 2015). More recently, the ECHA limited the aggregated concentrations of 8 carcinogenic PAHs[6] to 20 µg/g in crumb rubber (ECHA, 2019). A global evaluation of 78 crumb rubber samples from synthetic turf fields across 17 countries and 4 continents found that a minority of samples (3 samples) did exceed the 20 µg/g limit for the sum of the 8-ECHA PAHs in crumb rubber, whilst one-third of the samples had the sum of the 16-EPA PAHs detected at the 20 and 42 µg/g range (Armada et al., 2022).

As a SVOC, PAHs can volatilise into the breathing zone of the synthetic turf user or deposit onto the skin. Direct inhalation and dermal contact of PAHs are therefore assumed to be the potential primary routes of exposure; whilst ingestion of crumb rubber or dust particles from the field, and exposure to leachates released into the environment is considered secondary (Diekmann et al., 2019).

Due to the heating properties of crumb rubber that facilitate the volatilisation of PAHs as gases or as airborne dust (particulate matter[7]) resuspensions, human exposure to PAHs by inhalation under summertime conditions has been a focus of many studies. The higher inhalation rates of athletes playing on the synthetic turf may also exacerbate the uptake of PAHs. Several health risk assessments and reviews were conducted in Europe (ECHA, 2017; Marsili et al., 2014; Menichini et al., 2011; Persici & Lupi, 2016; Pronk et al., 2020; Ruffino et al., 2013; Schneider, Bierwisch, et al., 2020) and North America (Cardno ChemRisk, 2013; Ginsberg, Toal, Simcox, et al., 2011; Peterson et al., 2018; Vetrano, 2009) to assess the potential health impact of PAH emissions from synthetic turf crumb rubber. In general, studies found PAH emissions from synthetic turf crumb rubber to be less than national limit values or close to or below background ambient PAH levels. Typically measured B[a]P concentrations were below 2 ng/m^3, which

[5] 16 PAH priority pollutants designated by the U.A. EPA: Naphthalene (NAP), Acenaphthylene (ACY), Acenaphthene (ACE), Fluorene (FLU), Phenanthrene (PHEN), Athracene (ANTH), Fluoranthene (FLTH), Pyrene (PYR), Benzo[a]anthracene (B[a]A), Chrysene (CHY), Benzo[b]fluoranthene (B[b]F), Benzo[k]fluoranthene (B[k]F), Benzo[a]pyrene (B[a]P), Benzo[g,h,i]perylene (B[ghi]P), Indeno[1,2,3-c,d]pyrene (IND), and Dibenz[a,h]anthracene (DB[ah]A).

[6] 8 carcinogenic PAHs limited by ECHA in crumb rubber infill materials for synthetic turf: B[a]P, Benzo[e]pyrene (B[e]P), B[a]A, CHY, B[b]F, Benzo[j]fluoranthene (B[j]FA), B[k]F, DB[ah]A.

[7] Particulate Matter (PM) of aerodynamic diameter of 10 um is assessed in some studies as both inorganic (e.g. metals) and organic (e.g. PAHs) pollutants can bind to PM and contribute to health risks via the inhalation pathway.

were comparable to urban levels or well below national occupational exposure limit values (e.g.70 ng/m^3 in Germany to 10,000 ng/m^3 in Finland) (ECHA, 2017).

Of note, the European Risk Assessment Study on Synthetic Turf Rubber Infill (the ERASSTRI study) tested air samples from 17 synthetic sport fields across 6 European countries during summertime when volatile substances evaporate at higher rates. PAH concentrations above synthetic turf fields were not found to be different to those of background levels (Schneider, de Hoogd, Haxaire, et al., 2020) and no elevated health risks due to PAH inhalation were expected (Schneider, Bierwisch, et al., 2020). The study estimated the dermal and ingestion exposures of the 8-ECHA PAHs for children and adult players (both outfield players and goalkeepers[8]) and found that the excess lifetime cancer risks were below one in a million (1×10^{-6}) (Schneider, Bierwisch, et al., 2020), which are considered acceptable (ECHA, 2012). Similarly, a large evaluation study investigated 50 crumb rubber samples from 100 synthetic turf fields across Europe by the European Chemicals Agency (ECHA, 2017) (the ECHA study). The evaluation found that the excess lifetime cancer risk of the 8-ECHA PAHs for the inhalation, ingestion and dermal contact pathways were well below 1×10^{-6} for children and adult (for both outfield players and goalkeepers (ECHA, 2017). A number of Italian studies undertook biomonitoring via personal air samplers and skin surface deposits from athletes playing on synthetic turf fields or workers installing the fields (Menichini et al., 2011; Persici & Lupi, 2016). These studies found excess lifetime cancer risks of selected PAHs to be below 1×10^{-6} for the exposure groups (Menichini et al., 2011; Persici & Lupi, 2016).

Drawn from the results of 37 studies (103 samples), a North American multi-pathway assessment integrated the health risks of a comprehensive list of chemicals of concern including PAHs, heavy metals and other chemicals for all exposure pathways (ingestion, dermal and inhalation) (Peterson et al., 2018). Exposure scenarios were considered for adult, youth and child athletes and spectators. The incidental ingestion pathway was only considered for children and youth to account for the potential increased intake of crumb rubber due to hand-to-mouth activities. The study found less than 1×10^{-6} of excess lifetime cancer risks for all exposure groups (Peterson et al., 2018). B[a]P was one of the main contributors to cancer risk for child spectators via the ingestion pathway, however, summing up with other chemicals, the excess lifetime cancer risk was below 1×10^{-6} (Peterson et al., 2018). The study also assessed the cancer risk of natural soil fields and found that B[a]P was a greater contributor to cancer risk via the ingestion and dermal pathways when compared to synthetic turf. The higher cancer risk estimates suggested that PAHs in natural soil are more bioavailable. However, the cancer risks of natural soil across all exposure scenarios were still within an acceptable target risk range of 1×10^{-6} to 1×10^{-4} (Peterson et al., 2018).

The excess lifetime cancer risk and non-cancer risk of exposure to heavy metals in crumb rubber by ingestion, dermal contact or inhalation have generally been shown to fall within acceptable limits and hazard guidelines

The presence of heavy metals in the crumb rubber as well as the plastic pile blades of synthetic turf have been investigated due to their potential to cause carcinogenic or non-cancer toxicities (Cheng et al., 2014; Gomes et al., 2021). Metals found in crumb rubber typically include arsenic, cadmium, chromium, cobalt, copper, iron, lead, nickel and zinc (Cheng et al., 2014; Gomes et al., 2021).

Zinc is the most prevalent element found in crumb rubber due to the use of zinc oxide in the vulcanisation process of tyre making and is also found in the plastic pile blades (Cheng et al., 2014; Gomes et al., 2021; U.S. EPA & CDC/ATSDR, 2019). Zinc concentrations have been shown to be above 1,000 – 15,000 mg/kg in crumb rubber samples (Celeiro et al., 2018; Marsili et al., 2014; Menichini et al., 2011; U.S. EPA & CDC/ATSDR, 2019), which are much greater than the regulatory limits for zinc in agricultural soils (e.g. 600 mg/kg from Germany; 200 mg/kg from Australia; 1,100 mg/kg from the U.S.) (He et al., 2015). Zinc is an essential element for life and adverse effects are associated with its deficiency or excess intake that may cause anaemia and copper deficiencies (National Health and Medical Research Council [NHMRC], 2011).

[8] Crumb rubber had been implicated in contributing to cancer amongst adolescent and young adult synthetic turf users in the US, particularly lymphoma amongst soccer goalkeepers. As such, several health risk assessments considered goalkeepers as a separate receptor group for analysis (Bleyer, A. (2017). Synthetic turf fields, crumb rubber, and alleged cancer risk. *Sports Medicine*, *47*(12), 2437-2441. https://doi.org/10.1007/s40279-017-0735-x , Bleyer, A., & Keegan, T. (2018). Incidence of malignant lymphoma in adolescents and young adults in the 58 counties of California with varying synthetic turf field density. *Cancer Epidemiology*, *53*, 129-136. https://doi.org/10.1016/j.canep.2018.01.010).

Lead is also of particular concern due to its non-threshold developmental neurotoxic effects for infants and children (NHMRC, 2011). Lead has been found in crumb rubber and plastic pile blades (attributed to certain pigments used) at concentrations generally below 30 mg/kg (Celeiro et al., 2018; Marsili et al., 2014; Menichini et al., 2011; U.S. EPA & CDC/ATSDR, 2019). These concentrations are generally below various national soil quality guidelines (e.g. 200 mg/kg from USA, 300 mg/kg from Australia and 1,000 mg/kg from Germany (He et al., 2015)). For all the other metals, studies generally yielded concentrations below national guidelines with the occasional soil samples showing exceedances.

Whether the presence of heavy metals in crumb rubber may translate to adverse health effects was explored in several health risk assessments, where the ingestion or dermal contact pathways were primarily considered. Of note, the aforementioned North American multi-pathway health risk assessment found arsenic as one of the main contributors to cancer risks for youth and children via the ingestion pathway, however, summing up with other chemicals, the excess lifetime cancer risks for these groups were below 1×10^{-6} (Peterson et al., 2018). For non-cancer risk, the main contributor was cobalt for youth and children via the ingestion pathway, where the hazard indices were less than 1 and considered acceptable. However, the non-cancer hazard index was equal to 1 for child spectators, but further analysis by target organ groups showed that the hazard indices were less than 1 which were considered acceptable (Peterson et al., 2018). Natural soil analysis showed that more so than synthetic turf cancer risks for youth and children were attributable to arsenic, however, the risk estimates were still within acceptable target risk range of 1×10^{-6} to 1×10^{-4} (Peterson et al., 2018). The aforementioned ERASTTRI study also did not find cobalt levels as an inhalation source from synthetic turf fields to be different from background levels (Schneider, Bierwisch, et al., 2020). A Dutch study sampled from 100 synthetic turf fields (45 samples) and found that the dermal and oral exposure to cadmium, cobalt and lead leachates in children and adult athletes were at levels below guideline values (Pronk et al., 2020).

Recently, a large multi-pathway health risk assessment[9] analysed 103 crumb rubber samples from 13 countries across the globe reported higher cancer and non-cancer risk estimates for the ingestion and dermal pathways for adult and adolescent athletes and child and adult spectators (Graça et al., 2022). The main contributor to non-cancer risk was zinc for the ingestion pathway, with hazard indices estimated at greater than 1 across all exposure groups except for adult spectators (Graça et al., 2022). For cancer risk, the main contributor was chromium for adolescent athletes and child spectators and lead for adult athletes for the ingestion pathway, where the excess lifetime cancer risks exceeded the acceptable target risk range of 1×10^{-6} to 1×10^{-4} (Graça et al., 2022). For dermal exposure, the main contributors included cobalt, arsenic, lead and chromium, however, all levels fell within acceptable limits and hazard guidelines across all the exposure groups (Graça et al., 2022). This risk assessment did not compare the risk estimates of synthetic turf crumb rubber exposure with those of natural soil fields.

It is important to understand that health risk assessments can over-estimate the theoretical risk when there are gaps in the knowledge. The characterisation and estimation of the chemical content in synthetic turf crumb rubber have also followed very different procedures across different studies in the literature. For example, not all studies obtained values of migrated chemicals from the crumb rubber for the risk assessment even though this is considered more important than the chemical content values (Gomes et al., 2021). This is because synthetic turf users are only exposed to a fraction of the substance rendered bioavailable. Chronic exposure scenarios also generally assume users to play on the same type of field surfaces all year round. Finally, many of the chemicals of concern exist ubiquitously in the urban environment and cross contamination from other sources make it difficult to attribute the identified health risks completely to crumb rubber alone (Gomes et al., 2021).

The health risks of other synthetic turf chemicals including VOCs, plasticizers, antioxidants and additives were less well studied, but levels of detection were generally low and unlikely to pose appreciable health effects

The literature has identified approximately 300 chemicals associated with crumb rubber of which 45 were classed as known or suspected carcinogens (Perkins et al., 2019). Many more may have non-cancer toxicities. The literature has prioritised the assessments of the most prevalent chemicals in crumb rubber such as PAHs and heavy metals, however, many more chemicals from the car tyre manufacturing process are expected to be present in crumb rubber

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[9] This study was brought to our attention after the literature search had been completed.

infill. These are the aromatic extender oils, plasticizers, antioxidants and other additives (Celeiro et al., 2018; Gomes et al., 2021). It is also of note that many of these chemicals are present in pile blades and other components of synthetic turf. The following are some of those chemicals that may be of health concern.

VOCs

VOCs are used as solvents in tyre making. These VOCs include methyl isobutyl ketone, acetone, benzene, toluene and xylene. Given that crumb rubber can reach high temperatures, the volatility of VOC air toxics have been investigated in a few studies. Generally, emissions of selected VOCs were detected on synthetic turf fields at very low levels or at levels comparable to background levels. Of note, an Italian study collected air samples containing dust and gases above 6 synthetic and natural turf fields and from the centre of the city Turin (Ruffino et al., 2013). The study investigated the health risks of benzene, toluene and xylene (amongst a panel of chemicals including metals and PAHs) in the inhalation pathway estimated for children and adults soccer players (Ruffino et al., 2013). The study found excess lifetime carcinogenic risk to be lower than 1×10^{-6} and non-carcinogenic risk to be lower than the hazard index of 1. Carcinogenic health risks of dusts and gases from synthetic turf fields were also compared with that of vehicular traffic with the latter yielding higher carcinogenic risks for children and adults at around 2×10^{-6} (Ruffino et al., 2013). The study detected significant cross-contamination of traffic air pollution over the fields.

Plasticizers

Plasticizers are used in tyre making as they are used to reduce the viscosity of rubber. Chemicals such as bisphenol A (BPA) and some phthalates are commonly used in plasticizers and are of concern as they are endocrine disruptors restricted or banned from personal care products, food packaging and children's toys (Gomes et al., 2021). These chemicals may resuspend on airborne dusts, however there are limited outdoor synthetic turf field studies measuring them. A Norwegian study detected very low levels of 6 phthalates in two indoor facilities (Dye et al., 2006), which suggests negligible health consequences for health in the context of a more ventilated outdoor setting.

Antioxidants and additives

Chemicals such as benzothiazole (BZT), a vulcanisation additive in tyre making; and butylated hydroxytoluene (BHT), an antioxidant commonly used to preserve fats in food and a stabaliser in tyre making, are of particular concern due to their health effects and prevalence in crumb rubber (Ginsberg, Toal & Kurland, 2011; Gomes et al., 2010). These chemicals have been considered respiratory irritants and dermal sensitizers (Ginsberg, Toal & Kurland, 2011; Gomes et al., 2021). An American study measured personal air samplers and air above 4 outdoor synthetic turf fields detected above background levels of BZT, however the contribution of BZT to non-cancer or acute risks were below the acceptable hazard indices of 1 for children and adult athletes (Ginsberg, Toal & Kurland, 2011). BHT concentrations were not elevated above background levels in the study (Ginsberg, Toal & Kurland, 2011).

Preliminary studies suggest that microplastics from synthetic turf fields may contaminate surrounding soil or drainage systems, with the health impacts unknown

The ubiquitous presence of microplastics in the environment is a growing concern given the widespread global use of plastic. Microplastics do not biodegrade, remain in the environment for a long time and bioaccumulate in the aquatic food chain that can ultimately be consumed by humans. Microplastics can also act as a carrier of hazardous substances (Lassen et al., 2015). Microplastics from synthetic turf fields can travel towards water resources by dispersing to the surrounding soil or drainage systems, or be removed by shoes or maintenance services (Verschoor et al., 2021). Based on several fields studies conducted in Scandinavia, a review estimated that on average approximately 600 – 1,200 kg of crumb rubber is required to refill each synthetic turf field per year due to dispersion as well as from player compaction (Verschoor et al., 2021). The implication of microplastics on human health is still largely unknown.

Evidence does not support synthetic turf as a source of methicillin-resistant *Staphylococcus aureus* infection

Health concerns have also been raised regarding the harbourage of methicillin-resistant *Staphylococcus aureus* (MRSA) bacteria in synthetic turf that may cause skin infections and potentially severe health complications (Keller et al., 2020). However, MRSA is a bacterium commonly found on the human skin and in the nasal cavity and is mostly transmitted via person-to-person contact or through shared items. Equipment sharing and poor sanitary practices likely contribute to increased risk of MRSA infection (Begier et al., 2004). It is unlikely that synthetic turf materials would be the source of the MRSA due to unfavourable outdoor survival conditions such as high temperatures and the presence of UV (PennState Extension, 2016; Waninger et al., 2011). From a public health perspective, the risk of MRSA infection by synthetic turf appears negligible.

Theme 4: Chemical leachate runoff

Leachates are created when synthetic turf is exposed to rain or irrigation water. Leachates containing metals and organic compounds from the crumb rubber can discharge into ground or surface water, river catchment and drinking water resources to affect the environment and human health (Celeiro et al., 2021; Gomes et al., 2021).

Although the leaching dynamics of synthetic turf field chemicals are not well studied, preliminary studies indicate that leachates containing metals and PAHs are low and generally below regulatory standards

Zinc and PAHs were generally detected in high levels and can leach continuously under laboratory conditions in crumb rubber leachates, owing to their high prevalence in the material (Bocca et al., 2009; Kallqvist, 2005; Lu et al., 2021; Plesser & Lind, 2004; Pronk et al., 2020). Some studies analysed leachates directly collected from synthetic fields or stormwater runoff (Celeiro et al., 2021; Celeiro et al., 2018; Connecticut Department of Environmental Protection, 2010; Lim & Walker, 2009; Moretto, 2007). Synthetic turf leachates may contact the users' skin on the field or from surface or river catchment runoff, volatilise and be inhaled, or accidentally be ingested. In the absence of standards for crumb rubber leachates, the health risk of leachate contaminants can be inferred by referring to drinking water guidelines (Gomes et al., 2021). Whilst the chemical compositions of leachate samples across different studies were highly variable, in general, both metal and PAH concentrations were found to be below regulatory water quality standards (Cheng et al., 2014).

Theme 5: Physical, mental and the social dimensions of health

Lack of evidence that the replacement of natural turf fields with synthetic turf has effects on health and wellbeing associated with the loss of natural green space

The WHO states that urban greens spaces, which are inclusive of parks, sport spaces, trees, natural grasslands, wetlands have powerful opportunities for public health, as they are critical to delivering a range of positive health, social and environmental outcomes (World Health Organization, 2017). Losing grass sports fields to synthetic turf fields may be akin to losing natural spaces and the associated health and social consequences of the loss of green space. However, there are no studies to date that explicitly investigates how the two field types compare in terms of their potential impact on the physical, mental and the social aspects of health.

In a wider urban context, green space has been associated with improving individual physiological and psychological health due to an increase in physical activity opportunities and the stress-relieving effects of nature (Javadi, 2021; Maas et al., 2008; Richardson et al., 2013). Evidence in general shows decreased risks of cardiovascular diseases, diabetes and mental health conditions such as stress, depression and anxiety (Callaghan et al., 2021; Den Braver et al., 2018; Ngom et al., 2016; Richardson et al., 2013). Urban green space has also been associated with social cohesion and wellbeing as they encourage positive social interactions that cultivate social cohesion in ways that enhance health and wellbeing (Jennings & Bamkole, 2019; Maas et al., 2009).

Relationships have been explored through measurements of people's proximity to quantifiable green space, using matrices such as vegetation indices (Ekkel & de Vries, 2017). However, qualitative characteristics of green space also have restorative benefits. These include ecosystem perspectives in terms of biodiversity, habitat cover and ecological functions, as well as usability perspectives such as the presence of well-maintained site amenities (e.g. lighting, seatings, signs, cut-grass, sports grounds or space for physical activity) and feelings of safety (e.g. free of anti-social behaviour such as litter and graffiti) (Wood et al., 2018). Green space also has different typologies, from natural spaces that protect local ecology and biodiversity and provide people with access to nature; recreational spaces that provide people with a setting for informal play, physical activity, relaxation and social interaction; to formalised sport spaces where people can gather for structured competition, training, as well as informal recreation (Wood et al., 2017). Access to open spaces dedicated to recreational and sporting activities have been shown to be just as important as natural spaces such as bushlands on improving psychological health (Wood et al., 2017). Finally, all age groups generally benefit positively from green space (Javadi, 2021), but the benefits may be especially strong amongst the elderly within communities where green space may strengthen social contacts (Kemperman & Timmermans, 2014).

DISCUSSION

Sports-related injury may occur on both synthetic and natural turf fields at comparable levels and good maintenance regime is required to ensure player safety

In general, it is difficult to conclude with confidence that synthetic turf is associated with more sports-related injuries than natural turf, or which particular physical characteristics of synthetic turf accounted for the differences in injury rates and patterns. Both synthetic and natural turf fields are subjected to degradation over time by compaction and many environmental factors. Poorly maintained natural turf surfaces may contain bare spots, ruts and divots that can increase injury risk (Williams et al., 2013). Continuous infill maintenance and brushing are necessary to ensure player safety for synthetic turf (Dickson et al., 2020). Natural turf fields also require good maintenance regimes, which can result in additional playtime capacity to better meet the demands of their use (City of Ryde, 2017).

The heat retaining property of synthetic turf surfaces is a characteristic that can impact health during hot conditions and their use should only be recommended during suitable weather for users on or around the field, particularly for children and exercising individuals who are susceptible to heat exhaustion

The extent to which synthetic turf may contribute to heat-related illnesses is not well studied. The thermal behaviour of synthetic turf varies with the specific physical properties of synthetic turf components, the natural environment (e.g. weather conditions and natural shading), and the built environment around the field (e.g. morphologies of buildings and shading). Establishing local evidence will be important to inform policies to guide the safe use of synthetic turf under different times and weather scenarios for users on or around the field. This is particularly important given that large parts of Australia will likely be subjected to higher temperatures and heatwaves in increasing frequency and severity under climate change (CSIRO, n.d.). The considerations are also particularly important for children and exercising individuals who are more susceptible to heat exhaustion.

The contribution of synthetic turf fields to the UHI effect at scale is likely small, but the cumulative depletion of natural grass over time undermines the role of green space on cooling down the city’s land surfaces.

When a natural turf field is replaced with synthetic turf, the land is essentially switched from doing cooling work to heating work. Even though the contribution of synthetic turf fields to the wider UHI effect is likely small given their proportionately small area in cities, the replacement of natural turf does represent a gradual degradation of natural green space that may otherwise provide transpiration cooling of land surfaces and the reduction of UHI intensities. Using temperature records and landscape data from Perth, a regression model estimated that for every 1 km^2 decrease in shrubs, trees and grass during summer, the monthly land surface temperatures in those surfaces would increase by 12, 5.6 and 0.5ºC respectively and hence reducing the intensities of surface UHI (Duncan et al., 2019). A modelling study from Melbourne also showed that grass, shrubs and small trees were able to reduce UHI intensities in summer (Rakoto et al., 2021). Natural turf fields are part of an urban network of green infrastructure which has a role to play in relieving UHI effects and bolstering the adaptive capacities of cities to climate change (Rahman et al., 2022).

Even though the health risks of chemicals in synthetic turf are likely to be very low, progressive restrictive measures to limit potentially harmful chemicals in synthetic turf components may reduce unforeseen consequences to health

Extensive health risk assessments and field studies from North America and Europe show that the health risks of chemical exposure to synthetic turf components for users, including athletes and vulnerable population such as children, are very low. However, information gaps remain regarding the aggregated and long-term cumulative health risks. There are also some uncertainties around the generalisability of overseas studies to the Australian context, given that assumptions made about exposure routes and other human factors may be different. Studies done abroad are also based on synthetic turf fields that may differ in age, design and sources of recycled tyre materials. The latter is particularly important, as the composition of crumb rubber varies across individual studies and higher levels of hazardous metals and organic compounds can occasionally be detected. Geographically, Australia experiences higher UV exposures compared to Europe and North America (Loughran, 2021, December 21), with implications for the degradation rate of synthetic turfs and contaminants released into the air, water and soil. This review did not find existing health risk assessments or field studies undertaken in Australia. Establishing local evidence will be important in terms of informing policies or legislations around any measures required to restrict the exposure risk of synthetic turf chemicals.

In Europe, the legislation Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) was enforced to set a high level of protection of human health and the environment by making provisions on certain hazardous substances, mixtures and articles placed on the market ("Regulation 1907/2006," *REACH*, Regulation 1907/2006). Effective from late 2022, the 8-carcinogenic PAH content in synthetic turf infill materials will be limited to 20 mg/kg ("Regulation 2021/1199," *Amending annex XVII Regulation 1907/2006 PAHs in granules or mulches used as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications*, Regulation 2021/1199). This legislation signals a move to restrict the levels of potentially harmful chemicals in synthetic turf infill to reduce any unforeseen negative consequences to health and the environment.

Although leachate and microplastic runoff from synthetic turf fields are likely to be very low, measures to reduce chemical and microplastic pollution serve to reduce potential cumulative harm to aquatic and soil life, the environment and ultimately human health

Available evidence show that synthetic turf leachates generally do not reach concentrations that exceed drinking quality guideline values, whilst microplastic runoff or 'walk-off' do occur with unknown implications for human health. From a population health perspective, concentrations of synthetic turf leachates in ground water or river catchments are likely greatly diluted by the time they reach water bodies and would not have appreciable health consequences, whilst the attribution of microplastic pollution from synthetic turf in water bodies would likely be limited compared to the day-to-day microplastic runoff from the wider urban pollution sources.

Nonetheless, little is known about leachate and microplastic runoff dynamics of synthetic turf fields in Australia and the different climatic conditions will likely have different influences compared to Europe and North America. For example, periodic intense rain and flood conditions in Australia can overwhelm drainage systems and wash away leachates and microplastics in larger quantities. These conditions are expected to become more frequent and extreme under a changing climate. In Australia, drinking water catchments are largely protected from the risk of urban contamination. However, incomplete knowledge remains for the longer-term impacts of runoff into recreational waterways and harbours, bioaccumulation in aquatic or soil life, and ultimately environment and human health consequences. Field monitoring and research will be required to characterise the rate of release of leachates and microplastics and their transport pathways to the environment. Establishing local evidence will be important for informing policies or legislations around any measures required to monitor and restrict runoffs from synthetic turf fields.

In Europe, emerging societal trends to minimise microplastic use and release into the environment is driving a major policy decision for the ECHA to recommend a total ban on crumb rubber use on synthetic turf fields, or restrict their use if microplastics leaching can be kept below 7g/m^2 of the synthetic turf field (ECHA, 2020). The policy will prevent the release of 500 000 tonnes of microplastics over a period of 20 years (ECHA, 2020). This legislation signals a precautionary approach to minimise the risk of unforeseen and potentially harmful consequences of microplastics to human health and the environment.

The social and environmental context of each playing field is different and the implications on the physical, mental and social dimensions of health cannot be drawn without research or surveying the community

The current literature shows that natural green space is generally associated with physical and mental health benefits. However, whether the replacement of a natural turf sports field with synthetic turf may diminish the values of the original natural field cannot be made without considering whether that constitutes an erosion of restorative values such as biodiversity, ecological functions and amenities to the community. Therefore, whilst replacement of a natural turf field with synthetic turf represents a loss to natural green space, if the outcome is an improved and functional playing field with well-maintained amenities such as lighting, footpaths, playing areas that also provides thermal comfort via natural vegetation and shading, then a decrease in health benefits may not arise.

From a public health perspective, equity considerations are also important and any barriers to community's access to amenities should be considered. Some questions to consider include whether the replacement of natural turf fields with synthetic turf will tip the balance of public recreational use to private use (e.g. via rental by sports clubs); whether the conversion creates more or less health disparities by encouraging or discouraging use by different age groups such as elderly people, people with existing health conditions or disabilities and different ethnic minority groups; or whether the change erodes the community's contact with nature particularly if the surrounding urban area is already deprived of other publicly accessible green spaces. All together, these questions cannot be answered without understanding the local ecological, environmental and social contexts of the community within the proximity of the playing field.

Conclusion

This Report outlines the current state of knowledge on the potential health impacts of synthetic turf for human health. There is a general lack of epidemiological studies or health risk assessments conducted in Australia across the health themes explored in the Report. This knowledge gap will need to be addressed in order to provide a more accurate understanding on how outdoor synthetic turf fields may behave under local climatic conditions and the potential health risks involved. Nonetheless, the following can be summarised with regards to our current understanding of the human health implications of third-generation synthetic turf:

1. **Sports-related injury may occur on both synthetic and natural turf fields at comparable levels and a good maintenance regime is required to ensure player safety.**
2. **The heat retaining property of synthetic turf surfaces is a characteristic that can impact health during hot conditions and their use should only be recommended during suitable weather for users on or around the field, in particularly for children and exercising individuals who are susceptible to heat exhaustion.**
3. **The contribution of synthetic turf fields to the UHI effect at scale is likely small, but the cumulative depletion of grass surfaces over time may exacerbate UHI effects and increase heat exposure risk in the population.**
4. **Even though the health risks of chemicals in synthetic turf are likely to be very low, progressive restrictive measures to limit potentially harmful chemicals in synthetic turf components may reduce unforeseen consequences to health.**
5. **Although leachate and microplastic runoff from synthetic turf fields are likely to be very low, measures to reduce chemical and microplastic pollution serve to reduce potential cumulative harm to aquatic and soil life, the environment and ultimately human health.**
6. **The social and environmental context of each playing field is different and the implications on the physical, mental and social dimensions of health cannot be drawn without research or surveying the community.**

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Appendix 4

Independent review into the design and use of synthetic turf in public space – WRL Technical Review

Independent review into the design and use of synthetic turf in public spaces

WRL TR 2022/12, August 2022

By W Glamore, M Mason and F Flocard

UNSW Water Research Laboratory

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Executive summary

ES 1 Introduction

Synthetic turf (ST) fields have three main potential water related impacts: stormwater impacts in terms of the volume and timing of water entering the stormwater network (hydrologic impacts), impacts created by toxic chemicals leaching from the field into aquatic environments, and transport of microplastics (infill and turf fibres) into the aquatic environment. The chemical leaching risk is most thoroughly documented in the literature and appears to generally be low. However, due to variability, site specific testing is recommended for ST fields near sensitive areas. The microplastic transport risk is highly variable, although generally large for fields without mitigation measures. Australian specific studies and quantification of the effectiveness of mitigation measures are recommended, and it is also recommended that new fields be constructed with a raised curb and a surrounding drainage system with filters. The hydrology of ST drainage systems is also poorly documented, though it appears that ST systems have the potential to have either positive or negative impacts on the stormwater system. Further research, as well as the exploration of ST systems as tools for stormwater detention and recycling, are recommended.

ES 2 Field hydrology

The literature on ST field drainage and stormwater impacts is very sparse, and more insight into this topic is needed. However, based on limited literature and hydraulic supposition, some conclusions can be drawn regarding the comparative hydrology of different ST drainage systems. ST fields have high infiltration capacities. A modern, well designed and certified ST field is likely to experience surface runoff caused by exceeding the infiltration capacity at most a couple times in its lifetime. Under the ST surface, infiltrated water is usually managed by one of three main drainage designs: horizontal drainage, vertical drainage through a gravel aggregate base with pipes, or vertical drainage through a gravel aggregate base without pipes. Horizontally draining systems require the least vertical space, but are likely to create the flashiest stormwater hydrograph, with peaks only slightly below that of a fully impervious surface. Vertically draining bases delay and store rainfall for longer, placing less stress on the stormwater network. They can be intentionally designed to store large amounts of water (for stormwater management or water recycling purposes), although this use is not widespread in Australia. Vertical drainage systems with pipes are expected to pass through greater rates of rainfall, however, have less of a detention effect (less reduction in hydrograph peak) compared to bases without pipes. Compared to natural turf, vertical draining systems can range from a flashier to a more delayed stormwater response, depending on the drainage design and storage capacity. Although these general trends between designs are likely to hold true when comparing most ST drainage systems, many systems have their own idiosyncrasies (e.g., outlet flow limiting the system and creating upstream afflux), especially in cases of poor design, thus these trends are not universal.

Recommendations and research needs

Discharge data collection from ST fields can be achieved easily by logging water levels at the drainage outlet. A study measuring the discharge of several ST fields with the three different drainage designs is recommended. Rainfall measurements would also be needed to compare study sites. This data, as well as hydraulic modelling data and other data from industry would greatly expand our understanding about the effects of ST fields within the stormwater management system. This can include the potential use of ST fields with vertically draining profiles as stormwater management and recycling tools, a possibility which is largely under-explored.

ES 3 Leaching

Chemical leaching from the recycled tyre crumb rubber commonly used as infill material has been raised as a concern to aquatic ecosystems. The literature on toxicant leachate is relatively extensive, especially for recycled tyre rubber infill. Zinc appears to be the toxicant most likely to pose a risk to aquatic ecosystems, and it is regularly found in runoff from ST fields in quantities considerably exceeding the guideline values for freshwater ecosystems. Polycyclic aromatic hydrocarbons and other toxicants may also be of concern at some fields. Virgin rubber infill options appear to release less zinc and total toxicants overall, however, the leaching from other types of infill and from the different components of the ST system (e.g., turf fibres or shock pads) is less researched. Hence, these components may have a different (and potentially unknown) profile of toxicants of concern.

Recommendations and research needs

Although there is large variability and the toxicant profile of ST is not completely understood, due to dilution, leaching of toxicants from infill is unlikely to pose a large risk to aquatic ecosystems. The exception to this case may be if a field with a relatively high toxicant load is located close to a sensitive ecosystem, to be determined through an effects based assessment. If a ST field is draining into such an ecosystem, sampling and testing of ST runoff from the location where runoff enters the ecosystem would be advisable, to ensure zinc and other toxicant levels are within acceptable levels. If remediation is necessary, water sensitive urban design features, such as rain gardens, should be effective at reducing the toxicant load in discharge from ST fields.

ES 4 Microplastic transport

Both rubber infill and turf fibre blades pose a risk of being transported to waterways, where they pollute the environment and threaten aquatic life. Most rubber infill is denser than water, yet will be highly mobile even in slow moving runoff. Hydrodynamic behaviour of the rubber infill is dependent on the manufacturing process, as we found that some rubber infill was buoyant for a period of time (multiple days) until it became waterlogged. Such floating behaviour would increase the potential for infill mobilisation in water runoff. Tens to hundreds of kilograms of infill material are estimated to be washed into waterways and stormwater systems from a single field each year. Though various studies have measured or estimated infill flow to the environment, variation between fields makes generalisation difficult. Infill loss can be partially mitigated by changing the design and maintenance practices of ST fields, however quantification of the effectiveness of these strategies is limited. Moreover, fibre loss from ST fields can also be substantial, especially near the end-of-product-life or under poor maintenance. Turf fibre blades are less dense than water, hence more mobile in the environment, yet this source of microplastic pollution has been subject to less research, or threat assessments, than infill loss.

Recommendations and research needs

Numerous studies have the potential to further our understanding of the extent of microplastic transport from ST fields. Laboratory studies should be undertaken to test the transportability of different infill types and turf fibres on surfaces found around the ST field, including concrete, grass and in pipes. Furthermore, field surveys assessing the loss of microplastics from ST fields of different ages and with different mitigation strategies would be beneficial as it would assess the variability of loss between fields and would allow for quantification of effectiveness of mitigation strategies. Specifically, such a study should measure ST microplastics found in waterways, the surrounding environment (i.e., grass and soil) and in the stormwater system, and should seek to test fields with and without curbs and surrounding drainage. The study may also consider the effects of maintenance regimes on infill loss. Finally, the effectiveness of filters within drains surrounding ST fields (especially if specific proprietary devices are available) should be assessed by searching for microplastics downstream of the filter. Regardless of the lack of data on the effectiveness of mitigation measures, it is recommended that all new fields and fields undergoing renovations be constructed with:

1. a surrounding solid curb (to prevent microplastic loss, as well as overland runoff entering or exiting the field),
2. a drainage system which collects all water from the field surrounds to local drains, and
3. 200 μm filters within these drains, to collect microplastics which leave the field and are mobilised by runoff.

The drainage system surrounding the field is a key management tool as it allows for the ST effected stormwater to be collected and treated before entering the wider stormwater system. Other mitigation measures such as brushes and Water Sensitive Urban Design (WSUD) should also be considered.

Mobilised infill material or turf blades pose a unique challenge for stormwater treatment devices (GPTs and secondary treatment devices) due to their relatively low density, small size and easy mobilisation in comparison to more common pollutants or sediments typically found in urban runoff. Most stormwater treatment devices do not specifically target these pollutants, and may either not remove them or easily block and fail to function.

As such, it is recommended that proprietary stormwater treatment devices installed around ST fields have their performance independently verified, both in controlled conditions and validated in the field. The only standard that applies to the validation of stormwater treatment devices in Australia (Stormwater Australia's SQIDEP protocol) is not suitable for the assessment of these pollutants, so a suitably experienced and equipped, and independent organisation should assess the performance of proprietary devices.

ES 5 Conclusions

Overall, ST fields pose or have the potential to pose negative impacts to the environment and waterways. However, most of these impacts can be mitigated by changes to the design of ST fields, and the recommended future research (monitoring of the discharge hydrology of ST drainage systems, laboratory measurements of infill and fibre transport and field surveys of microplastic loss) will further elucidate what design changes are necessary to ensure minimal environmental impact. Furthermore, the establishment of a central repository of data would assist in the assessment of current knowledge. Data from industry as well as ST and natural turf field managers (mainly councils) is not currently widely available. However, it is known that many field managers, designers and installers collect data which would be highly relevant in assessing field drainage hydrology, infill top up requirements, current maintenance practices, the construction of current NSW fields (locations, materials, designs, etc.) and other topics. Moreover, council data from natural fields on irrigation and fertilizer use (and other input requirements) would allow for a more robust assessment of the impacts of the counterfactual to a ST field (i.e., a natural turf field). Therefore, as system to coordinate data sharing and to allow sharing of data from industry without proprietary risk would be highly beneficial. Finally, to reiterate, it is recommended that all ST fields be constructed with a raised curb, a surrounding local drainage system containing filters in drains and that chemical quality of runoff is tested if a sensitive ecosystem is nearby.

Third generation Synthetic Turf (ST) fields consist of a drainage system overlayed by a mat of plastic fibres, commonly infilled by crumb rubber. These fields are replacing natural turf fields in locations across NSW due to their decreased water use, ability to support more hours of play and playability in wet weather conditions. However, questions have been raised about the environmental impact of ST fields, especially of crumb rubber infill. This report assesses the available literature to evaluate the water related impacts of ST, as well as gaps in knowledge.

The literature on ST field drainage and stormwater impacts is very sparse, and more insight into this topic is needed. ST fields have high infiltration capacities. A modern, well designed and certified ST field is likely to experience surface runoff caused by exceeding the infiltration capacity at most a couple times in its lifetime. Under the ST surface, infiltrated water is usually managed by one of three main drainage designs: horizontal drainage, vertical drainage through a gravel aggregate base with pipes, or vertical drainage through a gravel aggregate base without pipes. Horizontally draining systems require the least vertical space, but create the flashiest stormwater hydrograph, with peaks only slightly below that of a fully impervious surface. Vertically draining bases delay and store rainfall for longer, placing less stress on the stormwater network. They can be intentionally designed to store large amounts of water (for stormwater management or water recycling purposes), although this use is not widespread in Australia. Vertical drainage systems with pipes can pass greater rates of rainfall, however they have less of a detention effect (reducing the hydrograph peak) compared to bases without pipes. Compared to natural turf, vertical draining systems can range from a flashier to a delayed stormwater response, depending on the drainage design and storage capacity.

Chemical leaching from the recycled tyre crumb rubber commonly used as infill material has been raised as a concern to aquatic ecosystems. The literature on toxicant leachate is relatively extensive, especially for recycled tyre rubber infill. Zinc appears to be the toxicant most likely to pose a risk to aquatic ecosystems, and it is regularly found in runoff from ST fields in quantities considerably exceeding the guideline values for freshwater ecosystems. Polycyclic aromatic hydrocarbons and other toxicants may also be of concern at some fields. Virgin rubber infill options appear to release less zinc and total toxicants overall, however, the leaching from other types of infill and from the different components of the ST system (e.g., turf fibres or shock pads) is less researched. Hence, these components may have a different (and potentially unknown) profile of toxicants of concern. Regardless, due to dilution, leaching of toxicants from infill is unlikely to pose a large risk to aquatic ecosystems unless a sensitive ecosystem is located in proximity to an outlet draining from a ST field. If remediation is necessary, water sensitive urban design features, such as rain gardens, may reduce the toxicant load in discharge from ST fields.

Both rubber infill and turf fibre blades pose a risk of being transported to waterways, where they pollute the environment and threaten aquatic life. Most rubber infill is denser than water, yet will be highly mobile even in slow moving runoff. Hydrodynamic behaviour of the rubber infill is dependent of the manufacturing process, as we found that some rubber infill was buoyant for a period of time (multiple days) until it became waterlogged; such floating behaviour would increase the potential for infill mobilisation in water runoff. Tens to hundreds of kilograms of infill material are estimated to be washed into waterways and stormwater systems from a single field each year. Though various studies have measured or estimated infill flow to the environment, variation between fields makes generalisation difficult. Infill loss can be partially mitigated by changing the design and maintenance practices of ST fields, however quantification of the effectiveness of these strategies is limited. Moreover, fibre loss from ST fields can also be substantial, especially near the end-of-product-life or under poor maintenance.

Turf fibre blades are less dense than water, hence more mobile in the environment, yet this source of microplastic pollution has been subject to less research, or threat assessments, than infill loss.

Overall, ST fields pose or have the potential to pose negative impacts to the environment and waterways. However, most of these impacts can be mitigated by changes to the design of ST fields. As ST fields in NSW are replaced, instillation of mitigation measures should be considered, both to prevent the spread of microplastics (curbs, brushes and improvement of surrounding drainage systems) and to mitigate increased stormwater flashiness and chemical toxicants (water sensitive urban design). ST fields also have the potential to be used as stormwater management and recycling tools, a possibility which is largely under-explored.

There is limited available data on the hydrology and microplastic loss from ST fields. It is highly recommended that a statistically robust data collection program designed for both the leachate quality and the dispersion of microparticles be undertaken for Australian ST fields. Measurements of the discharge from the drainage systems of ST fields, laboratory experiments of infill and turf fibre transport, and surveys of microplastic loss to the environment are key to further our understanding of the impacts of ST systems.

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1. Introduction

Synthetic turf (ST) sports fields, which require less water, are playable in wet weather, and can support more hours of play than natural turf fields, are becoming increasingly popular worldwide [1-3]. ST fields were first developed in the 1960s, and can take many forms, including sand infilled fields (used in tennis and cricket) and infill free fields (used in hockey) [4]. The focus of this report is third generation (3G) ST fields, which contain plastic fibres supported by performance infill, usually crumbed rubber. These fields are commonly used in public areas for the play of soccer, cricket, rugby or AFL. In recent times, these surfaces have come under scrutiny for their potential impacts on player health and the environment, with the impacts of rubber infill being a primary focus.

Although ST fields have been common in some countries for decades, including the USA and northern European countries, installation of ST fields began in Australia in the 2000s, with uptake in Victoria initially fostered by the Millennium drought. Installation of ST fields in the Sydney Metropolitan Area began approximately a decade ago, meaning that ST fields in NSW are now nearing their end-of-life. This has raised questions about how these fields may be upgraded or decommissioned, and whether they should be replaced with natural turf [5, 6].

In the following sections, the available literature, supplemented with background information from conversations with industry and local government, is reviewed to evaluate the water related impacts of 3G ST fields. The impacts discussed are focused on the hydrologic concerns (including stormwater management impacts, water use and flood risk), the risk of leaching toxic chemicals into waterways, and the risk of microplastic being transported to waterways. Where relevant, comparisons to natural turf fields are made, however, this report is by no means an extensive analysis of the impacts of natural turf fields. Additional research would be required to undertake an accurate risk/benefit analysis of replacing a natural turf field with ST, especially when considering chemical pollution of runoff.

1.1 ST Field Structure

A 3G ST field is a layered system. Moving from the bottom up, an Australian ST field typically has a waterproof liner, then a base of gravel sized stone, with finer aggregate stone or sand on top, to provide a smooth surface for the upper layers. Additionally, a shock pad (also called an elastic layer) may be placed to enhance the elasticity of the system. Not all fields have shock pads, with Eunomia estimating that globally, only one-third of fields had shock pads in 2017 [7]. However, shock pads are becoming more popular as they improve the performance of the field (especially for high impact sports) and minimise the amount of infill required [4]. Above the shock pad lays the ST mat, which consists of polypropylene, polyethylene or nylon turf fibres, held in place by a polyurethane backing. These fibres may be monofilament (solid) or fibrillated (longitudinally perforated) and are typically 40 to 70 mm long (above the backing) for a 3G field. Older fields tend to have shorter fibres, while more recent fields have fibres around 60 mm [4]. Infill is placed between the fibres of a 3G ST field to hold up the turf blades. Sand infill sits at the bottom, for stability. Above this, performance infill is placed to provide the desired field characteristics, such as rebounding capability. The performance infill is usually rubber crumb (of various types) but can also be an organic option such as cork. A typical cross-section of 3G ST field is shown in Figure 1.

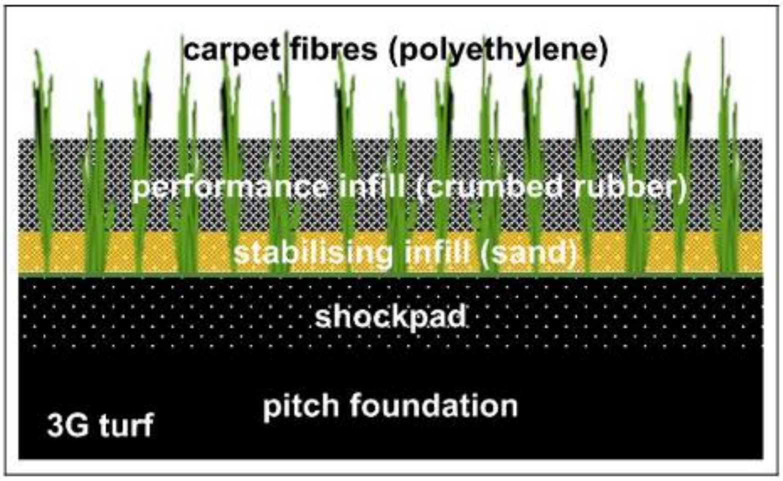

Figure 1: Cross section of 3G ST field from Fleming, Watts and Forrester (2020)

The field is maintained by regular (usually fortnightly) brushing, which decompacts the infill and raises the fibres to upright positions, and less frequent deep cleaning and infill top ups [6, 8].

2. Hydrology

2.1 ST infiltration

All modern 3G ST fields are designed to infiltrate the design rainfall (the maximum rainfall event a system is designed for), then deal with the stormwater in a subsurface drainage system. ST mats and shock pads contain regularly spaced holes, through which the rainfall infiltrates. For most fields in Australia, the design rainfall intensity and hence, the spacing of the holes will be determined by the field certification requirements. A FIFA Quality or Quality Pro certification requires an infiltration rate of 180 mm/h, an AFL certification requires 200 mm/h and a World Rugby Certification requires 500 mm/h [4, 9, 10].

A rainfall intensity of 500 mm/h is very large, only forecasted to be exceeded in Sydney by the one minute, 0.1% annual exceedance probability (AEP) storm (i.e. the one in one thousand year storm) [11]. A rainfall intensity of 200 mm/h is much more common, forecasted to be exceeded by the one minute 33% AEP storm or the five minute 5% AEP storm [11]. 180 mm/h is forecasted to be exceeded by the five minute 8% AEP storm [11]. Thus, a World Rugby certified field in Sydney is likely to never experience a rainfall event which surpasses its infiltration capacity in its lifetime. However, if the infiltration capacity of a Sydney ST field is near the AFL or FIFA certification threshold, it will likely experience a few events (lasting a few minutes) which can surpass its infiltration capacity during its lifetime, although the frequency of intense rainfall events may increase under climate change.

It is also important to consider how infiltration tests for field certification are typically conducted, as the meaning of the infiltration capacities calculated by FIFA are somewhat unintuitive. FIFA infiltration tests are carried out using a small infiltrometer rig in which 70 to 90 mm of water is poured [12]. Water is allowed to flow through the ST field, infiltrating through the ST mat and shock pad, to ensure the system is wet when measurements commence. When the water level reaches 30 mm, the time taken for the water to fall to 10 mm is measured. The infiltration rate is then calculated by dividing the depth of water which has fallen (20 mm) by the time taken. As the infiltration rate is calculated with a 30 to 10 mm head (height of water above the field), the infiltration rate which the turf can maintain without this much ponding or head would be lower. Therefore, if a field is determined to have a FIFA infiltration rate of 180 mm/h, at a constant rainfall rate of 180 mm/h, between 10 and 30 mm of standing water can be expected to be present on the field. Should the field have a slope, overland flow would likely occur. Thus, despite the high infiltration rate advertised, NSW ST fields close to the FIFA or AFL certification thresholds are likely to experience ponding and possibly surface flow on multiple occasions in their lifetime.

Despite this, in many cases, the infiltration capacity of the ST mat and shock pad is very high (up to 2000 mm/h), well above the certification requirements. Hence, ponding caused by insufficient infiltration capacity would be rare. In these cases, the drainage system under the field is likely to instead be the limiting factor in drainage capability [13, 14]. While the infiltration capacity is likely to cause issues in a small, very intense event, the subsurface drainage network would instead most likely be problematic in moderate but long lasting events. This is due to the drainage capacity being exceeded sufficiently long that the gravel base fills up, reaching the surface.

2.2 ST drainage

There are three common types of drainage layouts in ST fields, all of which can be found in Australia [4]:

1. Horizontal drainage
2. Vertical drainage to a pipe network ("ag-drain system")
3. Vertical drainage to a free-flowing aggregate base, without an underlying network of pipes

In all of these designs, the entire design rainfall is intended to infiltrate through the ST mat and be dealt within the surface below. This is as opposed to short-pile ST used for cricket and tennis courts, which typically are designed to drain through overland runoff to peripheral drains. Schematics of these designs are shown in Figure 2.

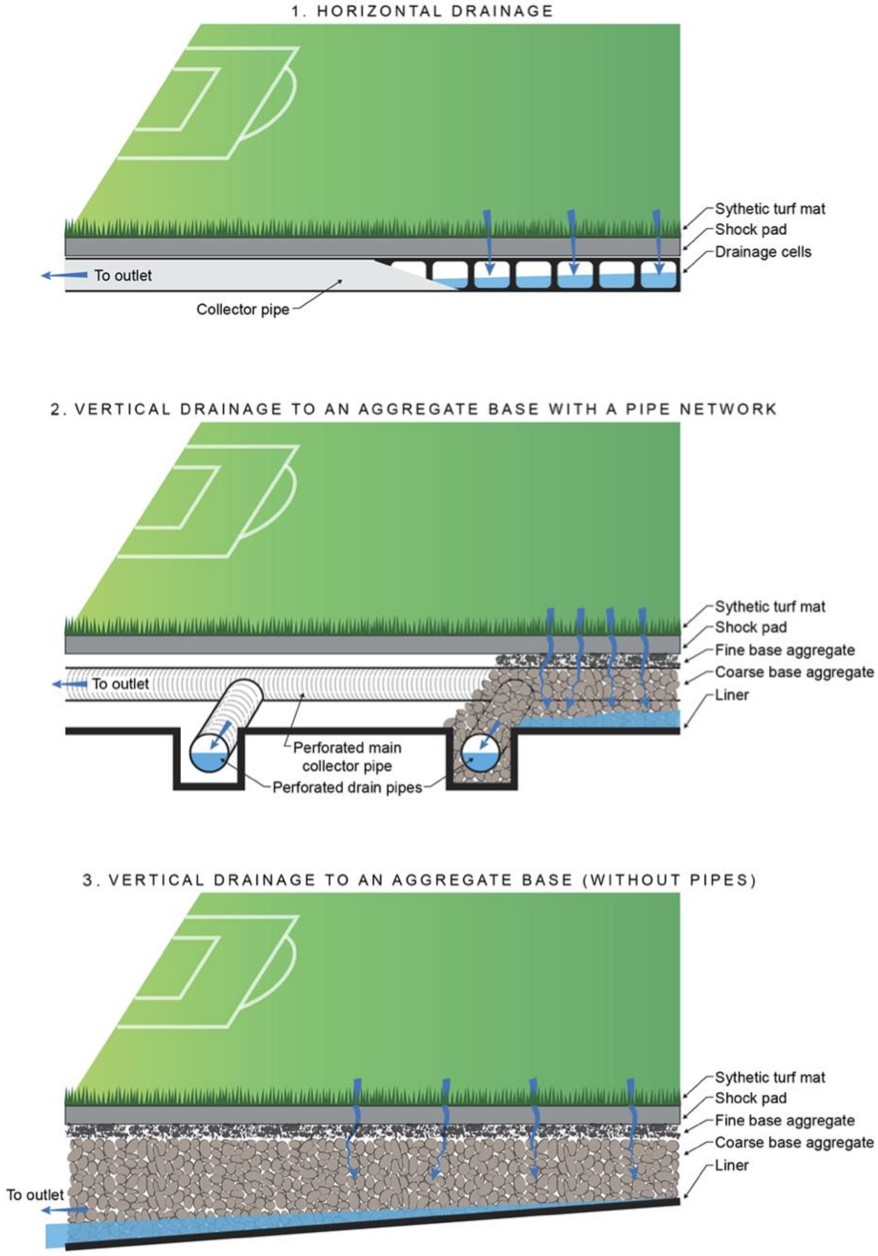

Figure 2: Schematics of the three main types of ST drainage systems: horizontal drainage (1) aggregate base with network of pipes (2) and aggregate base without pipes (3)

In the first drainage option, horizontal drainage, water infiltrates through the ST mat and then is directed horizontally to a main collector pipe located on the field margin. The water may be conveyed through drainage cells (flexible pipes) located under the ST mat and shock pad, as shown in Figure 2 (a) and Figure 3, or horizontal conveyance may occur within the ST profile itself. The horizontal drainage approach leads to a much thinner ST profile than the other drainage options, thus it is often used when there is limited depth available, for example in a situation of landfill capping [4]. This drainage construction also provides a stronger foundation and thus is used when the subgrade condition is poor.

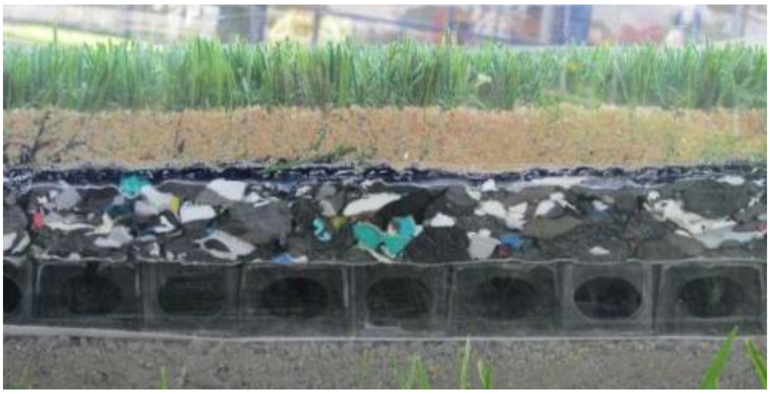

Figure 3: Cross section of a ST profile with horizontal drainage cells from Sheppard (2021)

In both the second and the third drainage layouts, a fine stone aggregate layer (sand or fine gravel) is placed underneath the shock pad, below which lies a coarser aggregate layer (gravel). In the second system, perforated pipes are laid at regular intervals in trenches within the coarse aggregate layer. Thus, water drains vertically through the turf mat, shock pad and fine aggregate layer, then drains horizontally to the nearest perforated drain, and discharges out of the system via the pipe network. Schematics of a typical "ag-drain system" design are shown in Figure 2 (b) and Figure 4.

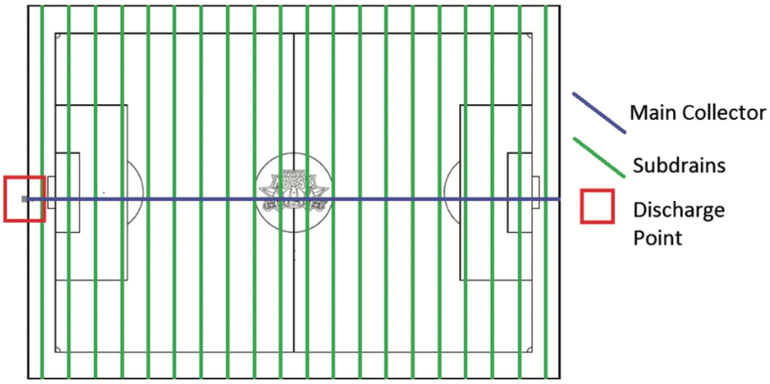

Figure 4: Plan view of a typical ST drainage system with a network of collection pipes ("ag-drain" system) from Hudepohl (2014)

The third drainage option is relatively similar to the "ag-drain system", except it lacks the network of perforated pipes within the gravel substrate. Instead, the base of the gravel aggregate layer is sloped, such that the stormwater drains through the aggregate and out to a single collector pipe at a field edge or corner. A schematic of this design is shown in Figure 2 (c). This approach has become the preferred design over time due to collapses experienced with the design containing underlying pipes [4].

Based on information provided by the Australian ST industry, most Australian installed ST systems (with any of the three drainage options) are lined. This means that groundwater rising to the surface and filling the ST base is unlikely to be a concern, and that the risk for groundwater contamination from the ST field (or vice versa) is limited. This also suggests that all stormwater infiltrating through the field can be collected at a single location, which may be desirable for treatment or recycling. However, impervious liners have the disadvantage of not enabling infiltration to the local groundwater, which may be desirable to recharge local aquifers, or reduce load on the stormwater system. If the ST system is lined, then all rainfall will either evaporate or flow into the stormwater system. The type of drainage system will have a direct influence on the quantity and timing of the water flowing into the stormwater system, and can either pass water through quickly, or delay and release water slowly, reducing the burden on the stormwater system.

2.2.1 Stormwater implications of horizontally draining ST

The horizontal drainage layout is designed such that water can flow through the mat and shock pad, through the horizontal drainage cells, and out the main drain at a rate equal to the design rainfall. Thus, except for a small quantity of rainfall (approximately 5 to 10 mm) which is likely to be absorbed and later evaporate from the ST mat and shock pad, the system will route all rainfall quickly, acting hydrologically similar to an impervious surface such as concrete [13]. Above the design rainfall, the system will become backed up and surface runoff may occur. In this case, the system would then behave like an impervious surface with surface runoff. The horizontal drainage system is the least desirable system in terms of stormwater management, as it puts the greatest load on the stormwater system (the most discharge in the shortest period of time). In locations where a ST field drained by horizontal flow is installed, the site may require retention basins or other features to mitigate the changes to stormwater generation.

2.2.2 Stormwater implications of vertically draining ST

Drainage options two and three, the two types of drainage systems with an aggregate base (either with or without a network of pipes) have the potential to store infiltrated water within the gravel base. The rate at which the stormwater flows out of the ST base will depend on the transmissivity of the gravel, and the rate of flow into the perforated pipes. Because of the high infiltration rates of many ST mats, the outflow rate of the drainage base is often the limiting factor in the routing through a ST system [13, 14]. As water is constantly draining out of the ST base, the quantity of water stored under the field depends on the difference between inflowing water (infiltration) and outflowing water (draining out of the base). For a 500 mm deep drainage profile with 40% porosity (porosity value from Sheppard (2021)), around 200 mm of storage is available, or 1.6 ML over an 8,000 m^2 field. If the entire base was to fill up, rainfall would cease infiltrating, and surface runoff would occur.

Presumably, the ST industry has undertaken extensive comparative modelling of the hydrology of various ST drainage systems. However, as this knowledge is considered proprietary, only very limited published literature is available to assess the hydrology of ST systems. Thus, our knowledge would benefit greatly from more measurements, sharing of existing data, and/or modelling. A few studies have attempted to model the hydrology of drainage underneath such ST fields. Magnusson (2018) estimated that the ST mat would absorb 5 mm of rain, while the shock pad and sand layers would absorb a further 7.5 mm. It was assumed that these quantities would later evaporate, hence a rainfall event would need to surpass 12.5 mm to generate flow which drained through the base. By this accounting, the amount absorbed and evaporated thus depends on the amount of rain that falls in a single event. Because of the large number of small events during the measurement period, Magnusson estimated that 72 to 79% of rain falling on the field later evaporated, while the remaining 21 to 28% flowed out through the base [15]. However, in Australia, where rainfall tends to occur in fewer, more intense events, the proportion of water which evaporates would likely be smaller.

Moretto (2007) used lysimeters below a ST field with a free-flowing aggregate base (no under field pipe network) and smaller “pilot” setups to calculate a water balance for the field. It was estimated that out of 750 mm of rain in a year, 30% evaporated, 7% drained out of the base and 63% infiltrated into the native soil beneath the base of the field [16]. Since Australian ST fields mainly have a liner, no water would infiltrate to the subsoil. However, the fact that such a large amount of water was detained sufficiently long in the base to infiltrate through, indicates that there is a considerable storage effect in the base of this free-flowing aggregate field, which will result in an elongated hydrograph with a much lower peak.

Hudepohl (2014) conducted extensive modelling of a ST field with a network of perforated pipes running through the base aggregate. The model was developed and calibrated on a real ST field in the USA. It was measured that the infiltration capacity of the ST mat and upper, fine gravel aggregate was 156 mm/h. For small events, all infiltrated rainfall remained in the pore space of the field. For larger events, the infiltrated water made it to the drainage trenches containing perforated pipes and began to discharge. When the outflow capacity of the drainage network was exceeded, the base aggregate began to store more water, and when the inflow capacity of the turf was exceeded (at 156 mm/h), surface runoff commenced. The monitored field was equipped with a network of 100 mm diameter buried pipes, spaced 6 m apart. Having smaller diameter pipes or greater spacing altered the system by reducing the outflow capacity, hence increasing the amount of water stored in the base for smaller events, or the amount of water outflowing in surface runoff for larger events [13, 14]. Hudepohl’s observations showed that the peak of discharge from the ST field lagged around 15 minutes behind the peak of a larger rainfall event, or around 45 minutes behind a smaller rainfall event, as can be seen in Figure 5.

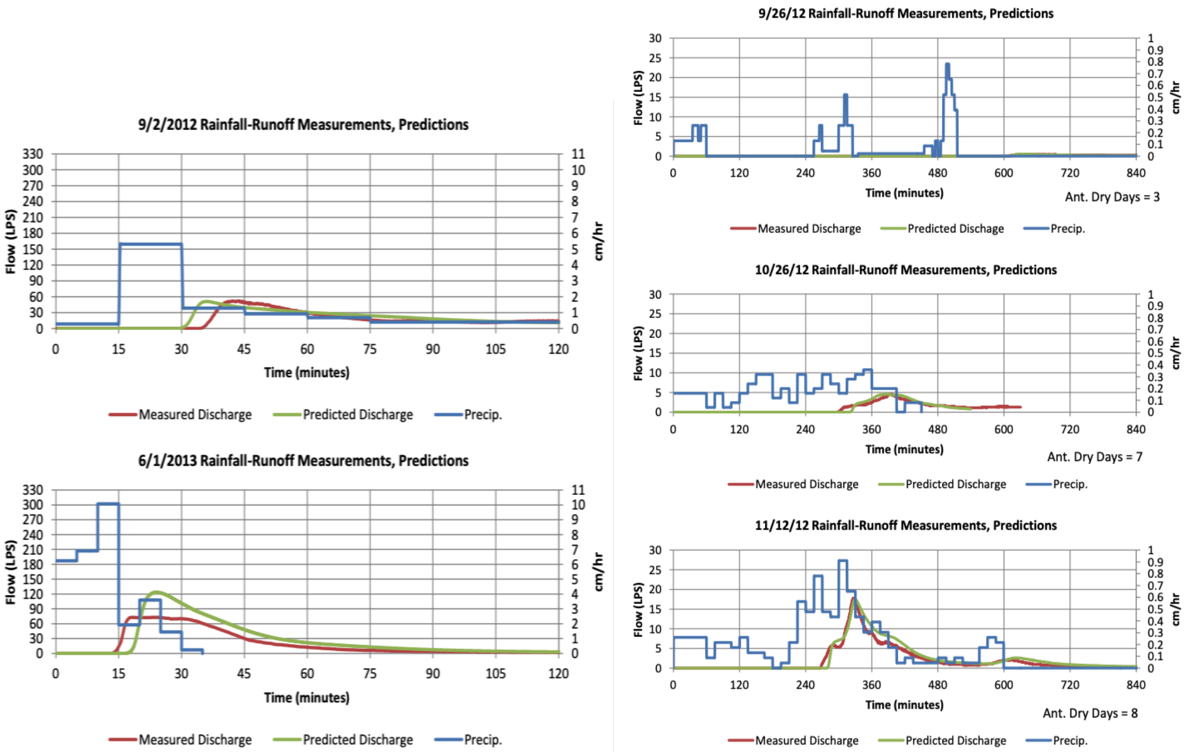

Figure 5: Observed and modelled discharge from a ST field with a network of drainage pipes flowing through a gravel aggregate base from Hudepohl (2014)

2.2.3 Comparative hydrology of ST drainage layouts

Based on the results of these three studies, the hydrological behaviour of ST fields can be summarised as follows. After small rainfall events (up to around 5 to 10 mm), the entire rainfall is likely to stay within the ST profile and evaporate through the surface. During a larger rainfall event, a ST field with horizontal drainage (drainage option one) will immediately route the infiltrating water to the stormwater system, behaving as an impervious surface. For fields with an aggregate base, the infiltrating water will be slowed as it percolates through the gravel base, delaying the peak of the hydrograph (outflow discharge). A field with an underlying network of pipes (drainage option two) will have a greater outflow rate than a field under which water flows through the aggregate to a single peripheral outlet (option three). Thus, a field without a pipe network will store more water within the aggregate base, further elongating the hydrograph, however it will be more susceptible to having its capacity surpassed during an extended high rainfall event. If the capacity is surpassed for long enough, the aggregate base will fill up and infiltration will cease. Hence, a field without an underlying network of pipes would generally require a thicker gravel base layer, to both increase the transmissivity (to outflow more water) and the storage capacity of the profile.

Therefore, fields with drainage option three (a free-flowing base with no pipes) can be most advantageous from a stormwater management perspective (aiming to reduce the peak of the outflow hydrograph), followed by option two (a pipe network), then option one (horizontal drainage). On the other hand, for a profile with equal thickness, option two (with pipes) will be able to route larger volumes of rainfall than option three (without pipes), and hence will be less likely to initiate surface runoff (which is to be avoided to minimise the risk of infill mobilisation). The hydraulic capacity of a horizontal drainage system (option one) will be dependent on the size of drainage cells, and is likely to be high. However, when outflow capacity is surpassed, there is no buffer provided by the filling storage in the base layer, hence surface runoff will commence immediately. Therefore, fields with horizontal drainage are likely to be most susceptible to overland flow, especially in brief, intense events. Additionally, another advantage of having water storage in the base is that it may provide a longer lasting water supply for evaporative cooling, mitigating the heat island effect created by ST fields [17, 18].

In summation, vertically draining synthetic turf systems (options two and three) have the *potential* to have large stormwater detention capacity, however this potential is proportional to the depth available for the drainage profile. Hence, if depth is limited (e.g., in a situation of capping, or if extensive excavation cannot be afforded), stormwater detention will also be limited. Additionally, it is important to consider the impermeable surfaces which accompany a ST field. It should be noted that a one to two metre wide concrete verge usually surrounds ST fields, and needs to be factored into calculations of comparative stormwater characteristics between ST and natural fields. Moreover, site specific considerations, such as hydraulic capacity of the downstream environment, are also be an important factor when choosing drainage design for ST fields.

2.2.4 Stormwater implications of natural turf

To provide a baseline for the comparison of different ST systems, the hydrology of natural turf fields is briefly discussed herein. Natural turf fields are typically closed for sporting activities during wet weather, to limit the risk of damage to the turf grass. After rain ceases, a field with coarser textured soil or improved drainage (amended soil or sand slit drainage) will dry out and become playable faster than an non-improved field [19, 20]. To minimise the amount of time the field is waterlogged and unplayable, there are numerous drainage and soil considerations which need to be made, which can drastically improve the drying time of a field. However, in comparison to ST fields for stormwater management purposes, it is only the behaviour of a field during a rainfall event that is of concern.

For stormwater management purposes, natural turf fields are considered permeable surfaces, as they will infiltrate and store rainfall to a much greater extent than other surfaces in an urban environment. The quantity of rain which a natural turf field will infiltrate and store depends on the subsoil of the field. The amount of stored water is of interest from a stormwater management perspective, as this is the water which the stormwater system does not need to cope with during the peak of a rainfall event. An unimproved sports field with loamy soil may only be able to infiltrate <10 mm/h at the start of a rainfall event, and will become saturated quickly, creating runoff which will flow into the stormwater system [19, 21]. A field with improved drainage will likely be able to infiltrate much more, up to hundreds of mm/h [19, 20, 22, 23]. However, depending on the drainage system in the field profile (e.g., sand slit drainage), though the infiltration rate may be high, appreciable quantities of water will flow into the stormwater system from under-field drainage, rather than being retained in the field profile.

In summation, there is substantial variability in the retention capabilities (as they apply to stormwater management) of natural turf fields. However, this is surpassed by the potential variability in ST fields. Horizontally draining ST fields will have flashier responses to rainfall, and hence are less desirable for stormwater management than natural turf fields. The storage capacity range of natural fields is likely to fall within the capacity range of vertically draining ST fields, with discharge peaks from most existing vertically draining fields in Australia likely not differing in orders of magnitude from the natural turf fields which they replaced. However, especially if storage and stormwater detention capacity are designed for (by having a slow outflow rate and a deep profile, possibly with dedicated storage cells), ST fields have the potential to provide greater stormwater retention than natural turf fields. Moreover, stormwater can potentially be collected and recycled from the ST base (discussed further in Section 2.5), which is not an option for natural turf fields. Finally, all ST fields are superior to natural turf fields in terms of playability in wet weather, as ST fields will remain playable except in extreme rainfall conditions.

2.3 Flooding

As mentioned previously, overland runoff, which initiates when the base drainage system reaches its hydraulic capacity, is an issue as it may lead to infill being transported off the field. In addition to this process, the field can also be at risk of flooding from external sources. Flooding can occur as overland flow (water moving with considerable velocity) or slower moving inundation in a floodplain, when the level of water in a river rises. Considering most sports fields are located on marginal land, the flood risk for many is relatively high. Furthermore, this risk may be compounded by changing rainfall regimes under climate change.

One risk of overland flow is the transport of infill particles from the ST field into the neighbouring environment. While most rubber infill is denser than water, it is still relatively light (around 1.2 g/cm^3), thus will be transported in even slow moving water. The transport of infill in runoff is discussed further in Section 4.3.2. Organic infills are typically less dense than water, and hence will be lifted even in situations of standing water.

Flowing water may also lift and move the entire ST mat, as can be seen in Figure 6, however this is only likely in cases of extreme flooding or poor installation. Overland flow flooding (especially at lower water levels) can be mitigated or decreased by the installation of a solid curb around the field. A solid curb is also recommended to prevent the transport of infill particles off the field.

Figure 6: ST mat on a Brisbane field which was lifted during the March 2022 flooding [24]

Finally, flooding (especially overbank flooding in a floodplain) has the potential to transport and deposit sediment and other debris onto the ST field. This is a risk for both ST and natural turf fields, however, natural turf fields are far more resilient to sediment deposition. On a ST field, the silt deposited has the potential to clog drainage pores and necessitate total replacement [25]. Thus, although risk of minor overland flow can be mitigated with a raised curb, ST fields cannot be fully protected from flooding in a floodplain, hence it would be advisable to site more resilient natural turf fields in locations which have a higher likelihood of flooding.

2.4 Water Use

A major benefit of ST fields in comparison to natural turf fields is that ST fields do not require irrigation. Lamble, Askew and Battam suggest that up to 2.24 ML/year would be required for an 8,000 m^2 natural turf field in the Lower Hunter (see Table 1) [26]. This is relatively low compared to other sources, such as Henderson (2007), which states that industry benchmarks in Brisbane are currently around 5 to 6 ML/ha/year for natural turf fields [27]. Irrigation practices, soil and drainage will have a large effect on the irrigation volumes required, with faster draining fields requiring more irrigation.

Table 1: Water use benchmarks for natural turf in the Lower Hunter from Lamble, Askew and Battam [26]

Sport wear levels per full sized football field	Water usage in a median year (ML/ha/year)	Water usage in a very dry year (ML/ha/year)
Low wear (<175 players/week)	2.1	2.4
Moderate wear (175 to 350 players/week)	2.3	2.6
High wear (>350 player/week)	2.6	2.8

Although some 3G ST fields overseas are watered to reduce surface temperatures, this practice is not widespread in Australia [4, 28, 29]. Hence, the water use of a ST field is negligible in comparison to natural turf fields. Note that unlike 3G ST fields, ST hockey fields are typically watered before play to give the field the desired play characteristics, although there is some movement towards introducing hockey fields which do not require pre-play watering.

2.5 Innovations

There are several hydrologic innovations for ST systems that have either been implemented or are discussed as future improvements, including water capture and recycling, evaporative cooling, and groundwater recharge. However, the literature on these options is currently limited.

ST fields have the potential to store sizable quantities of the rainfall which falls upon them in their base, either using the base as a retention basin (to delay stormwater flowing into the stormwater system) or to store and recycle water for irrigation. Detention basins are sometimes also situated below natural turf fields; however, these are not directly capturing the infiltrating water which falls on the field, and are instead taking inputs from the stormwater system. A ST field detaining water in the base would delay the inflow *before* it enters the stormwater system. As noted in Section 2.2.2, pore space in the base aggregate will provide some water storage, especially if the profile is thick and the system which drains it relatively slow. However, if water storage is the primary objective, storage in dedicated chambers beneath the field is the most likely option [30]. Storage and reuse under synthetic hockey fields (onto which water is applied before play) is being considered and may be in place already for some Australian fields.

Groundwater recharge or managed aquifer recharge (MAR) is another option for water stored under ST fields. Not only does MAR reduce the burden of the ST field on the stormwater system, but it also replenishes local aquifers. MAR already occurs on many ST fields world-wide, however, as most Australian fields have an impermeable liner at the base, all infiltrating water exits at the drains. Several impacts need to be considered if this liner is removed. First, there is the potential for groundwater to flood the field’s drainage system if the water table rises close enough to the surface. Additionally, leaching of ST water into the aquifer needs to be considered. As will be discussed later in Section 3, the toxicant risk is relatively low, but nevertheless, having no liner means the system is no longer closed, and the opportunity to treat outflowing water in a single location is foregone. Moreover, recharge will only be substantial in locations where native soils have high hydraulic conductivity, such as sands. If the native soil is fine textured, recharge will be low even if the liner is removed.

Tebakari et al. (2010) measured the effect of a Japanese ST field with a water retentive shock pad designed to encourage evaporative cooling. The shock pad consisted of rubber crumb infill sandwiched between two layers of polyester. It was found that the system reduced temperatures to near that of natural turf, and due to the higher retention of water (estimated to be 15 to 20 mm) only 12 to 14.5% of rainfall flowed into the stormwater system [17, 18]. The remainder of this water either evaporated or contributed to groundwater recharge (the system was not lined). However, a sizable portion of the 12 to 14.5% outflow from the system flowed off as surface runoff, rather than infiltrating and then draining [17]. This situation is not desirable as risk of infill transport is high. In the Netherlands, KWR installed a ST field which collects water in chambers under the field and returns water to the surface (for evaporation) through capillary action [31]. This allows for greater water storage underneath the field and could potentially allow greater infiltration (hence less surface runoff), than the system discussed by Tebakari et al. (2010) [17].

2.6 Summary and research needs

It is clear that ST systems have the potential to have a wide range of impacts on the stormwater contribution of a site. All ST fields are likely to have at least slightly less discharge to the stormwater system than a fully impermeable surface such as concrete, due to some water being retained and evaporated from the upper layers. ST fields with a vertical drainage system can potentially possess substantial retention capabilities, especially if there is significant depth available for the drainage profile or storage units. Despite this opportunity, it does not appear that Australian ST field installations are currently being designed as stormwater management devices. Instead, external mitigation (such as detention basins) is being used in some cases to mitigate the increased peak outflow from a ST field.

The literature available on ST field hydrology is very limited and relatively dated. To gain a better understanding of the hydrologic implication of ST fields in Australia, more information from the Australian industry should be sought, including the proportion of different types of drainage systems which are currently in place, and the modelling used to simulate the hydrology of these fields, especially state-of-the-art drainage systems. Independent modelling and field measurements of the hydrology of ST fields would also expand the body of knowledge. Since outflows from ST fields are usually collected into a single outflow pipe, discharge quantities from ST fields should be measured and monitored relatively easily. These measurements would help better assess the potential for downstream impacts of different field designs and could be used to validate modelling.

Finally, it is important to consider the risk of flooding on ST fields, as they can sustain significant damage by sediment deposition, or result in infill being transported by overland flow. As sports fields are often located in flood prone areas, not all locations of natural turf fields (which are relatively resilient to flooding) will provide an appropriate site for a ST field.

3. Chemical toxicants and leaching risk

There is detailed literature on the concentrations of toxic chemicals found in recycled tyre rubber crumb infill and in its leachate. Recycled tyre rubber crumb is referred to in this report as styrene-butadiene rubber (SBR), though tyres also contain natural rubber and other polymers. The chemical toxicant leaching potential of alternatives to SBR rubber, including ethylene propylene diene polymer (EPDM), thermoplastic elastomer (TPE), polyurethane coated recycled SBR (coated SBR), as well as other components of the complete ST system (see Section 1.1) are less studied, with limited literature on toxic constituents available.

3.1 Types of infill

SBR is made from recycled end-of-life tyres and can be made either cryogenically or at ambient temperatures [32]. Cryogenic processing is intended to decrease surface abrasions on the rubber particles, and hence weathering [32]. The differences in toxicants resulting from cryogenic and ambient temperature SBR are not explored in the literature. EPDM is a specialty vulcanised rubber polymer, which has additional strength and resistance to weathering when compared to SBR [2, 33]. TPEs are a family of copolymers made from a mixture of two or more polymers such that they can maintain the desired consistency at room temperature, and do not need to be vulcanized [2, 33]. Coated SBR can come in different colours (to increase aesthetics or reduce heat impacts) and is intended to slow down weathering of SBR particles, although additional toxicants may be introduced with the polyurethane coating [33]. Organic infills also exist, including crumbed cork, woodchips or coconut husk.

In Australia (and worldwide) SBR is currently the predominant infill used on ST fields. A limited number of Australian fields have been infilled with organic options (mainly cork) or EPDM. No fields in Australia have been reported to be infilled with TPE.

3.2 Types of toxicant tests

In regard to ST infill and its components, five general types of tests have been undertaken and documented in the literature:

1. Testing for toxicants in infill or other components [34-48]. There are more studies testing for toxicants in infill, especially within SBR, than these 15 studies, but [34-48] were chosen and summarised as they tested multiple types of infill or components, or also tested leachate.
2. Testing for toxicants in infill leachate in batch tests [35, 36, 38-41, 44, 49-54]. In these tests the infill is often broken-down using acid, ultrasound assisted extraction, microwave digestion, or other means, then the infill is agitated with the leachant for an extended period of time, such as 24 hours, in an attempt to extract all leachable content. The leachant is sometimes acidic, which is known to increase zinc leaching.
3. Testing for toxicant in leachate from a column test [41, 51-53]. In a column test, the lechant passes slowly through the test material, which could be a single component or a simulated layered ST system. This type of test is a more realistic simulation of the leaching likely to occur from rainfall passing through a field, and typically results in lower leachate concentrations due to decreased contact time.
4. Testing for toxicants in simulated rainfall over artificial turf setups, which allows for more control over the conditions (including controlled simulated weathering) [16, 55, 56].

5. Testing for toxicants in stormwater runoff from real world ST fields, which gives the most realistic values for stormwater contamination, but means it is difficult to isolate toxins to one component, or to control weathering [3, 15, 16, 37, 41, 45, 49, 57, 58].

3.3 Toxicants of concern

Available literature generally tests for the presence of heavy metals, organic compounds such as polycyclic aromatic compounds (PAHs), volatile organic compounds (VOCs), polychlorinated biphenyls (PCBs), phthalates and others. A large number of compounds are deemed of concern in the literature; however seven metals and four organic compounds or classes were compiled into a summary table of toxicants from ST components, which can be found in Appendix A.

These chemicals were selected as they were identified by multiple studies as toxicants which may leave ST systems at levels that pose a risk to the aquatic environment [32-37, 40-42, 44-46, 49, 54, 57, 59-62]. These toxicants are:

1. Metals
   a. Zinc
   b. Lead
   c. Chromium
   d. Cadmium
   e. Arsenic
   f. Copper
   g. Aluminium
2. Total PAHs
3. Total PCBs
4. Benzothiazole (BTZ)
5. Phthalates

Levels of these toxicants detected in materials, leachate or stormwater runoff from ST fields or component documented in 22 studies have been tabulated in Appendix A [3, 15, 34-42, 44, 45, 49-54, 57, 63]. Some studies, which report on values of toxicants over time, rather than maximum or median values, are further discussed in this report but not tabulated [16, 47, 56]. The reported toxicant values are compared whenever possible with the 2000 Australian and New Zealand Environmental Conservation Council Guidelines on Fresh and Marine Water Quality (ANZECC Guidelines). The European Committee for Standardization (CEN) is currently writing standards EN 15330-6, which will specify the maximum permissible amount of some (but not all) of these toxicants in leachate from European Union ST infill [64].

3.3.1 Zinc

Zinc, which is considered the metal of most concern in rubber infill, is present due to the use of zinc oxide as a vulcanization agent [2, 59]. Both SBR and EPDM are vulcanized, hence are likely to contain high levels of zinc, however TPE is not, and thus is expected to contain lower levels of zinc [2]. While the literature generally confirms that leachate from SBR contains the highest levels of zinc, and zinc levels in coated SBR leachate are greater than in EPDM leachate, which are greater than in TPE leachate, the levels are highly variable, likely dependent on the specific manufacturer of the infill material [35, 36, 40, 41, 44, 45, 51-54, 57, 58]. For example, truck tyres contain higher levels of zinc than car tyres and EPDM is vulcanized in multiple ways [33, 59]. Other variables responsible for the wide range of zinc concentrations are pH, as lower pH is known to result in greater leaching, and crumb size, as crumb size is inversely correlated with zinc leaching [65]. Furthermore, results of controlled weathering experiments, as well as observations of fields over time, show that zinc leaching can increase with weathering of SBR infill [51, 54, 56, 57].

The highest concentration found for zinc in batch test leachate was 129,000 µg/L (without acidification) found by Kruger et al. (2012) for 0.8 to 2 mm SBR [52]. However, more typical values for SBR leachate are 7,000 to 1,000 µg/L for batch tests and <500 µg/L for column tests [36, 38, 40, 41, 44, 51, 53, 54]. There are far fewer values in the literature for zinc leaching from other infill materials, however they are all <1,050 µg/L for EPDM and <500 µg/L for TPE [36, 44, 52-54]. However, Magnusson (2018) found higher zinc in infiltrate collected in lysimeters under an EPDM infilled field (median 17.5 µg/L from five rain events) compared to infiltrate from an SBR infilled field (median 2.95 µg/L over eight events), although this may be linked to different construction methods (the EPDM field had a shock pad while the SBR field did not) rather than infill specifically [15]. Plesser and Lund (2004) and Kruger et al. (2012) indicate that zinc is also leaching in considerable quantities from turf fibres (440 to 1,000 µg/L), though these are volumetrically a much smaller component of ST fields when compared to infill [44, 52]. Substantial quantities of zinc may also be leaching from the shock pad layer, which can be made from SBR or other rubber material [52]. Thus, once again it is important to consider the whole ST field composition, not only the infill, when assessing zinc sources.

Four studies measured zinc in natural stormwater runoff from SBR infilled fields [41, 45, 57, 58]. Clayton et al. (2018) measured zinc concentrations in the stormwater from a New Zealand ST field over the first two years of its life. They found a median zinc concentration of 9.29 µg/L, however a maximum of 3,492 µg/L. It was found that the ANZECC guidelines for the protection of 80% of species, 31 µg/L of zinc, was exceeded in 26% of samples, and that concentrations of metals were greater in surface runoff than in rainfall which infiltrated through the field, indicating that the sand and other base layers were playing a role filtering the stormwater [57]. The Connecticut Department of the Environment found a range of 10 to 260 µg/L with a mean of 84 µg/L for eight sampling events on two fields in Connecticut, while Lim et al. (2009) found a value of 59.5 µg/L in one sampling event at a field in New York and Zhang et al. (2021) found a range of 362 to 4888 µg/L in three sampling events at a field in China [41, 45, 58]. In general the values for zinc in stormwater runoff for ST systems with SBR infill are one to two orders of magnitude lower than the values for leachate testing, however, these values are still much greater than the ANZECC trigger values for freshwater systems (8 µg/L for the protection of 95% of species or 31 µg/L for the protection of 80% of species) [66]. It should be noted that the ANZECC guidelines are relatively conservative. For comparison, the US EPA guidelines are 90 µg/L for chronic exposure or 120 µg/L for acute exposure in freshwater ecosystems [66, 67].

Zinc is the toxicant of most concern for chemical contamination of stormwater from ST fields. While EPDM and especially TPE generally have lower concentrations of zinc in leachate, due to variation in manufacturing processes and sources for SBR and other infills, knowing the type of infill alone is insufficient to make conclusions about zinc contamination risk [33, 59]. Moreover, other parts of the ST system, such as the turf fibres or the shock pad, can also contribute substantially to zinc concentrations in runoff [44, 52]. Therefore, field measurements of sites near aquatic ecosystems would be wise to ascertain the magnitude of the toxicant risk.

3.3.2 Copper

Copper was found by Lim et al. (2009), Clayton et al. (2018), Connecticut Department of the Environment (2010) and Zhang et al. (2021) to surpass the ANZECC guidelines for the protection of 80% of species (2.5 µg/L) for fields with SBR infill [41, 45, 57, 58]. Zhang et al. (2021) reported a value of 103 µg/L of copper in stormwater runoff from a Chinese ST field, which is multiple orders of magnitude above other studies [58]. Clayton et al. (2018) found that copper concentrations in runoff ranged from 0.33 to 635 µg/L with a median of 7.22 µg/L, and exceeded the 2.5 µg/L ANZECC guideline in 87% of samples [57]. Overall, it was found that copper is not frequently investigated, possibly because it was not measured in the first study on SBR leachate, Plesser and Lund (2004), on which many later studies were based. Furthermore, there is no US EPA guideline on copper content in freshwater ecosystems. As such, it was not flagged in other early studies such as the Connecticut Department of Environmental Protection (2010) [44, 45, 67]. Copper levels in the ST fibres are higher than in SBR infill, thus it may be these, rather than the infill which contribute to the high levels of copper found in stormwater runoff [44].

Analysis of granule components indicate there is more copper in TPE than SBR or EPDM, indicating that TPE may pose the greatest risk for copper pollution [42, 44]. However, the copper levels in TPE leachate were below the limit of quantification for one study, indicating that copper in TPE may be inaccessible to leaching or may exist in variable quantities dependent on manufacturing [36]. Thus, copper is an under-researched toxicant from ST fields and more information is needed on its sources, especially in components other than SBR infill.

3.3.3 Other Metals

The following conclusions on other metals exclude the values found by Zhang et al. (2021) from their study of runoff from a ST field in China, which appears to be an extreme example of contamination in the nearby environment.

Lead and cadmium are typically found to be slightly below the ANZECC threshold for protection of 95% of species, for the Lim et al. (2009) runoff sample (while leachate samples indicate that levels do not vary as much as zinc between samples and are even lower for TPE and EPDM) [35, 36, 38, 40-42, 44, 54, 58]. However, Van Ulirsch et al. (2010) found high variability in lead content of ST fibres, with some containing considerable amounts of lead, especially in fibres containing nylon, though leachability or runoff was not measured [48, 68]. Thus, the one study measuring lead in runoff from a ST field (hence including turf fibres) may have happened to select a field with low turf fibre lead content, thus failing to capture the risk of lead pollution.

Arsenic concentrations in leachate and stormwater runoff are well below the guidelines [35, 36, 40-42, 44, 54, 58]. The Lim et al. (2009) value for chromium in SBR stormwater runoff (2.2 µg/L) is above the ANZECC threshold for protection of 95% of species (1 µg/L), which is specific to only chromium IV, but well below the threshold for the protection of 80% of species (40 µg/L) [41, 45]. It is unknown whether the chromium measured was chromium IV or III (chromium III is less toxic) [67].

Likewise, aluminium as measured by Lim et al. (2009) for SBR stormwater runoff (108 µg/L) was between the ANZECC guidelines for the protection of 95% and 80% of species (55 and 150 µg/L, respectively) [41, 45]. Analysis of granule components indicate there is more aluminium and chromium in TPE than SBR indicating it may pose more of a risk for leaching of these metals. However, more research, especially leachate and natural runoff studies, are necessary to determine if these metals are leachable in TPE, and to determine their levels in EPDM [42, 44].

Since the research on metals other than zinc has focused predominantly on SBR, other metals (versus the seven compiled in the table) may be of concern in EPDM, TPE or other ST components, including the leachability and presence of lead in turf fibres.

3.3.4 PAHs

PAHs are organic compounds consisting of two or more aromatic rings, which can be formed by the incomplete combustion of fossil fuels [59]. They exist naturally in some components of rubber infill, including in aromatic mineral oil additives used as plasticizers, and are also found in some inputs, such as carbon black, produced through pyrolysis [59]. PAHs are carcinogenic and pose a risk to both human health and the environment [32]. The PAHs are a large class of compounds, however the 16 PAHs identified as being of concern by the US Environmental Protection Agency (16 EPA PAHs) are often the PAHs included in assessments of ST material. In the summary table in Appendix A, the PAH value is listed as the sum total of all PAHs detected.

ANZECC Guidelines only list a guideline for Naphthalene, while stating there is insufficient data to provide trigger value guidelines for other PAHs. The ANZECC Guidelines for Naphthalene are 16 µg/L to protect 95% of species, while the highest concentration recorded in the literature of total PAHs was 3.3 µg/L, from an SBR infilled field [37]. The European Union Water Framework Directive (WFD) gives guideline values for seven PAHs, ranging from 130 µg/L for Naphtahlene to 0.0082 µg/L for Benzo(g,h,i)-perylene [69]. Celerio et al. (2021 and 2018) found the PAHs measured in runoff from SBR fields were below the levels specified in the WFD, except for the maximum value of Benzo(b)fluor-anthene, which was 0.02 µg/L observed in simulated runoff (WFD limit is 0.017 µg/L) [37, 49]. The European Union instituted a requirement that all infill have less than <20 mg/kg of eight PAHs, a requirement which the median field in four studies satisfies, although the median of indoor SBR infilled fields measured by Celerio et al. (2021) and outdoor SBR infilled fields measured by Plesser and Lund (2004) failed to comply with [34, 37, 42, 44].

Batch testing of individual components indicates that SBR generally has higher concentrations of PAHs in leachate than coated SBR, which has higher concentrations than EPDM or TPE [34, 37, 41, 42, 44, 49, 52-54]. However, this is not aways the case, with Ruffino et al. (2013) finding higher levels of PAHs in TPE than SBR [54]. Kruger et al. (2012) found PAH concentration in leachate from other turf components such as the turf fibres (1.14 µg/L), gravel (0.75 µg/L), sand infill (0.23 µg/L) and the bound elastic layer (shock pad) (0.75 µg/L) [52]. These values fell between the concentration of leachate from SBR (1.29 and 1.18 µg/L for coated and uncoated, respectively) and the concentration of leachate from EPDM (0.21 µg/L) or TPE (0.11 µg/L) [52]. This indicates that changing infill type will not necessarily have a substantial impact on PAH levels in stormwater runoff, which is corroborated by column tests of ST systems with varying infill, with total PAHs only ranging from 1.60 µg/L for coated SBR infill to 1.36 µg/L for EPDM infill [53].

3.3.5 BTZ

BTZ is a persistent, water soluble and toxic chemical which is sometimes used in ST materials as a vulcanization agent and as a UV-stabiliser [33, 59, 70]. Six of the 22 tabulated studies measured BTZ, all looking at SBR or SBR infilled fields [37, 40, 41, 45, 49, 57]. Two studies recorded considerable levels of BTZ, Celerio et al. (2018) found BTZ of 120 µg/L in stormwater runoff from a Spanish SBR infilled ST field, while Lim et al. (2009) found BTZ at 526.3 µg/L in batch test leachate and 215.3 µg/L in column test leachate [41, 49]. Halsband et al. (2020) also found high values in SBR leachate from fresh crumb produced in seawater (mean 1693 µg/L) and 10s of µg/L for leachate, which had been diluted to a level that could be expected for runoff from a ST field [39]. Leachate from a used SBR sample obtained from a field had much lower BTZ, 126 µg/L [39]. The remainder of the values were <11 µg/L for leachate and runoff [37, 40, 41, 45].

There is currently no ANZECC or US EPA guideline on BTZ concentrations in freshwater. However Pillard et al. (2000) found the concentration toxic to 50% of individuals (LC_{50}) is 65 mg/L for fathead minnows (*Pimephales promelas*) and 102 mg/L for water fleas (*Cerodaphina dubia*) [71]. Seeland et al. (2012) found that BTZ concentrations ranging from 0.4 to 3.94 mg/L had an inhibitory effect on the growth or reproduction for 10% of individuals (EC_{10}) for *Daphnia* and primary producers [72].

Thus, it is unlikely that BTZ leached from ST fields would pose a risk to the aquatic environment at the levels detected in the literature, especially considering dilution by the time it reaches the aquatic ecosystems and that exposure would be acute rather than chronic, occurring only after rain events. Nevertheless, with the variability in BTZ content of samples, and the high transfer rate of BTZ from crumb rubber to water leachate, it is worthwhile considering the presence of BTZ in ST stormwater runoff [49]. Moreover, there is no information on levels of BTZ in alternative infills or in other parts of the ST system, hence the source of the BTZ pollution cannot be determined.

3.3.6 PCBs

PCBs are a group of chlorinated organic compounds that are toxic to human health and the environment [59]. PCBs have been largely banned worldwide, including in Australia since 1975, but due to their longevity, continue to persist in the environment and have been found in freshly manufactured infill material [42, 44]. The ANZECC guidelines give no trigger values for freshwater ecosystems, however they indicate that a concentration of <2 µg/L should be maintained for aquaculture. Two of the tabulated studies measured PCB content, including measurements of SBR, EPDM and turf fibres, finding total PCBs existing at levels <0.5 mg/kg in these components [42, 44]. Postma and van der Oost (2018) found a median of 0.0001 µg/L of total PCBs in runoff from both natural and ST fields [3]. A leaching study done by Plesser and Lund (2004) did not find measurable leaching from SBR infill [42]. Hence, while the literature is limited, it appears that PCBs do not pose a significant risk to aquatic contamination.

3.3.7 Phthalates

The three phthalates tabulated in the literature are diethyl phthalate (DEP), dibutyl phthalate (DBP) and di(2-ethylhexyl) phthalate (DEHP). Three studies measured these phthalates, including a survey of global SBR fields, testing of various ST components, and measurements of runoff [34, 37, 44]. Armada et al. (2022) found that average content of DEHP is greater than DBT which is again greater than DEP, with the maximum concentration of DEHP found in SBR rubber being 9,470 mg/kg [34]. This is corroborated by Plesser and Lund (2004), who also found less phthalates in EPDM and in turf fibres than SBR (no TPE was measured) [44]. However, the solubility of phthalates decreases with increasing molecular mass, so DEHP is significantly less soluble than DBP and DBP is less soluble than DEP [73]. This trend is shown in leaching of phthalates, with the highest concentrations in stormwater observed for DEP (median 0.49 µg/L) and the smallest for DEHP (median 0.019 µg/L), with DBT at an intermediate value (median 0.15 µg/L) [37].

These reported levels are below the ANZECC guidelines for the protection of 95% of species (900 µg/L for DEP and 9.9 µg/L for DBT). The ANZECC guidelines states that there is insufficient data for a guideline on DEHP, however, toxicity tests on aquatic organisms indicate that DEHP is not toxic at levels that are soluble in water [63, 73]. Thus, phthalates from ST systems are unlikely to be a risk to aquatic ecosystems.

3.3.8 pH

pH was not discussed appreciably in any of the studies, although six studies measured pH [44, 45, 51-54]. SBR and TPE generally produced leachate that was near pH of 7, however EPDM produced leachate up to pH 11.36 in Plesser and Lund (2004) and pH values from 8 to 10 in two other studies [44, 52, 54]. No natural runoff from EPDM fields was measured, however the levels of pH from laboratory testing are concerning and should warrant field measurement campaigns of stormwater runoff from Australian ST fields.

3.3.9 PFAS

Per- and poly-fluoroalkyl substances (PFAS) are a group of persistent, fluorine rich compounds that are increasingly studied by the scientific community due to their widespread presence and high risk to human health and the environment. Preliminary studies have indicated that PFAS are present in artificial turf, and are known to be used as an aid in the fibre extrusion process [43, 74]. Naim (2020) tested 18 fields in Stockholm with SBR, EPDM, TPE, TPO, sand and cork infill. PFAS was found in 76% of the backing samples at concentrations ranging from 0.04 to 0.89 μg/kg and in 18% of infill samples at concentrations ranging from 0.03 to 0.21 μg/kg, while only one sample was found to have PFAS in turf blades [43]. PFAS was found to be the highest (both in the infill and the backing) in EPDM and SBR infilled fields [43]. Testing referenced by the Toxics Use Reduction Institute (2020) also found PFAS in backing [74].

The levels reported by Naim (2020) are considerably lower than the median levels of PFAS in soils deemed to be “background” rather than “contaminated” sites by a global survey of PFAS in soil (2.7 mg/kg), indicating that ST may not be an appreciable contributor of PFAS to the environment. It should be noted that total PFAS values vary considerably depending on what PFAS compounds are targeted [75].

However, leachability of PFAS from ST remains unknown, and to date there has been no peer-reviewed literature on PFAS in ST. Due to the large number of PFAS compounds and their low concentrations, further peer-reviewed testing is warranted [74, 75]. Further research focusing on leachability and transport in runoff, as well as testing of all parts of the ST system, is required to determine if PFAS from ST is a threat to the nearby aquatic ecosystem.

3.4 Ecotoxicity Testing

Four studies tested the ecological toxicity of ST leachate on organisms [16, 38, 50, 53]. Gomes et al. (2011) found no toxicity from column test leachate of SBR on *Daphnia magna* exposed for 48 hours and algae exposed for 72 hours [50]. Kruger et al. (2013) tested the ecotoxicity of batch test infill components as well as column tests of ST systems against *D. magna* and *Pseudokirchneriella subcapitata* (algae). They found that mortality was greater for batch tests than for column tests, as would be expected, as toxicants are more concentrated in batch tests, however, surprisingly found that batch tested EPDM leachate showed the highest toxicity [53]. It was found that the effect of EPDM against TPE could not be distinguished when they were tested as part of a column test with other infill components, while SBR infill showed no toxicity [53]. There was no correlation found with zinc or PAH concentration and toxicity, and toxicity for EPDM remained high even when pH was controlled [53]. This indicates that it may be a cocktail of chemicals, or chemicals not yet discussed in the literature which are responsible for toxicity. Gomes et al. (2010) compared ecotoxicity for leachate from coated and uncoated SBR particles using *Vibrio fischeri* bacteria and found that coated SBR had lower toxicity than uncoated SBR, although there were differences between the two coating types tested [38].

Two (2) studies tested the effect of stormwater runoff from fields on organisms [3, 16, 45]. Postma and van der Oost tested the effects of stormwater runoff on *D. magna* and the effect of benthic sediment containing infill on the benthic grazers *Hyalella Azteca* and *Chironomus riparius*, comparing results to runoff and sediment from adjacent natural turf fields. They found 100% mortality of *D. magna* in one runoff sample (site 8) out of 8, and a significant restriction of reproduction in one other sample (site 5). There was one site (site 6) with a significant difference in *H. Azteca* mortality between ST and natural fields, and no differences in *C. riparius* mortality. There were significant differences at one site (site 4) for growth of both grazer species. The differences in site 4 may be due to tolytriaxole (toxicity unknown) [3]. The differences in site 5 were hypothesized to be caused by geochemical differences rather than the presence of the ST field and the site 8 mortality was due to very high levels of zinc [3]. Moretto (2007) found no or negligible toxicity from stormwater samples which had infiltrated through an SBR infilled field on *D. magna* exposed for 24 hours and algae exposed for 72 hours [16]. Note that the Moretto (2007) study is not peer reviewed and was supported by industry. The Connecticut Department of Environmental Protection (2010) tested eight stormwater samples from three fields and found that three out of the eight samples (one from each field) were acutely toxic (>10% mortality for *Pimephales promelas* and *Daphnia pulex*), while the remainder of the samples showed little or no effect [45].

A large body of literature exists on the toxicity of tyre leachate, but there is much less data on ST leachate toxicity specifically. Fort et al. (2022) tested leachate from tyre rubber crumb which was crushed in the lab. They found that growth rates of two primary producer species (*Lemna minor* and *Desmodesmus subspicatus*) experienced growth inhibition when exposed to leachate while *D. magna* experienced 100% mortality when exposed for 24 hours [76]. Turner et al. (2010) tested the impact of tyre wear particles on marine algae *Ulva lactuca* and found that increasing exposure resulting in toxic effects with the greatest decreases in activity occurring with changes at low levels of leachate, while there was much less difference in effects at higher leachate concentrations [47]. When equivalent amounts of zinc were tested, ecotoxicity was significantly lower, indicating that other toxicants present in tyre wear particles (and hence likely in the SBR particles) are playing a sizable role in toxicity [47]. Halsband et al. (2020) ran tests for up to 17 days and found that crumb tyre leachate caused mortality in marine copepods at levels of leachate greater than or equal to 5 g of crumb per litre of seawater, and that the extent of the effects varied between species [39]. However, the 1 g/L SBR leachate prepared by Halsband et al. (2020) – the concentration that the inhibitory effects cease to be distinguishable from the control – appears to be on the order of magnitude for metal, PAH and BTZ concentrations as stormwater runoff measured in other studies [37, 39, 41, 49, 57, 58, 77].

Thus, leachate from SBR particles is ecotoxic to a variety of freshwater and marine organisms at high concentrations, with the source of toxicity being unclear. Limited research points to the concentrations of toxins likely to occur in the runoff from fields not having noticeable effects on organism over the 1 to 17 day periods tested [16, 38, 39, 53]. However, runoff may approach concentrations with ecotoxic effects in the most polluted fields, especially when an ecosystem is close to the stormwater outlet, with limited potential for dilution to occur. It should also be noted that there is currently limited research available on the ecotoxicity of infills other than SBR [53].

3.5 Toxicity over time

Studies that measure leachate toxicity over time, or in correlation to ST field age, note that toxicity is the greatest for fresh materials, although ST fields may be a constant source of pollution over time, especially for some toxicants [16, 37, 51, 54-58]. However, Postma and van der Oost (2018) found that the highest zinc concentrations and ecotoxicity came from the oldest ST field studied (e.g., 28 years is significantly older than the average ST field lifetime of 12 years) [3]. The cause of this was not determined, though it could be due to different materials being used, the sand layer reaching its sorption capacity or extensive weathering causing increased zinc release [3].

Although most studies only looked at SBR or SBR infilled ST fields, this trend appears to be true for EPDM and TPE too, according to Moretto (2007) [16]. However, Magnusson (2018) found that while heavy metals in the infiltrate decreased sharply over time in an SBR infilled field, they remained relatively constant in an EPDM infilled field [15]. In particular, zinc appears to be released over time, especially after weathering, as the crumb matrix degrades making more surface area accessible to leaching, resulting in an overall decline interrupted by peaks as weathering progresses [51, 55].

Thus, although ST fields are likely to be the source of toxicants over their entire lifetime, the risk is greatest when the field is first installed or during installation. Therefore, it is recommended that mitigation measures at the site to be operational from the beginning of construction of the ST field.

3.6 Organic infill

Natural or organic infill may require application of algicide, fungicide or herbicides to prevent growth within the infill [2]. These products have the potential to runoff, thus being an environmental hazard, however this has not been documented in the literature.

In Australia, some natural fields have been reported to use chemical treatment while others do not. Natural infill may also contain some PAHs and other toxicants discussed previously, however at much lower levels than rubber infill [2, 34]. Thus, overall natural infills are likely to contribute fewer toxicants to the environment than non-organic infills. However, considering the overall contribution of other parts of the ST system (turf fibres, shock pad, etc.) to toxicant leaching, natural infill will only reduce, not eliminate issues with toxicants [44, 48, 52, 63].

3.7 Natural turf

Natural turf can also be the source of chemical pollution. Fertilizer, herbicides and pesticides are often used on natural turf sport fields to maintain the quality of play. These inputs can have negative impacts if they runoff into the nearby environment or leach into groundwater.

Phosphorus is generally the limiting nutrient for surface water, hence high phosphorous runoff creates a risk of algal blooms in surface water [78, 79]. The literature on pollutant runoff from turfgrass sports fields is surprisingly limited, with most of the data coming from golf courses or residential lawns. In a literature review, Sodat et al. (2008) found values for phosphorous in runoff from turfgrass to range from 0.2 to 18% of applied phosphorous, or from 4 to 30,000 μg/L, with normal loads around 100 to 1,000 μg/L [78]. Situations where runoff occurred directly after rain caused the highest phosphorous loads. Baris et al. (2010) surveyed 20 years of data from US golf courses and found that the mean concentration of total phosphorous was 430 μg/L (with local guidelines for runoff being exceeded 86%

of the time) [80]. The mean concentration of nitrate was 230 μg/L (with local guidelines being exceeded 22% of the time) [80, 81]. The ANZECC trigger values for phosphorous in aquatic ecosystems in south east Australia range from 10 to 50 μg/L depending on the body of water [66]. While almost all the values in Sodat et al. (2008) exceed this trigger, dilution also needs to be considered. It is noted that pollutant loads from turfgrass are generally much lower than from cropland, as uptake rates are high, sediment loss (on to which nutrients can sorb) is much lower, and infiltration is higher [78, 79, 82].

Baris et al. (2010) found that, of a survey of 161 pesticides in runoff from golf courses, pesticide levels only exceeded recommendation in 0.15% of groundwater samples and 0.56% of surface water samples [80]. Postma and van der Oost (2018) found similar levels of organochlorine pesticides in runoff from ST fields and nearby natural turf fields (median 2.15 and 2.25 μg/L, respectively) although the maximums for natural turf fields were higher (up to 19.6 μg/L) [3]. No values were found for herbicide export from natural or ST fields, although both are likely to export them. ST fields use herbicides on the edge of the field and surrounding pavement, where export in runoff is likely to be relatively large, as it is an impermeable surface.

It is noted repeatedly in the literature that well managed turfgrass can have limited pollution impacts [78, 79, 83]. However, sports fields are unlikely to fall into this category as their high use will result in bare spots (creating runoff and sediment transport), which suggests that nutrient uptake will not be as efficient as possible. Moreover, nutrient losses are greater in sandy soils than loams due to their high flow rates and low cation exchange capacity [79, 81]. This suggest that natural turf sports fields with sand amendments or slit drainage installed are likely to have greater pollution export issues than most turfgrass discussed in the literature, especially if lower conductivity soils (with high cation exchange capacity) do not lie between the field and local aquifer. On the other hand, fertilization rates of fields in NSW are generally lower than the recommended amount, due to budgetary constraints. Lamble, Askew and Battam found that 63% of fields in the Lower Hunter suffered from macronutrient deficiencies [26]. This suggests that uptake rates of the fertilizer applied will be high, regardless of field wear level. Additionally, the grassed area around a field may not be fertilized or managed with other chemicals, hence would provide a buffer strip for the removal of nutrients. Such buffer strips, when well vegetated and sufficiently sized, are known to be effective at removing pollutants [84]. Because of these conflicting factors, it is difficult to make conclusions about the risk of nutrient and toxicant mobility from natural turf fields compared to golf courses and residential lawns.

Though there appears to be very limited literature on nutrient and other exports from ST fields, the literature on exports from residential lawns and golf courses is far more extensive than the summary provided in this report. Hence, more thorough conclusions could be drawn with a more comprehensive review of the literature and understanding of the effects different uses of sport fields will have compared to existing studies. Nevertheless, from this brief review it appears that natural sports fields may have non-negligible negative impacts to the aquatic environment, with phosphorous posing the greatest risk.

3.8 Toxicant leaching mitigation

There are multiple options to reduce the toxicants leaching from a ST field. First, it is important to note that some filtration will be naturally provided by the sand in the ST system. 3G ST fields contain sand infill below the performance rubber or natural infill and may also contain sand in the drainage base of the field. It is known that sand is an effective filter for many pollutants, and Clayton et al. (2018) noted that copper and zinc loads were higher in surface runoff from a ST field than in stormwater, which infiltrated through the field [57, 85, 86]. Moreover, the use of a calcite ($CaCO_3$) rich base aggregate has been shown to be highly effective at reducing zinc loads (through sorption) by Cheng and Reinhart

(2010) [87]. It was shown that inputs of 1,000 μg/L were reduced to <50 μg/L concentration by a 10 cm layer of aggregate containing 11.6% calcite, and it was estimated that this sorption could be maintained for four years [87]. Calcite media has also been shown to be effective at removing PAHs [86].

Alternatively, water sensitive urban design (WSUD) strategies such as raingardens, biofilters and constructed wetlands are highly effective at the removal of heavy metals and other pollutants. A one meter thick sand filter (with no vegetation) was found to have a zinc removal efficiency of >96%, and it was estimated to be able to absorb concentrations of 250 μg/L (which is a moderate approximation of what concentrations may be from a ST field) for four years before zinc concentrations in the biofilter reached local soil guidelines (14,000 mg/kg) [85]. Biofilters are generally effective at removing heavy metals including zinc (>70% for three designs with 50 cm filter layers measured by Hatt et al. (2009) and 62 to 99% for nine studies reviewed in Ahiablame et al. (2012)) [84, 88]. Permeable pavements, swales and constructed pavements are also generally effective at removing heavy metals [84]. For the removal of PAHs, sand filters, calcite, zeolite, iron filings and soil with granular activated charcoal have been shown to be highly effective (>90% removal) [86, 89]. BTZ can be removed by both absorption and biodegradation, thus a vertical flow vegetated constructed wetland was deemed optimal (65% removal) with horizontal flow constructed wetlands also removing some BTZ, and incorporation of granular activated charcoal further aiding removal [90]. Pritchard et al. (2018) found higher removal rates of BTZ (97%) with longer treatment times of seven days in biofilters vegetated with *Carex praegracilis* [77]. Cao et al. (2014) found the removal of 48% to 82% if DEHP is a biofilter [91].

Thus, WSUD constructions have the ability to remove some or all of the toxicants of concern from ST fields, and have especially high effectiveness at removal of heavy metals such as zinc , which is likely to be the contaminant of most concern for ST fields [77, 84-86, 88, 90, 91]. A well maintained vegetated or unvegetated biofilter will likely be sufficient to improve water quality from any ST field to an acceptable level for release in the aquatic environment. However, clogging of the filter with infill material may become an issue depending on the drainage setup, hence filters which can be regularly emptied should be placed within drains leading to the biofilter. WSUD is also highly effective at removing nutrients, and hence would be useful to improve runoff quality from natural turf systems as well, although leaching into groundwater would remain an issue [84, 85, 88].

3.9 Summary and research needs

Overall, ST systems are the source of several chemicals of concern to the aquatic environment, mainly metals, although PAHs, BTZ and PFAS (which is under-researched) may also be at levels of concern. However, due to the relatively low levels of exposure and the intermittent inputs into the environment, in most cases all toxicants are likely to be diluted sufficiently to prevent ecological harm by the time they reach the freshwater environment, especially if sensitive ecosystems are not located nearby and if filtration through a sand underlayer is considered [3, 32, 45, 68]. This only applies to leachates and does not necessarily apply to situations where infill particles themselves are transported into aquatic environments resulting in higher concentrations of toxicants.

Moreover, due to large variability in infill toxicant levels, as well as lack of knowledge about toxicity of other components of ST systems, it is possible that some ST fields may leach toxicants at a level that impacts aquatic ecosystems. As such, it is recommended that site specific monitoring and potential mitigation are implemented for ST fields near any sensitive receivers, to be determined per an effects based assessment. Moreover, fields are likely to pose the greatest risk during construction and in their first years after installation, so mitigation measures are of utmost importance from the beginning of the ST field construction in sensitive areas.

The literature indicates that all infill options and components of the ST system contain toxicants, yet research is limited in the toxic potential of TPE, EPDM, coated SBR, turf fibres and shock pads. Hence, in order to make informed decisions about how to construct low toxicant fields, or better understand fields without infill (e.g., tennis, cricket, bowling), further research into individual components is necessary, and simply replacing the infill with a natural alternative may be insufficient to fully remove the risk of negative impact to the nearby environment.

Finally, the lack of stormwater runoff samples from EPDM or TPE infilled fields, or second-generation fields (sand infill) is a significant literature gap, indicating a very limited understanding of the pollution risk from this type of fields. More data regarding the pollution risk from natural turf fields is also needed to make accurate comparisons of the costs and benefits of replacing natural turf with ST. Hence, measurement of runoff from neighbouring ST and natural turf fields would be valuable, although further research would still be needed to make judgments about comparative risk, considering the pollution from natural and ST fields differs in nature.

4. Microplastic pollution

4.1 Microplastics

Microplastics are defined as synthetically produced polymer particles less than 5 mm in any direction [92, 93]. Although rubber particles, as thermoset elastomer polymers (rather than thermoplastic polymers), are often included in surveys of microplastics, they may not be included in some definitions of microplastics and are sometimes referred to as microrubber [93, 94]. In this report, the term microplastics is used to describe rubber crumb infill and turf fibres and fibre wear particles that are lost to the environment. Note that infill crumb rubber (with a diameter around 1 to 3 mm), though it meets the definition of a microplastic, is larger than the microplastics most studies focus on (<1 mm) and are larger than tyre wear particles, which are the focus of several studies [93-96]. In addition to the size and material, microplastics are often classified by shape. Infill material would fall into the microplastic shape classification of spherule or spheres. Small weathered particles of turf fibres, typically made of polypropylene or polyethylene, would be classified as fragments [97]. Whole turf fibre blades, although fibres in shape, do not meet the size criteria of microplastics (<5 mm), hence studies that refer to microplastic fibres would not apply to turf fibre blades, although these are included under the common denomination of microplastics in this report.

4.2 Impact of microplastics in the aquatic environment

The impact of microplastics in the environment is wide ranging and still not fully understood. Here, a brief overview is first provided to highlight some of the risks of microplastic pollution. The loss of microplastics from ST fields is then explored.

Microplastics are sources of all the chemicals discussed in the chemical hazard section of this report, in addition to the ecotoxicological hazard posed by ingesting the particle itself, which may cause acute mortality and longer-term impacts on growth and reproduction when present in living organisms. Khan et al. (2019) and Cunningham et al. (2022) both demonstrated the potential effects of microplastics beyond the associated leachate toxicity. However, both used tyre wear particles of size <0.5 mm, hence the same conclusions may not apply to infill particles, which are larger [94, 98, 99]. Smaller particles are more likely to be consumed by organisms and spherical particles are more likely to be excreted, whereas fragments or fibres are more likely to lodge in organisms [100, 101]. Additionally, micro and nano scale particles have been postulated as “trojan horses” which cross biological membranes and release toxins intercellularly, and smaller particles were shown by Cunningham et al. (2022) to be more toxic [94, 99]. As such, small fragments from turf blades and the disintegration of rubber infill are more likely to pose a toxic risk due to their presence as microplastics, whereas larger particles such as whole infill granules are likely to be ecotoxic primarily through leaching of toxic chemicals. Finally, microplastics and specifically rubber particles may provide vectors onto which external contaminates, such as heavy metals and biotic pathogens, can sorb and then be transported into new environments [93, 102].

4.2.1 Ecotoxicological testing of infill microplastics

Only one study was found that tested the ecotoxicity of ingesting infill particles. Ottosson et al. (2016) tested the effects of EPDM infill ingestion on *Oncorhynchus mykiss* and found that results reaching the threshold of 5% significance were not found when monitoring the nutrient uptake of the fish [103]. However, the study only lasted seven days, which may have been too short a period to observe effects.

Postma and van der Oost (2018) also studied the ecotoxicity of benthic sediment samples on *Hyalella Azteca* (3 to 8 mm crustaceans) and *Chironomus riparius* (mosquito larvae), hypothesising that, though the infill particles are too large to be consumed, the particles may interrupt grazing or fragments may be consumed. They found no significant decreases in mortality for samples at the outlet of ST fields compared to natural fields, and significant differences in growth between ST fields and natural fields in only one out of 10 sampling locations [3]. However, no attempt was made to quantify the difference between leachate and microplastic particle toxicity, and the location that had significant differences in organism growth did not have more infill particles than other sampling locations [3].

4.3 Microplastic loss

ST fields require regular replenishments of infill [6, 104, 105]. This replenishment is required due to a combination of compaction and loss to the environment [104, 105]. Fleming, Forester and McLaren (2015) studied the compaction in a ST system and found that around 25% compaction had occurred after 500 cycles of a roller, however, almost all of this compaction could be reversed with raking [106]. However, some compaction is inevitable with use, and more compaction will occur if maintenance is suboptimal, or on fields without a shock pad [8, 104, 107]. In estimates of the mass balance of infill on ST fields, DTI (2018) estimated that, out of 2,200 kg of replacement infill per year, 1,470 to 1,900 kg (67 to 86%) offsets compaction, while Verschoor et al. (2021) estimated that, out of 600 to 1,200 kg/year of infill required, 500 to 600 kg (42 to 100%) offsets compaction [104, 105]. The remainder of the infill, equivalent to hundreds of kilograms per year, is lost from the field.

The loss of fibre (pile) length per year has been measured on average as 3.2 mm/year by Sharma et al. (2016) [108]. If turf fibres are assumed to be 60 mm long, this is a loss of 5% per year, which results in a loss of 320 to 560 kg/year, when using estimates of turf density of 0.8 kg/m^2 from Källqvist (2005) or of 1.4 kg/m^2 from FIFA data provided in Hann et al. (2018), across a 8,000 m^2 field [60, 92]. Lassen et al. (2015) used a higher estimate of 5 to 10% loss of pile per year to obtain an estimated loss of 500 to 900 kg/year of turf fibres, which is likely an excessive rate of loss for a field expected to last >10 years [109]. Based on confidential data from FIFA, Hann et al. (2018) provided an estimated loss of 0.5 to 0.8% of pile annually, leading to an estimated loss of 64 to 40 kg/year [92]. These estimates only apply to degradation of fibre tips, not loss of entire fibres from the mat, which has been observed to also occur, (see Figure 7) [110]. Loss of whole fibres has been reported to be greatest when a field nears its end-of-life.

Figure 7: Turf fibre pollution observed near two different ST fields in the Sydney region

Bø et al. (2020) compared average ST inputs in Swedish ST fields to the mass of material received by recyclers and found an average of 83 tons of infill, 0.6 tons of turf fibres and 43 tons of sand were lost over the lifetime of a ST field [5]. The mean lifespan of the fields studied was 11.4 years, thus this would amount to a loss of 7,280 kg/year of infill and 53 kg/year of fibres. However, it may be that a proportion of these losses come during installation, decommissioning and transport to the recycling centre, rather than regular use. The Bø et al. (2020) estimate is higher for infill losses and lower for fibre losses than other studies. One possible explanation for this (other than errors in previous estimates, variability between losses, or losses occurring during installation and deinstallation) could be that not all the infill and sand is being separated from the turf mat, resulting in overestimates of recycled mat material and underestimates of infill.

4.3.1 Quantification of loss to waterways

Of the infill that is lost to the environment, some is likely to end up in water networks (stormwater systems and natural waterways). Several studies have attempted to quantify the amount of infill entering these networks. Widström (2017) measured the accumulated SBR rubber granulate in stormwater pits surrounding four fields in Sweden and found 4 to 73 kg per field [111]. No attempt was made to quantify transport over time. Weijer and Knol (2017) estimated the loss from five fields in the Netherlands, three of which were infilled with SBR, one with TPE and one with cork. They estimated that up to 100 kg/year were lost into surface water systems near the field, while the loss to stormwater systems was only measured at two locations and found to be 0.3 and 0.9 kg/year [112]. These estimates were obtained by measuring infill quantity in sediment and extrapolating to total loss. Based on basic lab tests, Weijer and Knol (2017) estimated that 35% of infill would settle out quickly in still water, hence sediment infill quantity could be assumed to be 35% of total infill ending up in waterways. However, this estimate is unlikely to apply to EPDM and especially not to cork, both of which have a lower density. Note also that rudimentary observations of infill from Sydney ST fields do not necessarily concur. SBR infill from one field settled immediately when submerged, although surface tension suspended a large number of particles. A large proportion of particles from another sample of infill continued to float after surface tension was broken, with settlement only occurring over the long term (weeks), see Figure 8. It is unknown what type of rubber this sample is, however, being black it is assumed to be SBR. Thus, the value of 35% settlement is not likely to be widely applicable and highly dependent on the manufacturer.

Figure 8: Rubber infill material in water after one hour (left) and one week (right)

Regnell (2018) measured the microplastics larger than 10 μm which could be found in the stormwater system for a Swedish ST field with filters fitted within the stormwater drains. It was found that 15.5 kg/year were collected in the 200 μm filters the drains surrounding the field [113]. A further 0.01 kg/year of microplastics were detected in stormwater pits farther in the system, the majority of which were other microplastics, while only 10% were infill material which had passed through or escaped the filter [113]. 0.07 kg/year of microplastics, mainly <200 μm, were collected in the stormwater that infiltrated through the field [113]. This field also had a rigorous procedure for brushing off players and maintenance equipment, to reduce the transport of infill from the field, hence this estimate for infill loss to drainage systems (15.6 kg/year) is likely an underestimate for a field with suboptimal infill management protocols [113].

Lundström (2019) quantified the infill caught in filters in drains around two Swedish locations with ST fields over 49 days [114]. One location comprised three full size fields and one smaller seven player field, all infilled with SBR. This location was found to lose 10.3 kg over the 49 days, which would extrapolate to approximately 22 kg/year per full sized field [114]. The second location had one EPDM infilled field and was found to lose 1.5 kg, which would extrapolate to a loss of 11.2 kg/year [114]. A nested system of filters was used, ranging from 200 to 50 μm and it was found that >99% of material was caught in the 200 μm filter. Hence, 200 μm filters were recommended for future use, to minimise the risk of clogging and biofilms inherent with small filter sizes [114]. It was also noted that silicone sealant was needed to ensure no infill was able to escape around the edge of the filter (see Figure 9) [114]. Li (2019) also found that the vast majority of infill microplastics (>90%) found in stormwater pits around four fields were 1 mm or larger, and recommended using 400 μm filters [115]. There does not appear to be an industry standard design for these filters (also called granulate traps) however one example is shown in Figure 9.

Figure 9: Example of a filter installed in drains surrounding ST fields to trap infill particles (left) and infill bypassing the filter where the seal is poor (right), from Lundström (2019)

4.3.2 Dispersal routes

From Regnell (2018) it is clear that the amount of microplastics in water which infiltrates through the ST field is very small [113]. The majority of microplastics found in water networks are instead being transported through surface mobilisation. This could come either directly from surface water runoff from the field, or from transport of material that was moved off the field to the surrounding area before a rainfall event. As certified ST fields generally have high infiltration rates, surface runoff from a properly constructed and certified ST field should be a rare event. Thus, the majority of infill in drainage systems can be assumed to come from infill which was transported off the field by other means, and is then picked up by runoff [11].

Methods by which infill material (as well as degraded turf fibres) can be transported off a field include [116]:

1. “Walk off” on players’ shoes and clothing
2. Runoff in extreme rainfall events when the infiltration rate of the ST field is exceeded or when fields are not correctly bunded
3. Maintenance vehicles or equipment
4. Removal with snow (deemed negligible in Australia)
5. Removal with leaves
6. “Splash” from play
7. Wind

Estimates for the amount of infill transported by players have been proposed by a few studies, however the most thorough, Forskningskampanjen (2017), which is based on 592 games, gave a value of 0.54 g/player in dry weather and 1.6 g/player in wet weather, resulting in an estimate of 40 kg/year [104, 105]. The majority of this is likely to be dealt with at home, when the player undresses and washes their clothes, however, it may also be deposited in the area around the field, or in the wider environment on the player’s way home.

Much of the material transported by players, maintenance, splash or wind to the area around the field will not end up in waterways, as it will either remain in the soil surrounding the field or be swept up by maintenance crews. In fact, DTI (2018) estimates that 250 kg/year (11% of added infill) ends up deposited on paved areas or soil, and does not make it into waterways, while Weijer and Knol (2017) estimated that this amount was 20 to 280 kg on five fields [104, 112]. In samples taken by Weijer and Knol (2017), an average of 12% of soil by mass on grass verges around fields was infill material, with more infill being located in the upper layers [112].

Infill that is neither swept up and removed nor becomes lodged in soil, is likely to be transported by any sizable rainfall event. The approximate densities of SBR, EPDM and TPE are 1.2 g/cm^3, 1.1 g/cm^3 and 0.8 to 1.2 g/cm^3, respectively [92]. Hence, all infill (except for some TPE) is denser than water and would tend to settle. Nevertheless, because it is near the density of water, infill is highly transportable and difficult to separate in the stormwater system [93, 94, 112]. The Weijer and Knol (2017) and Windström (2017) studies confirm that a substantial amount of transported infill remains in the sediment of waterways and stormwater systems [111, 112]. However, it is clear from experience and preliminary hydraulic calculations that some infill material will be transported in even slow-moving water, both in drains and in sheet flow on pavements and other flat surfaces. Transport would require higher velocities on rough surfaces such as grass and would occur at lower velocities for lower density particles such as EPDM and TPE, or smaller particles. Moreover, observations show that small infill particles can easily be suspended by surface tension, further increasing transport. EPDM and TPE, despite being touted as more environmentally friendly, may pose more of a microplastic pollution risk due to their lower density and hence increased mobility. Regarding organic infill, cork is much less dense than water, and hence will be highly transportable by wind and water.

The density of polypropylene and polyethylene is <1 g/cm^3, meaning that they will not settle out in slow moving water, and movement will need to be arrested by filters or friction. Although some fibres would become trapped in swales, wetlands and gross pollutant traps (GPTs), these interventions will likely be less effective than against infill, as the fibres do not settle. Aeolian transport would also be more of a problem for turf fibres. Some older fields may use nylon fibres, which are denser than water, hence creating less transport risk, however nylon has been largely replaced by polypropylene and polyethylene fibres, as they are less harsh on player's skin [4].

4.3.3 Australian conditions

Conversations with the Australian maintenance industry suggest that the average infill top up requirements (replacing both compacted and lost infill) for Australian ST fields are similar in magnitude to those estimates for the literature from Europe, around two metric tonnes per year, although this occurs in small top ups during regular maintenance and one or two major top ups of around 10 tons.

Nevertheless, the Australian environment differs in those from which the infill migration data is derived (northern European countries) in a few notable ways, which may make the total mass balance estimates inapplicable. Foremost, snow removal is a large vector for infill migration in these studies but is not an issue in Australia. Rainfall amounts also vary, with the mean annual rainfall in Sydney being 1,213 mm/year, whereas annual rainfall in the Netherlands is 700 to 900 mm/year and in the Stockholm area is 500 to 600 mm/year, two areas where infill loss data is derived [112-114, 117]. The rain that falls on Australian locations can be presumed to generally occur in more intense events, for example the 10 minute, 10% AEP storm for Sydney is forecast to have an intensity of 140 mm/hour while the 10 minute, 10% AEP storm for Stockholm is forecast to have an intensity of 84.1 mm/hour [11, 114]. Finally, Australia has intense UV conditions which may accelerate the degradation of turf fibres beyond the averages for UK fields measured by Sharma et al. (2016) [108].

One preliminary study by Browne and Tedesco (2021) searched for microplastic pollution in Blackman Park, Lane Cove West. Sediment samples were taken from three locations: from the verge near the ST field, in the freshwater ecosystem of the creek near the field, and in the marine ecosystem at the location of the outlet of this creek into the Lane Cove River (see Figure 10). They found material suspected to be rubber infill in terrestrial, freshwater and marine sediments, and found plastic blades suspected to be turf fibres in freshwater and marine sediment samples (results summarised in Table 2) [118]. These results confirm that infill and turf fibre loss and dispersal to aquatic ecosystems is occurring in Australia and indicate that turf fibres may pose more of an issue in aquatic ecosystems. This is likely due to their lower density causing dispersion over greater distances.

Figure 10: Map of sampling location at Blackman Park, taken from Browne and Tedesco (2021)

Table 2: Presence or absence of millimetre sized particles resembling infill and turf fibres in sediment samples taken from Blackman Park from Browne and Tedesco (2021). Particles were tested for thermoplastic behaviour with a hot iron rod and were then exposed to hydrogen peroxide to dissolve any organic matter.

Sample	Assessed with warm iron rod		After exposure to hydrogen peroxide for 24 hours	
	Rubber	Plastic Blade	Rubber	Plastic Blade
Terrestrial 1	**Present**	Absent	Absent	Absent
Terrestrial 2	Absent	Absent	Absent	Absent
Terrestrial 3	**Present**	Absent	Absent	Absent
Freshwater 1	**Present**	Absent	**Present**	Absent
Freshwater 2	**Present**	Absent	Absent	Absent
Freshwater 3	**Present**	**Present**	**Present**	**Present**
Marine 1	Absent	**Present**	Absent	**Present**
Marine 2	**Present**	Absent	Absent	Absent
Marine 3	Absent	**Present**	Absent	**Present**

4.4 Infill migration mitigation

Several mitigation measures to limit the spread of microplastics to the environment are recommended by the ST industry and governing bodies [1, 107]. For the most part, these mitigation strategies have not been studied, or their effectiveness quantified.

The exception to this is Regnell (2018) which quantified the effectiveness of 200 μm filters placed in drains, and of rigorous brushing of maintenance vehicles and players [113]. It was concluded that all transport on players shoes and clothing could be prevented, however, the potential spread without brushing measures in place was quantified by the amount of infill collected at the brush station, hence the calculated "amount of spread prevented" would, by design, always be 100% [113]. It is likely that players (and maintenance vehicles) still retained some infill which was not measured in this study, and this would be especially likely in non-experimental conditions if mitigation is not rigorously enforced. A better experimental design would be to sample infill in the environment (soil, stormwater, etc.) before and after mitigation measures are introduced. The study also tested filters in drains and found that <1% of microplastics detected made it past the filters. This finding is corroborated by Lundström (2018) which quantified the effectiveness of various filter sizes at collecting particles >10 μm, and found >99% of particles were caught in a 200 μm filter. However, this only applies to water entering the drain, not infill which is spread to the wider area and may enter stormwater drains or waterways without mitigation in place.

A number of ST fields in the Sydney area were observed to lack drainage networks immediately surrounding the field, hence microplastic rich runoff could not be filtered before it entered the environment. Furthermore, filters may be less effective in real world instances where the seal may be imperfect, allowing particles to bypass, or clogging and overflow to occur [113, 114].

In conclusion, there is an overall lack of data on the effectiveness of mitigation measures, especially for real world use. Nevertheless, measures have been anecdotally seen to be effective, and the suggested measures will be briefly summarised in the following paragraphs.

4.4.1 Organic infill and fourth generation fields

When infill is present, some migration to the environment is inevitable. Thus, one strategy is to eliminate infill entirely. Fourth generation ST fields are designed to have limited or no infill, however these are not yet recognised by certifying bodies [4].

Alternatively, organic infill, which is non-toxic, may be used. However, organic options are generally more expensive and have reduced performance. Moreover, organics may require use of fungicides, herbicides or antimicrobial treatments which may be hazardous to the environment if infill is spread, although some Australian ST fields infilled with cork do not use any chemical treatments. Additionally, due to the organic materials being lighter, transport by wind and water is more of a problem, hence the infill loss is generally much higher. With either the fourth generation or organic infill option, loss of turf fibres will remain a problem.

4.4.2 Preventing microplastics from leaving fields

The next best solution is to stop infill from leaving the field. Suggestions to prevent this include:

1. A field slope of <0.5% or no slope at all [1, 116].
2. Increasing the amount of UV stabilisers in turf fibres to prevent degradation [4]. However, UV stabilisers such as BTZ may also pose chemical risk [33].
3. Using a shock pad to minimise the amount of infill required [116]. This can reduce infill requirements by 50 to 60% [7]. Having denser turf fibres will also decrease the amount of infill required, but increase potential fibre microplastic spread [4, 107].
4. A fenced field with brush carpets at the field exits to facilitate infill removal from the field users' shoes [1, 12, 107, 116].
5. A raised curb, plinth or lip at least 200 mm above the height of the field to block some of the movement of infill and fibres by splash, movement with surface water runoff, or wind [12, 25, 116]. This has the added benefit of preventing overland flow from the surrounding area washing over the field and transporting infill and means that runoff will be contained if the infiltration rate of the field is exceeded, so long as water levels stay below the height of the curb.
6. Brushing off of maintenance vehicles in a location which can capture infill [25, 116].
7. Avoiding use of leaf blowers to remove leaves or debris from the field. Raking, brushing or a soft sided drag mat can be used instead [116].
8. Reducing exposure during wet conditions when infill transport is highest [104, 105, 113]. Considering that the ability to play in wet conditions is a major advantage of ST fields, it is unlikely that play will be minimised when the field is wet. However, ideally maintenance should be avoided during wet conditions, and this was shown by Regnell (2018) to result in a reduction of infill material on the maintenance vehicle from 24.1 kg to 12.4 kg per brushing session [113].

4.4.3 Preventing microplastics from entering waterways

Once infill or turf fibres have been mobilised from the ST field, a number of strategies are available to prevent them from entering the water network (or the soil) and include:

1. Having a concrete verge around the field perimeter and regularly sweeping it to prevent further mobilisation into the nearby environment [12, 116].
2. Having a local drainage system fitted with suitable filters around the field to ensure the microplastics are not being transported to the wider stormwater system [12, 116]. 200 μm filters are recommended by Regnell (2018) and Lundström (2018) while 400 μm is recommended by Li (2019) [113-115]. FIFA and the European Committee for Standardization recommend a system of two filters, a coarse primary filter to catch intact infill, and a second, finer filter to catch any remaining small particles [12, 116]. Mesh sizes for the respective filters are not specified.
3. A grass verge over which water must flow before reaching any waterways or parts of the stormwater system not equipped with filters. Grass has been anecdotally reported to be effective at preventing the spread of infill in overland flow conditions, and the large amounts of infill accumulated in the sediment profile of the verges observed by Weijer and Knol (2017) support this. Although infill can be considered a pollutant within the grass verge, trapping it there has the advantage of preventing further spread to the wider environment and waterways. However, even a wide verge will not be effective at stopping all infill transport. For example, Figure 11 shows infill transported over several meters of grass verge to a roadside gutter.

Figure 11: SBR Infill (upper half of photo) located in a gutter. SBR infill was mobilised over several metres of grass verge from a Sydney ST field.

4.4.4 Catching ST microplastics in the stormwater system

Rain gardens have been shown to effectively reduce the amount of microplastics in stormwater, proving especially effective on rubber and spherical particles (85.4% removal of microplastics 1.5 to 2 mm and 95.2% removal of microplastics 2 to 2.5 mm in Werbowski et al. (2021) and 92% removal of all microplastics in Smyth et al. (2021)) [96, 119]. However, clogging of a raingarden or biofilter may be an issue with heavy microplastic loads.

Lange et al. (2021) found that GPTs were ineffective at removing tyre wear particles, likely due to their low density decreasing sedimentation rates, although it should be noted that the study focused primarily on particles 0.1 to 0.3 mm, much smaller than the usual size of infill material [95]. Removal of microplastics similar to turf fibres was not explored.

Mobilised infill material or turf blades pose a unique challenge for stormwater treatment devices (GPTs and secondary treatment devices) due to their relatively low density, small size and easy mobilisation in comparison to more common pollutants or sediments typically found in urban runoff. Most stormwater treatment devices do not specifically target these pollutants, and may either not remove them or easily block and fail to function.

As such, it is recommended that proprietary stormwater treatment devices installed around ST fields have their performance independently verified, both in controlled conditions and validated in the field. The only standard that applies to the validation of stormwater treatment devices in Australia (Stormwater Australia's SQIDEP protocol) is not suitable for the assessment of these pollutants, so a suitably experienced and equipped, and independent organisation should assess the performance of proprietary devices

It was reported that constructed wetlands can be effective at removing microplastics, however are most effective when the water passes through the substrate during treatment (providing filtration), as the density of microplastics means they fail to settle efficiently in wetlands relying on horizontal flow rather than infiltration [120, 121]. Sedimentation basins were reported to remove 81% of microplastics by Chen et al. (2021) while vegetated wetlands were reported to remove 28% of microplastics by Pramanik et al. (2020), although both studies focused on particles which are smaller and less dense than infill crumb rubber, but may be similar to turf fibres [122-124]. Ziajahromi et al. (2020) found a floating wetland removed only 47% of microplastics, but was most effective at removing larger microplastics, including tyre wear particles, and was especially effective at removing larger particles >0.5 mm (which would include crumb rubber infill) [125].

Wastewater treatment plants have also been proven effective at removing microplastics, despite not being designed for this purpose, with Sun et al. (2019) showing the removal of >97% of microplastics in plants with tertiary treatment [120, 123, 126, 127].

4.5 Summary and research needs

Review of the available literature indicates that a wide range of loss rates for various pathways have been measured or estimated [5, 92, 104, 105, 109, 111-115, 128, 129]. Figure 12 Figure 13 show schematics of the estimates for infill mass balances based on literature reviews [104, 105]. The relatively large variability in infill loss values can be attributed to the sparse data, practical challenges in conducting measurements and variability in loss from different fields.

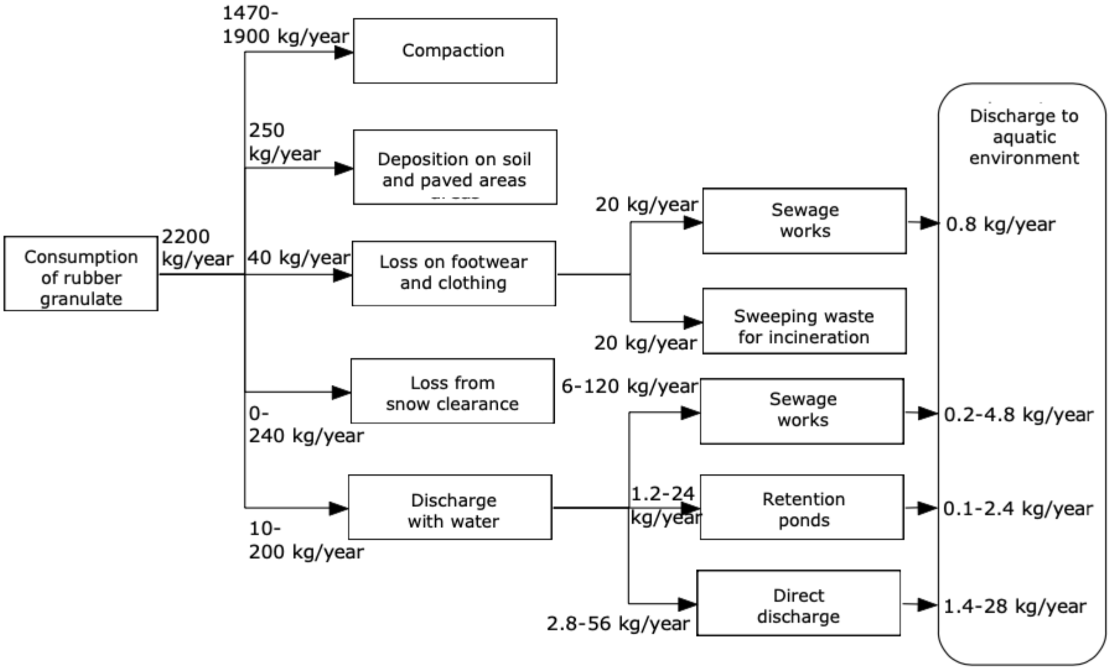

Figure 12: Schematic of infill loss estimated for Dutch conditions created by DTI (2018) based on a literature review

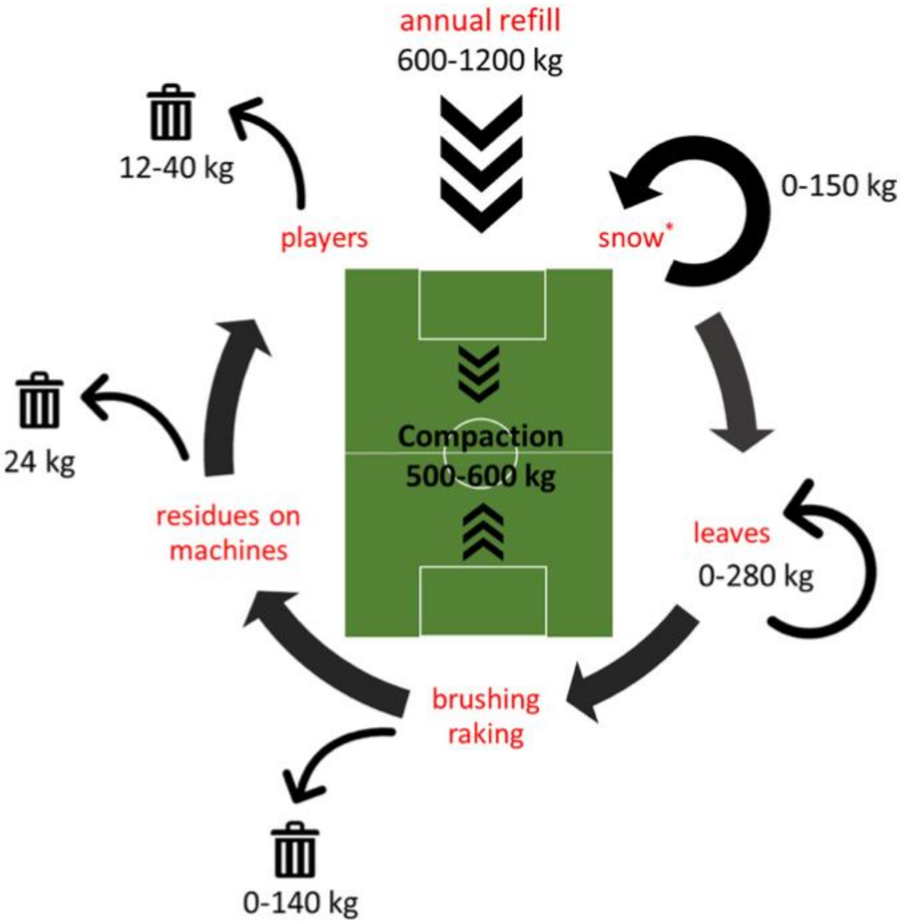

Figure 13: Schematic of infill loss estimated for European conditions created by Verschoor et al. (2021) based on a literature review

As ST sites have different construction processes, layout and mitigation systems in place, and are exposed to a wide range of climatic conditions, the amount of infill lost, and the sinks in which it is lost to, can be expected to vary significantly. Thus, quantification, though it may help to provide an idea of the possible scope of the problem, is currently insufficient to provide any determination on the extent of environmental pollution caused by any one ST field, especially considering the lack of data specific to the Australian environment.

As compaction is likely to be similar regardless of climate (being mainly controlled by maintenance regimes) and reported infill top up rates generally align with the European data, the same total flux to the environment (100s of kilograms) can be generally applied to Australian fields. However, due to variability between sites, the amount of infill ending up in water networks (rather than soil, or removal by maintenance) is likely to vary widely (as was observed in the literature).

Most of the mass balance studies on microplastic loss to sinks originate from Northern European countries with very different weather conditions and maintenance regimes from ST fields in Australia. As such, it would be beneficial for a similar study to the Dutch study by Weijer and Knol (2017) to be conducted in NSW or Australia, to better estimate the infill loss process from Australian ST fields.

It is recommended that such a study (or studies) be designed to test a range of ST field layouts or designs (including potential mitigation measures) as these will have a significant influence on overall microplastic migration and loss. The study should compare different fields, or measure migration before and after mitigation measures are implemented around a ST field. This contribution to the literature would be valuable, as it may lead to conclusions which are generalisable between fields of similar layouts. This would enable identification of which ST fields may be most problematic, in addition to providing a robust assessment of the best mitigation measures which could minimise environmental impact.

In the absence of Australian specific data, it can be reasonably estimated that around 10 to 100 kg of infill per year is likely to be transported to the stormwater system or waterways for a ST field with no strategies to reduce infill migration in place. The amount of turf fibres lost from a ST field per year is likely to be in the 100s of kilograms per year, however this type of loss from ST field is far less studied, and no estimates of transport into water networks currently exists. Due to the lower density of the turf fibres and hence higher mobility, they may pose a greater pollution risk for aquatic environments than infill.

The lack of data on fibre loss is a major gap in the literature, and the potential for quite large volumes of fibre loss highlight that switching to organic infill will not remove plastic pollution risk from ST fields, and that mitigation measures will still be needed in the future. Moreover, current mitigation measures may need to be modified to better prevent fibre transport, as ST turf fibres are more transportable by both wind and water. For example, curbs may need to be higher than 200 mm, or fences may need to be solid rather than chain link.

Controlled laboratory testing of the mobility of the microplastic pollution sourced from a range of ST fields (SBR, EPDM and TPE infill, turf fibres and turf fibre fragments) in runoff over various surfaces (concrete, grass, ST field) could help quantify the relative risk of transport of these particles. Notably, virgin infill such as EPDM and TPE may pose a larger environmental threat due to increased mobility, an issue which has been largely overlooked. Additionally, loss of microplastics (both infill and fibres) during field installation and decommissioning has not been investigated, and may be substantial when compared to loss during lifetime. Hence, future research into these three areas (loss of turf fibres, water runoff transport of ST microplastics and loss during installation and decommissioning) is recommended.

5. Conclusions

Most ST fields in NSW are likely to have some negative impacts on the aquatic environment. However, these impacts (especially the risk of chemical leaching) appear to not be as threatening as some sources suggest. Moreover, mitigation strategies have the potential to reduce some of the leaching of toxicants and microplastic transport from ST fields. It is understood that a number of ST fields in NSW are reaching their end-of-life, creating an opportunity to install improved ST fields with better mitigation measures to treat stormwater and trap microplastics.

Replacement of SBR with virgin rubber infill (EPDM and TPE) or organic options is sometimes viewed as a solution to the risk of leaching of toxicants and transport of damaging microplastics to the environment. However, EPDM and TPE pose their own (under-researched) toxicant risk profile and being less dense, are more likely to be mobilised in runoff and lost to the environment. Moreover, the entire ST system poses a toxicant risk, and turf fibres are also a large source of microplastic pollution in the environment. Thus, replacement of SBR infill (even with organic infill) in the future is not expected to fully solve pollution problems associated with ST fields. SBR, given its low cost and recycling benefits, is likely a good option for many fields, provided effective mitigation measures, and possibly toxicant monitoring, are in place, especially for ST fields near sensitive ecosystems (to be determined using an effects based assessment).

The hydrologic implications of ST fields are not well documented in the literature; however, it appears that vertically draining fields have the potential to be used as stormwater management devices, especially if they are intentionally designed for this purpose. This is an exciting possibility and highlights the need to consider the risks and opportunities of ST fields as more than just sporting facilities but useful elements of WSUD. It is also important to consider the nuances of ST fields in determining the location of future fields, as ST fields are susceptible to different risks from flooding.

Our knowledge of ST fields, especially in terms of their hydrology and the effectiveness of microplastic migration mitigation strategies, would benefit from further studies, and especially from studies applicable to the Australian environment. The ST industry likely already possesses significant research and data in this area, hence a system where this information can be shared without compromising competitiveness between companies would be desirable. Academic research can also play a role in furthering knowledge of the effects of ST fields, especially to correct potential bias from industry.

It is recommended that all new ST fields, or existing ST fields undergoing replacement, are constructed with minimal slope and to be fitted with a surrounding curb of at least 200 mm height. Furthermore, these fields should be designed such that all runoff from the surrounding concrete verge flows to local drains in which filters are placed, to avoid unnecessary microplastic rich runoff entering the wider stormwater system. Although there is very limited data on the effectiveness of infill mitigation options, common sense and experience with Sydney ST fields shows that these measures will reduce a large amount of infill loss to water networks.

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Appendix A Table of toxicant leaching

Legend

	test within material
	leachate batch test
	leachate column test
	runoff (natural or simulated) from a ST field
	groundwater test

Authors	Title	Year	Component	Test Type	Units	Field Age (years)	Location	No. of fie' sar
ANZECC	95% of species protected	2000	Freshwater Guidelines		ug/L			
ANZECC	80% of species protected	2000	Freshwater Guidelines		ug/L			
EPA	Chronic	2022	Freshwater Guidelines		ug/L			
EPA	Acute	2022	Freshwater Guidelines		ug/L			
Plesser	Potential health and environmental ef	2004	SBR	in material	mg/kg	new	Norway	1
Plesser	Potential health and environmental ef	2004	SBR	leachate	ug/L	new	Norway	1
Plesser	Potential health and environmental ef	2004	Polyethylene turf fibers	in material	mg/kg	new	Norway	1
Plesser	Potential health and environmental ef	2004	Polyethylene/polypropylene tur	in material	mg/kg	new	Norway	1
Plesser	Potential health and environmental ef	2004	SBR	in material	mg/kg	new	Norway	2
Plesser	Potential health and environmental ef	2004	EPDM	in material	mg/kg	new	Norway	1
Plesser	Potential health and environmental ef	2004	SBR	leachate	ug/L	new	Norway	2
Plesser	Potential health and environmental ef	2004	EPDM	leachate	ug/L	new	Norway	1
Plesser	Potential health and environmental ef	2004	Polyethylene turf fibers	leachate	ug/L	new	Norway	1
Plesser	Potential health and environmental ef	2004	Polyethylene/polypropylene tur	leachate	ug/L	new	Norway	1
Bocca	Metals contained and leached from ru	2009	SBR	leachate	ug/L	varies	Italy	32
Lim	An Assessment of Chemical Leachin	2009	SBR	column test	ug/L	varies	USA	31
Lim	An Assessment of Chemical Leachin	2009	SBR	leachate	ug/L	varies	USA	31
Lim	An Assessment of Chemical Leachin	2009	SBR	groundwater	ug/L	<1-7	USA	4
Lim	An Assessment of Chemical Leachin	2009	SBR	runoff (natural)	ug/L	1	USA	1
CDEP	Artificial Turf Study - Leachate and S	2010	SBR	runoff (natural)	ug/L	2-4	USA	4
Gomes	Toxicological assessment of coated	2010	SBR	leachate	ug/L	new	Portugal	1
Gomes	Toxicological assessment of coated	2010	Coated SBR	leachate	ug/L	new	Portugal	1
Gomes	Toxicological assessment of coated	2010	Coated SBR	leachate	ug/L	new	Portugal	1
Li	Characterization of substances relea	2010	SBR	leachate	ug/L	varies	USA	13
Gomes	Design of a new test chamber for eva	2011	SBR	leachate	ug/L	new	Portugal	1
Van Ulirsch	Evaluating and regulating lead in syn	2010	Polyethlyene turf fibers	in material	mg/kg	3-9	USA	17
Van Ulirsch	Evaluating and regulating lead in syn	2010	Nylon turf fibers	in material	mg/kg	4-12	USA	18
Van Ulirsch	Evaluating and regulating lead in syn	2010	Nylon/polyethylene fibres	in material	mg/kg	6-10	USA	5
Menichi	Artificial-turf playing fields: contents	2011	SBR	in material	mg/kg	not specifed	Italy	4
Menichi	Artificial-turf playing fields: contents	2011	TPE	in material	mg/kg	not specifed	Italy	2
Menichi	Artificial-turf playing fields: contents	2011	Coated SBR	in material	mg/kg	not specifed	Italy	2
Kruger	Comparison of batch and column tes	2012	SBR	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	Coated SBR	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	EPDM	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	TPE	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	Sand	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	Turf fibers	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	gravel	leachate	ug/L	new	Germany	1
Kruger	Comparison of batch and column tes	2012	Elastic bound layer	leachate	ug/L	new	Germany	1
Kalbe	Development of Leaching Procedures	2013	SBR	leachate	ug/L	new	Norway	1
Kruger	New approach to the ecotoxicologica	2013	Elastic bound layer	leachate	ug/L	new	Germany	1
Kruger	New approach to the ecotoxicologica	2013	SBR	leachate	ug/L	new	Germany	8
Kruger	New approach to the ecotoxicologica	2013	EPDM	leachate	ug/L	new	Germany	3
Kruger	New approach to the ecotoxicologica	2013	Column with SBR, shockpad, sand and ST mat	column test	ug/L	new	Germany	1
Kruger	New approach to the ecotoxicologica	2013	Column with EPDM, shockpad, sand and ST mat	column test	ug/L	new	Germany	1
Kruger	New approach to the ecotoxicologica	2013	Column with TPE, shockpad, sand and ST mat	column test	ug/L	new	Germany	1
Kruger	New approach to the ecotoxicologica	2013	Column with coated SBR, shockpad, sand and ST mat	column test	ug/L	new	Germany	1
Ruffino	Environmental-sanitary risk analysis	2013	SBR	leachate	ug/L	1.5	Italy	1
Ruffino	Environmental-sanitary risk analysis	2013	SBR	leachate	ug/L	1.5	Italy	1
Ruffino	Environmental-sanitary risk analysis	2013	TPE	leachate	ug/L	3	Italy	1
Ruffino	Environmental-sanitary risk analysis	2013	SBR	leachate	ug/L	3	Italy	1
Ruffino	Environmental-sanitary risk analysis	2013	SBR	leachate	ug/L	3	Italy	1
Ruffino	Environmental-sanitary risk analysis	2013	Natural grass	leachate	ug/L		Italy	1
Canepari	Release of particles, organic compou	2018	SBR	leachate	ug/L	new	Italy	1
Canepari	Release of particles, organic compou	2018	TPE	leachate	ug/L	new	Italy	1
Celerio	Determination of priority and other ha	2018	SBR	runoff (natural)	ug/L	new	Spain	2
Clayton	Copper and Zinc Concentrations from	2018	SBR	runoff (natural)	ug/L	0-2	New Zealand	1
Magnussun	Assessment of environmental impact	2018	SBR	infiltrate	ug/L	0-2	Sweden	8
Magnussun	Assessment of environmental impact	2018	EPDM	infiltrate	ug/L	0-2	Sweden	5
Postma	Rubber Granulate on Synthetic Turf F	2018	SBR	runoff (natural)	ug/L	0-28	Netherlands	8
Postma	Rubber Granulate on Synthetic Turf F	2018	Natural grass	runoff (natural)	ug/L	not specifed	Netherlands	8
Halsba	Car Tire Crumb Rubber: Does Leachi	2020	SBR	leachate	ug/L	new	Norway	1
Halsba	Car Tire Crumb Rubber: Does Leachi	2020	SBR	leachate	ug/L	not specifed	Norway	1
Halsba	Car Tire Crumb Rubber: Does Leachi	2020	SBR	leachate	ug/L	new	Norway	1
Halsba	Car Tire Crumb Rubber: Does Leachi	2020	SBR	leachate	ug/L	not specifed	Norway	1
Celerio	Evaluation of chemicals of environme	2021	SBR	runoff (simulated)	ug/L	varies	Portugal	8
Celerio	Evaluation of chemicals of environme	2021	SBR	in material	mg/kg	varies	Portugal	8
Celerio	Evaluation of chemicals of environme	2021	SBR	in material	mg/kg	varies	Portugal	8
Celerio	Evaluation of chemicals of environme	2021	SBR	runoff (natural)	ug/L	varies	Portugal	4
Zhang	Distribution and Health Risk Assessn	2021	SBR	runoff (natural)	ug/L	not specifed	China	1
Armada	Global evaluation of the chemical haz	2022	SBR	in material	mg/kg	varies	Global	78

Authors	Statistic	Comments	pH	Zn	Zn range	Pb	Pb range	Cr
ANZECC				8		3.4		1(CrVI)
ANZECC				31		9.4		40(CrVI)
EPA				90		2.5		11(CrIV)
EPA				120		65		16
Plesser	single measurement			17000		17		<2
Plesser	single measurement	lower leachant pH	7.54	590				-
Plesser	single measurement			3100		<2		<2
Plesser	single measurement			3300		<2		<2
Plesser	single measurement	coarse and fine grained		7400	7300-7500	18	15-20	<2
Plesser	single measurement			9500		8		<2
Plesser	single measurement	coarse and fine grained, also did test at lower p	7.7	1755	1220-2290			-
Plesser	single measurement		11.36	80				<2
Plesser	single measurement		7.12	1000				-
Plesser	single measurement		6.95	860				-
Bocca	median	lechant at pH 5		2300	2-62,120	1.6	<LOQ-6	0.9
Lim	mean	ph 4.2 lechant used		292				
Lim	mean	ph 4.2 lechant used		1947		12.8		<10
Lim	mean							
Lim	single measurement			59.5		1.7		2.2
CDEP	mean		6.6-8	84	10-260			
Gomes	single measurement	close to LOQs, possibly not peer reviewd		6900		3		3
Gomes	single measurement	coating R1, close to LOQs, possibly not peer reviewed		1700		3		<1
Gomes	single measurement	coating R2, close to LOQs, possibly not peer reviewed		3000		19		2
Li	median	acidfied lechant		2200	220-3600	0.19	0.05-3.5	0.14
Gomes	single measurement			6900		3		3
Van Ulirsch	median					1.7	:0.92-1,500	
Van Ulirsch	median					4300	36-8900	
Van Ulirsch	median					94	25-1100	
Menichi	mean			407	10229-17772	21	12-26	2.28
Menichi	mean			3465	118-6813	45	43-46	53
Menichi	mean			10219	1063-19375	16	<0.7-28	31.1
Kruger	median		6.76-7.49	1430	129000-690			
Kruger	median		8.13	80				
Kruger	median		7.8-9.63	750	1050-200			
Kruger	median		7.48-8.5	<30				
Kruger	median		6.37-7.04	70	60-110			
Kruger	median		7.67-7.82	450	440-460			
Kruger	median		7.9-9.04	<30	<30-60			
Kruger	median		6.59	230	200-10000			
Kalbe	single measurement	leachate prepared as synthetic rain water	6.67	6050				
Kruger	median		6.59	7350				
Kruger	median		7.03	3700				
Kruger	median		9.57	580				
Kruger	median		5.72	480				
Kruger	median		4.49	350				
Kruger	median		4.46	310				
Kruger	median		7.33	<30				
Ruffino	single measurement	only 8 PAHs measured	6.63	1141		<4.2		<0.71
Ruffino	single measurement	only 8 PAHs measured	6.63	1525		<4.2		
Ruffino	single measurement	only 8 PAHs measured	7.36	452		<4.2		
Ruffino	single measurement	only 8 PAHs measured	6.51	1530		<4.2		
Ruffino	single measurement	only 8 PAHs measured	6.41	2729		<4.2		
Ruffino	single measurement	only 8 PAHs measured	9.86	<0.18				
Canepari	single measurement	also has in rubber granules, pH of 3 for lechant		5000		13.2		1
Canepari	single measurement	also has in rubber granules, pH of 3 for lechant		<LOQ		0.2		0.092
Celerio	single measurement	different kinds of samples, also did column tests						
Clayton	median	has data over the course of rainfall events		9.29	0.84-3492			
Magnussun	median	infiltrate from a lysmeter under field		2.95	1.4-8.5	<0.1	<0.05-0.31	<0.2
Magnussun	median	infiltrate from a lysmeter under field		17.5	2.4-83	<0.05	<0.05-0.39	<0.2
Postma	median			<10	<10-3800			
Postma	median			<10	<10-42			
Halsba	single measurement	100g/L seawater leachant		8400		3.8		4.5
Halsba	single measurement	100g/L seawater leachant		22400		7.3		5.8
Halsba	single measurement	1g/L seawater leachant		1900		1.6		3.7
Halsba	single measurement	1g/L seawater leachant		2100		1.7		4
Celerio	median							
Celerio	median	outdoors						
Celerio	median	indoors						
Celerio	median							
Zhang	mean			1696.91	362-4888	485.92	109-2182	111
Armada	median							

Authors	Cr Range	Cd	Cd Rang	As	As Range	Cu	Cu Range	Al	Al Range	PAH	PAH Range	BTZ
ANZECC		0.2		24		1.4		55 (pH>6.5)		16 Naphthalene		
ANZECC		0.8		360		2.5		150 (pH>6.5)		85 Naphthalene		
EPA		0.72		150		-		-				
EPA		1.8		340		-		-				
Plesser		2		<2		70				76		
Plesser												
Plesser		<0.1		<3		59				<1		
Plesser		<0.1		<2		68				<2		
Plesser		1		<3		29	20-35			63	51-74	
Plesser		<0.5		<2		<3				1		
Plesser										0.66	0.44-0.87	
Plesser												
Plesser												
Plesser												
Bocca	0.2-10	0.2	<LOQ-2.4	0.12	<LOQ-2.4	2.2	0.2-216	67	2-3940			
Lim												215.3
Lim		<5		<10		296.3		<100		1.4		526.3
Lim										<5		<0.83
Lim		<0.35		<1.8		5.4				<5		
CDEP						3.2	1.5-5	108	25-210			0.153
Gomes		1										
Gomes		1										
Gomes		<1										
Li	nd-0.19	n.d	nd	nd	ND-0.14	0.84	0.28-7.2					0.155
Gomes		1										
Van Ulirsch												
Van Ulirsch												
Van Ulirsch												
Menichi	<0.3-4.6	1.3	0.62-1.9	0.19	0.1-0.41	16.7	8.7-22	407	164-755	19.4	7.25-45.1	
Menichi	49-56	0.24	0.11-0.37	0.54	0.14-0.94	27.91	0.82-55	3341	1.2-6680	1.86	0.04-3.67	
Menichi	6.2-56	1.01	0.12-1.9	0.18	0.12-0.24	36	12-60	759	490-1028	15.2	1.9-28.5	
Kruger										1.29	0.41-1.49	
Kruger										1.18		
Kruger										0.21	0.2-0.93	
Kruger										0.11	0.1-0.52	
Kruger										0.23	0.14-3.41	
Kruger										1.14	0.86-1.42	
Kruger										0.75	0.28-1.24	
Kruger										0.4	0.07-0.74	
Kalbe												
Kruger										0.52		
Kruger										0.68		
Kruger										0.21		
Kruger										not determined		
Kruger										1.36		
Kruger										1.44		
Kruger										1.6		
Ruffino				<5.3						0.09		
Ruffino				<5.3						0.15		
Ruffino										0.18		
Ruffino										0.07		
Ruffino										0.03		
Ruffino										<0.001		
Canepari		0.4		<LOQ		48						
Canepari		<LOQ		<LOQ		<LOQ						
Celerio										~1		120
Clayton						7.22	0.33-635					
Magnussun	<0.2-0.29			0.97	0.37-1.6	6.9	4.1-11			<0.02	<0.02-0.025	
Magnussun	<0.2-0.32			0.82	<0.2-1.6	2.1	0.39-3.8			<0.3	<0.3	
Postma				5.9	<5-61					0.03285	0.0152-0.1565	
Postma				<5	<5-7.8					0.03805	0.0109-0.1785	
Halsba		2.2				49				4.4		1693
Halsba		0.6				39				2.8		126
Halsba		<0.2				34				3.3		80
Halsba		<0.2				28				5		27
Celerio										1	0.3-3.3	1.5
Celerio										17	6-54	2.8
Celerio										53	28-57	11
Celerio										0.6	0.2-1.5	11
Zhang	28-471	9.6	2-51	13.22	1.72-44.48	102.99	9.61-368.39					
Armada										17	0.81-230	5.5

Authors	BTZ range	total PCB	PCB range	DEP	DEP range	DBT	DBT range	DEHP	DEHP range
ANZECC		<2 recomended for fre		900		9.9		insufficent data	
ANZECC		<2 recomended for fre		1100		40.2		insufficent data	
EPA									
EPA									
Plesser		0.404		<1		3.9		29	
Plesser		<0.08							
Plesser		<0.147		<1		<1		1.7	
Plesser		<0.147		<1		1		8	
Plesser		<0.52		<1		3.4		21	21
Plesser		<0.52		1.5		1.6		3.9	
Plesser				7.45	6.6-8.3	2.7	2.1-3.3	5.4	5.1-5.6
Plesser									
Plesser									
Plesser									
Bocca									
Lim									
Lim									
Lim									
Lim									
CDEP	0-0.268								
Gomes									
Gomes									
Gomes									
Li	nd-0.26								
Gomes									
Van Ulirsch									
Van Ulirsch									
Van Ulirsch									
Menichi		0.18							
Menichi									
Menichi									
Kruger									
Kruger									
Kruger									
Kruger									
Kruger									
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Kruger									
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Kalbe									
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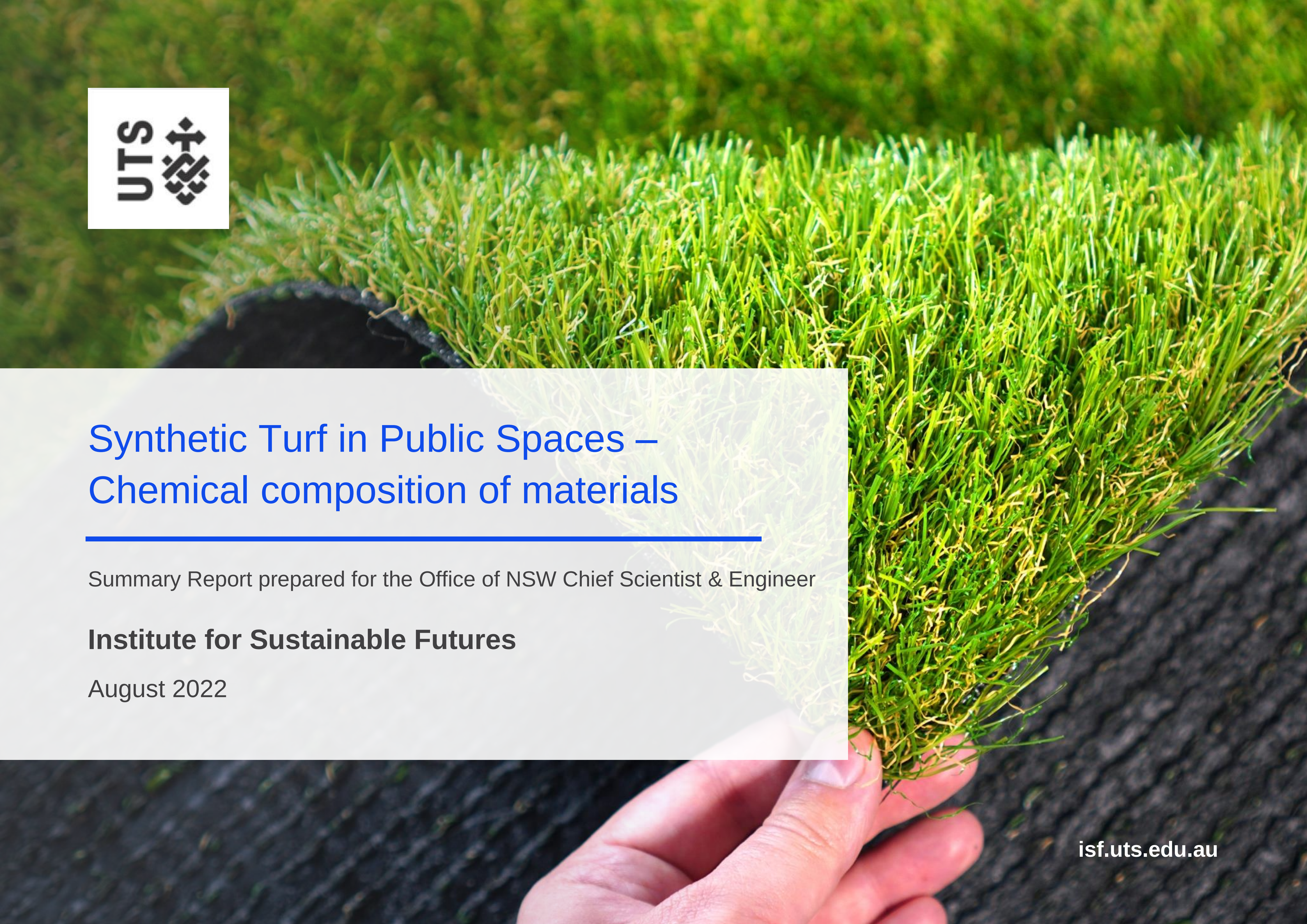
Kruger									
Kruger									
Ruffino									
Ruffino									
Ruffino									
Ruffino									
Ruffino									
Ruffino									
Canepari									
Canepari									
Celerio									
Clayton									
Magnussun									
Magnussun									
Postma		0.0001	0-0.0002						
Postma		0.0001	0-0.0003						
Halsba									
Halsba									
Halsba									
Halsba									
Celerio	0.7-9.4			0.34	0.2-0.5	0.19	0.02-0.52	0.023	0.02-0.06
Celerio	1.2-62			0.083	0.03-0.70	0.69	0.1-11	19	6.2-59
Celerio	5.4-26			0.5	0.1-3.8	4.3	0.8-14	39	12-173
Celerio	9-13			0.49	0.1-1.5	0.15	0.04-0.6	0.019	0.01-0.04
Zhang									
Armada	0.03-36			0.42	0.05-12	1.5	0.13-56	28	0.9-9470

Appendix 5

Synthetic Turf in Public Spaces – Chemical composition of materials



Synthetic Turf in Public Spaces – Chemical composition of materials

Summary Report prepared for the Office of NSW Chief Scientist & Engineer

Institute for Sustainable Futures

August 2022

isf.uts.edu.au

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About the authors

The **Institute for Sustainable Futures (ISF)** is a transdisciplinary research and policy institute at the University of Technology Sydney with over 100 research staff and students. Since 1997, ISF has been working collaboratively with governments, businesses, organisations and communities to create change towards sustainable futures. Our work in Australia and around the world aims to protect and enhance the environment, human wellbeing and social equity. We do this by developing transformative ideas into strategies that deliver impact and have a strong record of achievement in advancing circular economy and resource stewardship initiatives.

Disclaimer

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Contents

1. Components and properties of materials used in the manufacture and installation of synthetic turf sports fields

1.1 Objectives of this report

This document has been prepared on behalf of the NSW Office of the Chief Scientist & Engineer to investigate the components and properties of materials used in the manufacturing and installation of synthetic turf sports fields. In addition, this report aims to provide advice on relevant standards, degradation characteristics, opportunities for reuse and recycling and relevance of product stewardship schemes. The final section highlights key knowledge gaps.

1.2 Introduction to synthetic turf

The materials used in synthetic turf have evolved significantly since they were first developed in 1960s (DPCD, 2011). Changes in materials and composition have largely been made to address usability, sport players' wellbeing and environmental impacts. The first generation of turf that attempted to simulate the conditions of natural grass used a high-density knitted nylon product nicknamed "Astroturf" (DPCD, 2011). This first generation was not popular and in the second generation it was improved by replacing abrasive nylon with softer polypropylene fibres. Second generation turfs were also filled with sand providing better stability and enabling better control of balls (DPCD, 2011). Although these fields were popular for community soccer, at the top level of soccer the ball was bouncing too high, and the player footing was not reliable enough. While these types of fields were ideal for hockey, it required further development for professional soccer (Smart Connection Consultancy, 2021). The third generation of synthetic turf was then developed with the adoption of softer polyethylene fibre and the ability of the surface to take a normal stud used in soccer and rugby (Smart Connection Consultancy, 2021). A typical third generation synthetic turf components, most commonly installed in Australia, include synthetic turf carpet (including yarn), infill (performance infill and stabilising infill), backing (primary and secondary backing), sometimes shock pad (either in-situ, foam or prefabricated) and base (pavement, sub-base and drainage components). These third-generation systems also heavily rely on strong and consistent maintenance as specified by the manufacturer. Maintenance is required to maintain designed performance and safety characteristics (Jastifer, et al., 2019).

Table 1 summarises the main characteristics including the materials and components of the three generations of the synthetic turfs. Characteristics of synthetic turfs that have evolved for specific sports are summarised in Table 2.

A **fourth generation**, currently being developed, has evolved from the third generation with performance characteristics tailored for specific sports but also with the aim to remove the need for rubber crumb infill (DPCD, 2011). Table 2 highlights the broad range of different constructions, materials and components. Adhesive, in prefabricated rolls or in liquid form (described briefly later in the report), is used to glue together the turf carpet with the base. An estimate of the volume of materials is provided in Table 7.

Hybrid surface fields are fields where natural turf is:

- supported by **mat, carpet or grid backing** (similar to those used in synthetic turfs) with natural turf growing from the mat;
- where natural turf is **permanently stitched** (injected) with synthetic fibres;
- synthetic turf in **small specific areas**, where sport's fields have more use, for example at the goal mouth.

Some of the big stadiums around the world apply the hybrid mat system, including a few of the bigger stadiums in Australia. The permanent stitching system is less common due to costs and maintenance challenges. At the community level however, hybrid grass installations are installed in high wear areas, goal squares, centre bounces, soccer boxes, linesman runs and cricket run-ups (Smart Connection Consultancy, 2021).

Table 1: Summary of the characteristics, including materials and components of 1st, 2nd and 3rd generation synthetic turf. Information source: synthetic turf suppliers and literature referenced in the report. Image source: (DPCD, 2011)

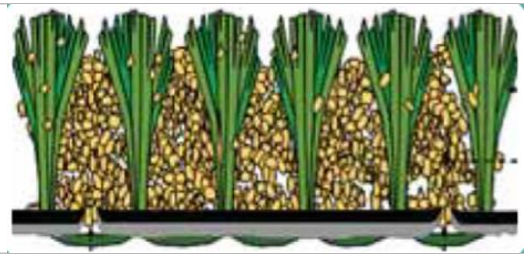
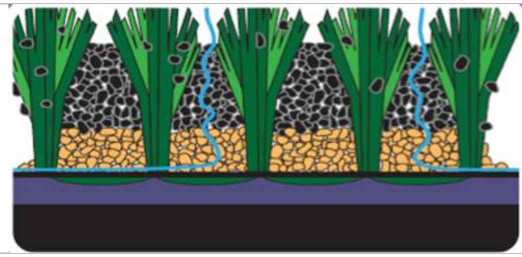
	1st Generation	**2nd Generation**	**3rd Generation**
			
Timeline	Developed in 1960s, used for hockey at the 1976 Montreal Olympics	Developed in late 1970s, UK professional soccer, banned 1980s for being unplayable	Developed late 1990s
Characteristics	• Unfilled, hard, abrasive • Issues with dyes used for fibres • Fibres susceptible to UV degradation	• Better stability, less bounce • Fibres more durable	• Softer • Ability of surface to take a normal stud (suitable for soccer and rugby union)
Turf fibre	• Short pile (10-12 mm) • Nylon (polyamide) fibres	• Medium pile (20-35 mm) • Monofilament or fibrillated polypropylene fibres	• Longer piles (40-65 mm, 65 mm for rugby union) • Monofilament/fibrillated polyethylene or polypropylene fibres
Infill	• Unfilled	• Infilled with rounded sand	• Infilled with sand or rubber granules or mixture of sand and recycled rubber granules, or other material
Backing	• Foam backing	• Carpet backing with drainage holes	• Primary backing cloth from woven polypropylene or urethane • Anchored with a latex-based secondary backing material
Shock pad	n/a	• Initially no shock pad	• Shock pad normally included but not always
Base	n/a	n/a	• Asphalt • Natural subgrade • Geotextile • Drainage system • Leveling layer

Table 2: Summary of characteristics of 3rd and 4th generation synthetic turfs tailored for specific sport use. Information source: synthetic turf suppliers and literature referenced in the report.

3rd & 4th Generation	Description	Turf fibre	Infill	Backing	Shock pad	Base
AFL	Sand dressed polyethylene carpets	Polyethylene with longer pile (40-60 mm)	Rounded sand grains or crumbed rubber infill (20 mm)	Polypropylene	20 mm preformed shock pad (polyurethane)	
Athletics	Permeable or non-permeable construction, including: • In-situ resin bound rubber crumb system (structural spray) • In-situ composite (sandwich) • In-situ cast elastomer (full polyurethane rigid foam (PUR)) • Prefabricated sheet synthetic surface	Super long pile (80-85 mm)	Deep infill (60 mm)	n/a	Included in construction	Rubber granules/fibres and elastomer, poured out in-situ, prefabricated or cast
Bowls	Sand filled or sand dressed synthetic turf Woven carpet (tensioned) or needle punch carpet	Piles (13-15 mm) Needle punch surface includes also an under felt	Sand	Polypropylene	Sometimes included (with carpets)	Stone base
Cricket	Carpet glued to concrete base or polyethylene carpet	Polyethylene short dense pile (8-12 mm) or longer pile (40-60 mm)	No infill	Polypropylene	Included especially when ground is shared with AFL	Concrete base
Football	Variation on 3rd Gen.	Mix of monofilament, textured fibres of varying length 40-60 mm	Rounded sand grains or crumbed rubber infill (20 mm)	Primary backing: polypropylene Secondary backing: Polyurethane	Not included with SBR but included with EPDM, TPE or organic infills (polyurethane)	
Hockey	Variation on the 2nd Gen. sand filled pitches. • Filled, • dressed and • water-based surfaces.	• Short dense nylon fibres (8-12 mm) for wet dressed • Medium polyethylene, polypropylene (20-35 mm) for sand dressed	• No infill (water based) • Dressed with sand only with medium pile • Hybrid (water and sand)	n/a	Shock pad (hot mix of rubber shreds/crumbs bound with polyurethane set in situ)	

3rd & 4th Generation	Description	Turf fibre	Infill	Backing	Shock pad	Base
Oztag/Touch		Short dense pile	Sand only			
Rugby League	Variation on 3rd Gen. Mix of monofilament, textured fibres of variable lengths without infill	Longer pile (40-65 mm) Polyethylene mono-filament yarn	Rounded sand grains (stabilising infill) and crumbed rubber performance infill (20 mm)	Carpet backing	Shock pad	Asphalt layer Sub-base stone Geotextile layer
Rugby Union	Variation on 3rd Gen. Mix of monofilament, textured fibres of variable lengths without infill	Longer pile (40-62 mm)	Rounded sand grains or crumbed rubber infill (20 mm)	Carpet backing	Shock pad	

Maintenance of synthetic turfs

Synthetic turfs require regular maintenance following the manufacturer specifications. Maintenance techniques include grooming, cleaning, decompaction and infill top-ups (Fleming, et al., 2020).

Standard maintenance includes raising matted-down fibres by brooming and raking. The frequency of these maintenance operations varies but may be required as frequently as weekly on surfaces with daily use.

Compaction has been found to be a problem on synthetic turf infills and brooming and raking can also serve the purpose of loosening the top layer of the infill material. To loosen the infill to a greater depth, other special devices are used a few times per year (Jastifer, et al., 2019). However, some of the infill gets lost during the maintenance process as well as in use owing to the infill material adhering to players clothing and equipment and due to environmental factors (e.g., wind, flooding). Nevertheless, as Dickson et al (2020) observed, there is a greater loss of infill in non-maintained turfs compared to the regularly maintained. Therefore, the infill depth needs to be routinely monitored and maintained to the manufacturer specifications. While following manufacturer's recommendations in terms of frequency is considered best practice, Dickson et al. (2020) observed that the recommended routine by manufacturers has not necessarily developed on scientific findings. Furthermore, the authors recommended investigation on combinations of maintenance techniques to better understand how consistent maintenance increases the performance and lifespan of the turf.

Debris, litter, and leaves, need to be regularly removed to maintain drainage and to minimise growth of algae and moss. Nevertheless, most of synthetic turf manufacturers recommend in their maintenance guidelines to apply a moss/weed killer (which can be water-based systematic weed killer) once per year (FieldTurf, 2020).

Bodily fluids are also of concern, and it is recommended that are either diluted with water and flushed from the surface or treated with antibacterial solutions. Laundry detergent and ultraviolet light might be comparatively effective (Jastifer, et al., 2019).

Regular maintenance ensures the synthetic turf performance in relation to playability, player safety and lifespan.

1.3 Description of the chemical composition and properties of key components and materials

Table 3 provides an overview of the materials that are generally used for the main components (third and fourth generation) including: a high-level description of the likely manufacturing processes, the main performance characteristics of the components and materials when in use, as well as some possible disposal options at end-of-life.

Table 3: Main materials used in the synthetic turfs (3rd and 4th Generation). Source: collected information from synthetic turf suppliers and literature referenced in the report.

	Materials	Manufacturing processes	Components and materials performance characteristics when in use	Disposal at end of life
Pile	Polyethylene Polypropylene Nylon Colour pigments	Polymers that come in small bead form are melted using a combination of heat and pressure before they are extruded into shape that replicates natural grass blades. During the melting and extrusion phase pigments and UV additives are added. Also, other additives stabilising the polymers are added (e.g., antioxidants and acid scavengers)	Piles give the grass feel and look	Disposed to landfill, repurposed for other applications, e.g. cut in smaller pieces and used in private setting, recycling processes being developed.
Primary Backing	Polypropylene Urethane	Backing is a non-woven textiles normally manufactured from polypropylene. It is a layer on which fibres are sewn.	Backing material gives the synthetic grass structure, and holds everything together.	Landfill, recycling processes being developed
Secondary Backing	Polyurethane Latex	Polyurethane is coated on the back of primary backing and then perforated for drainage purposes.	For drainage purposes.	Landfill, recycling processes being developed
Stabilising Infill	Silica sand	Mined from gravel pits, sometimes coated with an elastomeric or acrylic coating	Chemically stable, fracture resistant, non-toxic and rounded. Does not get very hot from heat absorption from sun Hard and abrasive, prone to compaction, can generate dust	Reused Can be recycled

	Materials	Manufacturing processes	Components and materials performance characteristics when in use	Disposal at end of life
	Water			
Performance Infill	SBR (styrene butadiene rubber) – recycled postconsumer material	Mechanical – high mechanical strength is used to shred and granulate the rubber Cryogenic – liquid nitrogen is employed to freeze the rubber to facilitate its grinding	Small rubber particles stick onto clothes Retains heat from the sun and gets very hot May release PAHs and VOCs May leach heavy metals	Recycled or disposed to landfill
	SBR mixed with sand		Better field safety and playability Segregation of rubber and sand particles Mixed infill needs to be loosened periodically	Rubber can be separated and recycled or disposed to landfill
	EPDM (ethylene propylene diene monomer)	Made from virgin materials Manufactured specifically for granulation Available in variety of colours May include fire retardant additives	Durable and claimed to be more environmentally friendly Less heat absorption Chemicals from manufacturing can leach in water	Recyclable
	TPE (thermoplastic elastomers)	Made from virgin materials Does not contain UV stabilizers Heated and compressed into grains or various shapes for performance.	Less heat absorption than rubber, May harden over time Degradation from UV Elastic in nature Durable, however not suitable in hot climates	Recyclable
	Organic infills (natural plant fibres, cork, coconut fibre, timber)	Requires antimicrobial treatment to prevent degradation	Non-toxic, environmentally friendly Less heat absorption Resists UV May break down and float if flooded Can be infected by insects Compaction	Recyclable into other products, biodegradable.

	Materials	Manufacturing processes	Components and materials performance characteristics when in use	Disposal at end of life
	Rubber coated sand	Softer filler material needs to be added to the acrylic material	No compaction and dust issues like uncoated sand Less heat absorption Coating may break down over time	Can be recycled
Shock pad	Polyethylene Polyurethane SBR Polypropylene Textile	Foam pads are made from recycled or virgin materials and can be made to provide drainage; Selection of materials, additives, density and thickness deliver performance needed for different sports.	Made from foam protecting players not getting injured from falls.	Reuse (up to three times in the same application)
Adhesives	Urethane Epoxy Latex Isocyanate	Ingredients are dissolved with solvents. Other compounds are then added to create the adhesive.	Glue and tape are used to join the rolls of turf together.	

Turf fibres

The main three materials used in turf fibres are nylon, polypropylene and polyethylene.

The first artificial grass was made of **nylon** fibres and is still used today in some synthetic turf applications as it is extremely resilient, springs back maintaining upright position, is resistant to UV radiation and abrasion, and is more heat resistant to the alternatives. These properties however cause a "turf burn". Nylon is also semi-permeable and absorbs water (Greens, 2021).

Polyethylene makes the most realistic looking grass, is resistant to water absorption, it is softer than nylon and more durable than polypropylene. However, it is not as abrasion resistant and wears and tears faster than the alternatives. It is also susceptible to UV degradation becoming brittle in the sun, therefore it almost always needs to be combined with UV stabilizers (Greens, 2021).

Polypropylene (a group of polymers) provides the thinnest and softest blade of the three materials, which makes it susceptible to flattening. It is very resistant to absorbing moisture (Greens, 2021).

To attain required turf piles performance and stability during use and weathering, additives such as antioxidants, UV stabilisers, slip agents and acid scavengers are added. Acid scavengers are added specially to address the impact of the residual catalyst and other processing impurities. Additives, such as lubricants are added to enable the extrusion process (Spalding & Chatterjee, 2017).

Plastic fibres are a potential source of heavy metals, particularly lead (Pb). Some manufacturers produced plastic fibres encapsulated with a lead chromate pigment however this is no longer a common approach (Cheng, et al., 2014). Excessive levels of lead had been found in some artificial turf fibres made of nylon or polyethylene/nylon blends, while fibres made of polyethylene commonly contained very low or undetectable levels of lead (Cheng, et al., 2014). Leaded pigment particles do not leach from intact nylon fibres but deterioration of these fibres over time can result in the formation of lead-containing dust (Cheng, et al., 2014).

Chemical analysis of several types of turf have found elevated levels of heavy metals which were attributed to the colouring pigments and UV inhibitors in the polymers. Australian Standard AS 2001-4: B02-2001 (AS 2001.4.B02-2001, 2001) specifies a method for determining the resistance of the colour of textiles to the action of an artificial light source which is representative of natural daylight. This method assesses the change in colour to the reference material but does not inform about the safety of the colour pigment. The safety of the colour pigment is not addressed by any Australian standard. However, a German Standard, DIN 18035 (Table 8) does provide guidance on acceptable heavy metal levels in synthetic sports fields.

Turf density (number of tufts per m^2) influences the mobility of infill and the more the infill is mobile, the higher likelihood is for the infill to be dispersed into the environment. In addition to the density, the shape of tufts also impacts the mobility of the infill. For example, in the long pile synthetic turf, a short pile layer of curly turf that is texturized or curled is added.

Infill

Recycled rubber tyres, styrene butadiene rubber (SBR), are commonly used as an infill. It has been estimated by industry that 75% of all fields in Australia use SBR (Smart Connection Consultancy, 2021). SBR provides good performance and have excellent durability. However due to a range of chemical vulcanisers, oil-based plasticizers, antioxidants, antiozonants, and fillers they can be a source of a slow release of volatile organic compounds (VOCs) via volatilization (emissions to air) and leaching of heavy metals under natural conditions (Cheng, et al., 2014, Graca, et al., 2022).

Air pollutants such as aliphatics, aromatics, poly aromatic hydrocarbons (PAHs), methyl isobutyl ketone, styrene, and benzothiazole are attributed to decomposition of rubber polymers, vulcanization accelerators, and plasticizers during tire shredding and grinding. Benzothiazole is the most abundant pollutant observed over rubber crumb (Cheng, et al., 2014). The concentration levels increase significantly within two weeks of shredding and then remain constant afterwards.

While internationally regulated metals (arsenic (As), silver (Ag), barium (Ba), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), and selenium (Se)) have been found to leach from the tyre shreds and chips, the concentrations were found to be below the regulatory limits (Cheng, et al., 2014). Tyre rubber leachate typically contained elevated levels of zinc (Zn), but other heavy metals such as Cd, Cr, copper (Cu), iron (Fe), magnesium (Mg), and manganese (Mn) were often present in relatively low concentrations (Cheng, et al., 2014). These metals are assumed to originate primarily from the metal oxides and residual steel belt wires in the tire shreds.

Other potentially toxic compounds found in tyres are nitrosamines (formed during vulcanisation process), benzothiazoles (accelerators in the vulcanisation process) and secondary amines (antioxidants in the rubber) (Gomes, et al., 2021).

Typically, tyres contain 40-60% of rubber polymer (synthetic and natural), 20-35% of reinforcing agents (carbon black and silica), 15-20% aromatic extender oils and other additives (See Table 6 for a more detailed breakdown).

Alternative to SBR thermoplastic polymers (TPE) and ethylene propylene terpolymer (EPDM) are also used. These materials are specifically manufactured as an infill for synthetic turfs, therefore can be produced with enhanced shapes, sizes and colours. They can also incorporate flame retardant additives particularly for indoor applications.

Instead, or in addition to plastic infills, organic infills, such as cork, coconut fibre or timber, are used providing a more natural playing surface. They however require moisture to keep them at optimum conditions and require periodic replacement during the lifetime of the synthetic turf. They also float in heavy rain increasing maintenance requirements. Organic infills, especially when watered, are also cooler compared to the plastic infills.

Backing

Backing materials are made from urethane or latex. Analysis of backing materials for heavy metals found very low levels of lead, indicating that it was not a commonly used additive in the production of backing materials (Cheng, et al., 2014).

Shock pads

Shock pads take many forms, including polyurethane bound rubber mixes laid in-situ or factory produced panels or rolls manufactured from a range of materials such as rubber granules, polyurethane foam, expanded polyethylene beads and recycled polyethylene foam.

Base

Base includes support and drainage systems. The Sport and Play Construction Association provides guidelines for the design (SAPCA, 2020). Materials used are drainage aggregates and asphalts with flexible drainage pipe systems. Alternatively, the aggregate sub-base layer can be replaced, or the materials used reduced by using preformed interlocking systems which also provides drainage. Asphalt bases contain 3-4% of bitumen.

Synthetic turf, textile surfaces, shock pads or polymeric surfaces can be installed directly on the unbound binding layer constructed from range of aggregate particle sizes regulating the sub-base.

Sub-base

Permeable sub-base materials – materials allowing water to percolate through the structure, include crushed rock, crushed blast furnace slag or recycled concrete aggregate. In the Sport and Play Construction Association guidelines, it is stated that fine materials (smaller than 0.425 mm) must be non-plastic. (SAPCA, 2020)

Impermeable sub-base materials – includes unbound mixtures of crushed rock, crushed slag, crushed concrete, recycled aggregates or well burnt non-plastic shale (with up to 10% wt. natural sand smaller than 4 mm) (SAPCA, 2020).

Perimeter edgings

Perimeter edgings are built from hydraulically pressed concrete kerbs ensuring retention of infill material following design recommendations in the European Standard: CEN Technical report 17519 (CEN, 2020). Alternatively, field boundaries panels from brickwork, timber, plastic extrusions, metal work or other material are recommended in the Standard.

Synthetic surfaces in athletics (IAAF Athletics, 2008)

Synthetic surface assemblies for athletics have different construction to the sport fields described above. Here is a brief overview of the most common assemblies and materials used:

Prefabricated sheets – made from a rubber compound, processed by pressing and smoothing, followed by curing and rolling. It is non-porous and has an embossed or textured surface finish to improve traction and slip resistance. The sheet is bound to the base of the track with a weather-sensitive adhesive. Sometimes a prefabricated base layer is bonded to the base with adhesive and then coated with a top layer mixed from raw materials and applied on site.

Cast elastomer in-situ (Full Polyurethane) – free flowing liquid polyurethane forming non-porous synthetic surfaces. The cast polyurethane resin is prepared by mixing two components: liquid polyol with isocyanate. To this mixture is either added chopped rubber crumb at the base and finished with specially formulated coloured EPDM rubber granules for textured finish, or the chopped rubber crumb is added on the top of the polyurethane mixture in layers (three) and finished with coloured EPDM.

Resin-bound rubber crumb in-situ (Spray Coat) – comprise a principal layer of polyurethane resin-bound rubber crumb, finished with texturized surface coating of polyurethane paint with fine rubber aggregate. This type of surface is the most commonly installed in athletics. They are porous, have better performance properties compared to the cast elastomers, however they are less durable.

Composite systems in situ (Sandwich) – hybrid of cast elastomer and resin-bound rubber crumb products. The base mat is formed of resin-bound rubber crumb, grouted with a very fine rubber crumb, and then cast elastomer layer is applied as a top surface.

Adhesives

Adhesives are used to bond synthetic turf seams and inserts or turf to the base. The adhesives need to be resistant to water, fungus and mildew. Synthetic turf adhesives include: one-part adhesives (urethane), two-part (epoxy or urethane), hot melt, and water based (latex) and one part (solvent/isocyanate free) adhesive (SMP) (STC, 2022).

1.4 Volumes of materials used in synthetic turfs in Australia

In this section are described the overall high-level flows of materials commonly used in synthetic turfs, including tyre sales and recovery flows and the estimated quantities of the most common materials currently installed in synthetic sport fields in NSW.

Overall flows of the polymers found in synthetic turfs

In 2019-20, nearly 3.5 million tonnes of plastic products were consumed in Australia, of which only 40% were manufactured locally from both virgin resins and recyclate-based resins (O'Farrell, et al., 2021). Table 4 provides a summary of volumes of plastic consumption by polymer type that are commonly used in synthetic turfs for the whole built environment in Australia, and in relation to the total consumption of polymers in Australia and NSW. Built environment includes materials from construction and demolition related applications, including plastics into building products, roads, railway sleepers, and landscaping. Also shown is the recycled content for the selected polymers processed in Australia.

As it can be seen in Table 5, only a small proportion of the plastics from the built environment reaching end of life in 2019-20, were recycled and reprocessed either locally or exported for reprocessing. The polymer types shown in the table are polymer types also commonly used in synthetic turfs. It needs to be noted that from 1st July 2022, waste plastics in Australia need to be sorted into single resin or polymer types and further processed before export (DCCEEW, 2022).

Table 4: Plastic consumption by polymer type and application area in 2019-20 in Australia (and NSW) and recycled content for polymers from local reprocessing by polymer type. (O'Farrell, et al., 2021)

	Consumption in the built environment - Australia [t]	Total consumption in Australia [t]	Recycled content in Australia [%]	Consumption in NSW [t]
PE	19,000	370,800	8	118,300
PP	34,800	480,500	7.5	153,300
PA (nylon)	16,000	105,700	0.2	33,900
PU	17,700	85,300	4	27,200
Rubber	80,300	264,800	0.15	84,400
Bioplastics	0	8,500	1	2,700

Table 5: Post consumer plastic by polymer type generated and recycled (locally for local use and for export) and exported for recycling in 2019-20 in Australia and NSW (O'Farrell, et al., 2021)

	End of Life Built Environment [t]	Locally reprocessed for local use [t]	Locally reprocessed for export [t]	Exported for reprocessing [t]	End of Life post-consumer in NSW [t]	Recovery in NSW [t]
PE	380,000	29,800	6,500	4,000	108,400	7,500
PP	450,000	36,200	2,400	7,300	128,400	11,700
PA (nylon)	70,000	200	0	7,000	24,700	4,000
PU	63,000	3,400	0	0	17,900	2,400
Rubber	238,000	400	1,000	2,600	68,000	1,200
Bioplastics	7,000	100	0	0	2,100	0
Total	2,497,000	168,600	31,600	126,400	970,200	154,700

Tyre sales and recovery

This section summarises tyre imports (sales), recovery rates and their fate.

In 2019-20, there were 558,000 tonnes of tyres sold in Australia (37% passenger, 35% truck and 28% off-the-road) (O'Farrell, et al., 2021). About a third were sold in NSW (TSA, 2022).

Since the closure of Bridgestone Tyres in Adelaide, in 2010, Australia has not manufactured any tyres. All consumed tyres in Australia are imported (Randell, et al., 2020).

On average, new tyres contain 76% of natural and synthetic rubber (including rubber additives), 22% steel and 2% synthetic fabrics (only used in passenger tyres). A more detailed description is provided in Table 6.

Average tyre's lifespan has been estimated to be 3.4 years for passenger tyres, 1.5 years for truck and 1 year for OTR tyres (Schandl, et al., 2020).

O'Farrell et al. (2021) estimated that in 2019-20 460,000 tonnes of tyres reached end of life, of which 15% were reprocessed locally, 57% exported for recovery and the remaining 28% disposed (predominantly to landfill). OTR used tyres are typically disposed onsite, either at a mining site or other onsite disposal sites. It has been estimated that 81% of OTR are disposed on site in 2018-19 (Randell, et al., 2020).

Of the recovered tyres 37,000 tonnes (8%) is processed into crumb, granules and buffings which are produced in NSW, Queensland, South Australia and Victoria (Schandl, et al., 2020).

Australia's capacity for crumbing has been estimated to be 58,500 tonnes per year of which only 39,500 tonnes is currently in use (Schandl, et al., 2020).

Schandl et al. (2020) estimated that about 5,000 tonnes per year in Australia of the crumb rubber market would be used as crumb for infill in sport fields.

Table 6: Australian tyre sales in 2019-20 by material type, tyre group and composition (O'Farrell, et al., 2021)

Material	Passenger [t]	Truck [t]	Off-the-road [t]	Total [%]
Rubber - natural	32,000	58,000	45,000	24%
Rubber - synthetic	60,000	25,000	19,000	19%
Steel wire	33,000	49,000	39,000	22%
Nylon	6,000	0	0	1%
Polyester	6,000	0	0	1%
Carbon black	24,000	24,000	18,000	12%
Silica	24,000	24,000	18,000	12%
ZnO	2,000	4,000	3,000	2%
Sulphur	2,000	2,000	2,000	1%
Other additives	16,000	12,000	9,000	7%
Totals	205,000	198,000	153,000	

Material volumes in synthetic turfs installed in NSW

The "number of synthetic sports fields in NSW" were collected from the publicly available information (predominately from the sports organisations reports). It is very likely that the numbers are underestimated as it was sometimes hard to determine whether the sport fields are synthetic or natural. Other uses of synthetic turfs in public spaces include playgrounds, schools and on commercial properties. These applications are not included in these estimates as many are used in private settings, which were out of scope for this study.

The material quantities were estimated for each sport specifically, using the most common construction assemblies, sports fields construction standards and from publicly available material characterisation and properties (Table 7). Sports, such as oztag, touch football and softball are excluded from the table as they are played on shared fields. When known, Australia specific characteristics were considered. For example, an environmental impact study on artificial football turf commissioned by FIFA (Eunomia, 2017) identified that 49% by weight of the system composition is stabilising infill (sand) and 44% by weight is performance infill, with the turf backing and yarn only 4% by weight. However, for Australia it is anticipated that the performance infill could be lower owing to the higher number of turfs using shock pads, which reduces the amount of infill needed (Smart Connection Consultancy, 2019). Therefore, it was assumed in the calculations that 83% of football fields use SBR as performance infill without shock pad, with 6% using EPDM, 6% TPE and the rest use organics or mix with a shock pad.

In the cricket fields are also included cricket pitches in practice nets and cricket pitches in ovals. It is common practice to have the synthetic pitches included with the natural grass ovals. There were identified 1,347 cricket pitches in practice nets and 800 cricket pitches in ovals in NSW.

Synthetic turfs appear to be widely established in hockey (77) and football (88). On the other hand, in rugby league and rugby union the uptake in Australia (NSW) has been small with only 4 fields installed so far (2 in league and 2 for union). For lawn bowls, 27 fields were identified to be synthetic, however this is likely to be an underestimate due to difficulty obtaining information on break down between synthetic and natural fields.

Synthetic turf is also used in some tennis courts in public and private settings. The total number of tennis courts in NSW and distribution by type was not reliably available and therefore tennis courts are not included in Table 7. However, based on the reported information for Greater Sydney (Tennis NSW, 2022), there are 371 venues and 1,503 tennis courts. Assuming that 73% of the courts are constructed from synthetic grass, it is estimated that at least 238 tonnes of fibre and at 9,464 tonnes of sand are currently in these courts. The construction assembly was assumed to be tufted synthetic carpet laid on a base filled with sand to hold the carpet in place, provide a firm playing surface and to facilitate the drainage of surface water (Tennis Australia, 2003).

Table 7: Number of synthetic fields by sport and main materials, in tonnes, used in synthetic turfs by sport application in NSW.

	AFL/Cricket	Athletics	Lawn bowls	Football	Hockey	Rugby League	Rugby Union	Total (NSW)
No of fields	*12*[1]	*23*[2]	*27*[3]	*88*[4]	*77*	*2*	*2*	*231*
PE	1,429		86	964	1,001	19	22	3,522
PP	357		16	241		5	5	624
PU	1,072	2,616		1,542		150	174	5,419
SBR				9,298		208	241	9,746
EPDM				174				174
TPE				174				174
Organic				87				87
Silica	17,507		540	11,815	3,589	232	268	33,950

[1]*includes 5 AFL and 7 cricket fields; includes in calculations also 1347 cricket pitches in practice nets, 800 cricket pitches in ovals in NSW*
[2]*includes 23 track fields, 68 jump pits, 26 high jump fans, 35 pole vault pits, 33 discus circles, 52 shot put circles, 29 javelin runways, 11 hammer circles*
[3]*likely underestimated*
[4]*includes 11 junior fields and 24 futsal fields*

More than half of the materials currently installed in synthetic turfs in NSW is sand, used as a stabilising infill (Figure 1). SBR, also used as infill is the second most used material (18%), followed by polyurethane (10%). Almost 7% of the materials in the synthetic sports fields is polyethylene, used for the turf piles or in shock pads. Nevertheless, these are still small quantities in comparison of the total consumption in NSW (Table 4) or even recovery rates (which are poor) (Table 5).

It should be noted that the infill is constantly lost to the environment and needs to be refilled at a regular basis. In the estimate in Table 7 the loss to the environment has not been accounted for. Therefore, the amount of infill used for the existing synthetic sports fields is higher. Bertling et al. (2021) estimated that 3 tonnes of performance infill are lost per year. Using this assumption, 252 tonnes per year of infill are needed for refill in NSW.

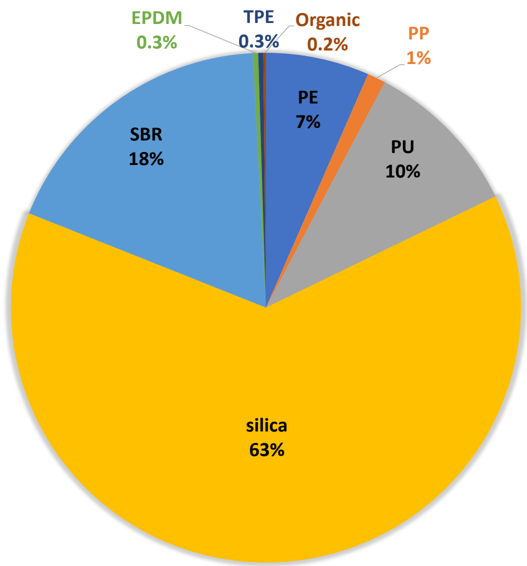


Figure 1: Overall distribution of materials in synthetic turfs currently installed in NSW

1.5 Behaviour of materials in synthetic turfs

The materials of concern in synthetic turfs are heavy metals, volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs) and microplastics. The majority of these chemicals are reported to be found predominantly in the infill and have been subject to numerous studies over the past few decades.

Cheng et al. (2014) reported that exposure to oxygen, ozone, heat, sunlight (UV), and liquids can cause changes in physical and chemical properties of tyre rubber crumb, and consequently release contaminants from the degraded rubber matrix (Figure 2).

A range of anti-degradants and waxes are used by tyre manufacturers to inhibit the degradation of tyres. However, they are gradually lost or used up through the life of tyres making rubber crumb from used tyres susceptible to a more significant attack from oxygen, ozone, and sunlight. Cut up tyres also have a large surface area that can enhance volatilization of organic contaminants into air and leaching of heavy metals and organic contaminates into the percolating water through the rubber crumb. They are also more subjected to degradation due to their high surface-to-volume ratio.

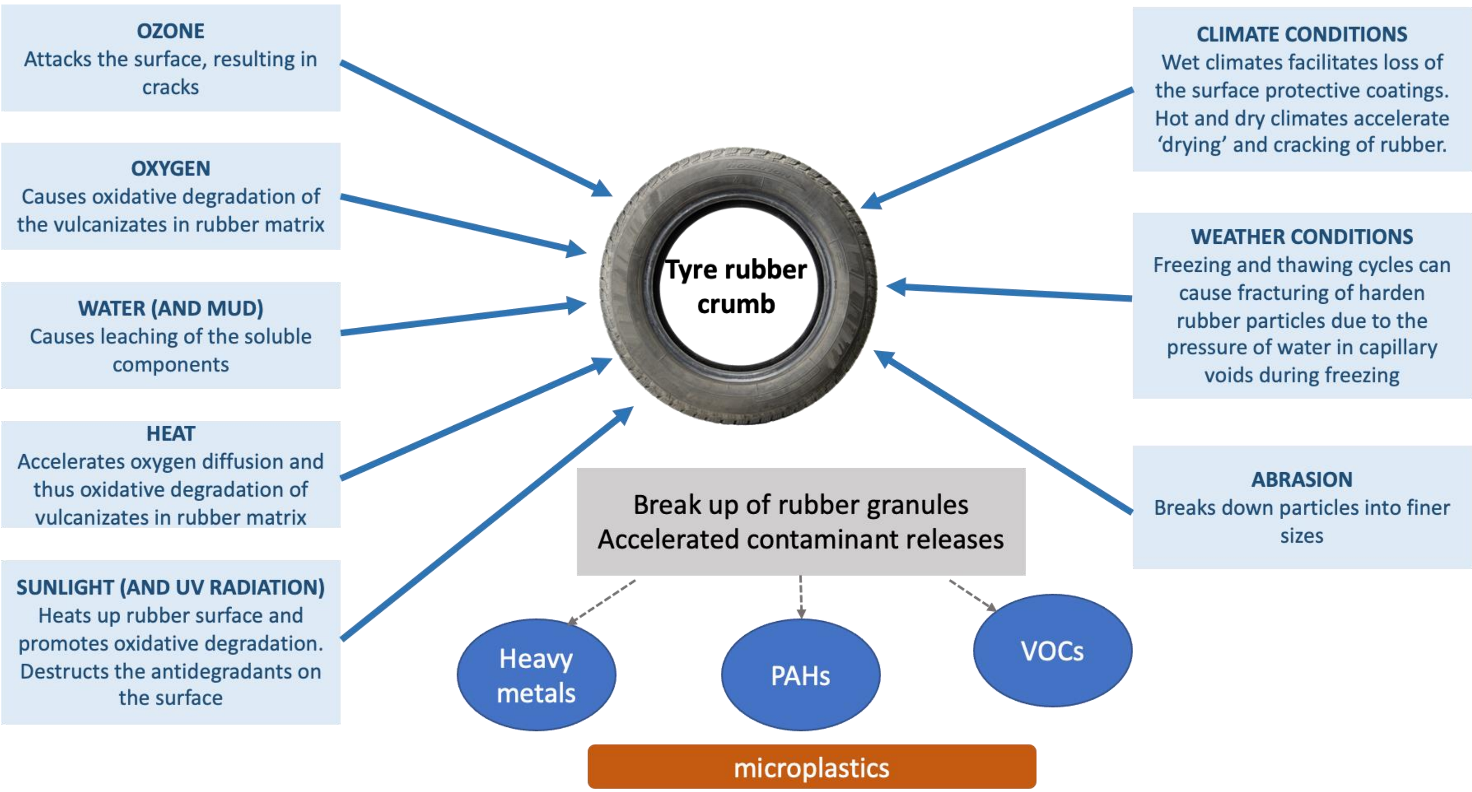


Figure 2: Influence of the major environmental factors on degradation of tyre rubber crumb in artificial turf fields. Adapted from (Cheng, et al., 2014)

Leaching of heavy metals (Zinc, Lead and Cadmium)

Several studies demonstrated the presence of heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), iron (Fe) in the crumb rubber at concentrations up to thousands of micrograms per gram (μg/g) (Armada, et al., 2022).

Heavy metals are nondegradable and persist in the environment. High amounts of zinc oxide (ZnO) used as a vulcanisation activator (1.2 tonnes in a typical soccer pitch) pose an environmental concern in terms of contamination of water (Cheng, et al., 2014). However so far, the industry has not been successful in substituting ZnO with alternative vulcanisation activators.

Graca et al. (2022) investigated the presence of metals in 103 synthetic turf pitches in 13 different countries, including those used in indoor and outdoor environments, and at different ages. They found Zn to be the most abundant element accounting for 66% of total metal concentrations. The second most abundant element was Fe (9%) probably due to the presence of steel in tyres. Magnesium (Mg), aluminium (Al) and potassium (K) are usually employed in the form of silicates as rubber fillers. Graca et al. (2022) found synthetic turf contained 7% Mg and 7% Al. Together with K, sodium (Na) and cobalt (Co) these metals accounted for 98% of the assessed metal concentrations (Graca, et al., 2022). Co is added to the tyre fabrication as an adhesion promoter between steel tyre cord and rubber. Na is resulting from silica which is used as a filler replacing carbon black (Graca, et al., 2022).

There is no legislation in EU specifically for the presence of metals in crumb rubber used as infill for turf pitches. Therefore Graca et al. (2022) used the limits set for rubber toys and the limits for sewage sludge applied to soils as a proxy for crumb rubber. They found that concentrations of Zn exceeded the limits. Co and Pb concentrations were also found to be higher than in limits for toy materials. Co is unlikely to leach from crumb rubber, however it might be inhaled with rubber dust that is released during the match. The other metals and metalloids were found to be below the legislated limits (Graca, et al., 2022).

Distribution of metals by country appeared to be similar, and trends were similar for indoor vs. outdoor as well as the age of the pitch.

When analysing other components of the synthetic turfs, blades, carpet backing and geotextiles used in the pitches, for metal content, it indicates that Zn predominantly leaches from crumb rubbers (Gomes, et al., 2021).

Some of the synthetic turf certifications, when considering the limits of heavy metals, refer to the DIN 18035 standard (Table 8) (IST, 2002).

Table 8: DIN 18035: Environmental requirements (soil and ground water) and testing of bound elastic supporting layers, elastic layers and synthetic turf layers (including infill material of pile layer).

Heavy metal	Concentration [mg/l]
Lead (Pb)	≤ 0.04 mg/l
Cadmium (Cd)	≤ 0.005 mg/l
Chromium (Cr) total	≤ 0.05 mg/l
Chromium VI (CrVI)	≤ 0.008 mg/l
Mercury (Hg)	≤ 0.001 mg/l
Zinc (Zn)	≤ 3.0 mg/l
Tin (Sn)	≤ 0.05 mg/l

US EPA performed bio-accessibility tests for 19 metals in tyre crumb and have found the amount of metals released into simulated biological fluids to be low: on average about 3% in gastric fluid and less than 1% in saliva and sweat plus sebum (US EPA, 2022).

Volatilization of volatile organic compounds (VOCs)

VOCs in synthetic turf have been reported to originate predominantly from the infill. VOCs found in rubber granulate are mainly coming from the solvents used in the rubber conversion industry to bind different layers of rubber or rubber-coated components and as mould-releasing agents. In tyre production solvents are also used in the extruding, side-wall, curing press spray and finishing paint processes (Gomes, et al., 2021).

No specific regulations are available for the presence of VOCs in crumb rubber, however limits have been set for most common VOCs in terms of exposure. These chemicals are water soluble and extremely volatile therefore the regulations exist for their safe concentrations in drinking water, rivers, lakes and air.

The studies of VOCs in crumb rubber reflect its presence in the tyre production. US EPA study on synthetic turf field recycled tyre crumb, identified at the elevated temperature (60°C) increased emission factors for some of the targeted SVOCs and VOCs, with methyl isobutyl ketone and benzothiazole being the highest (US EPA & CDC/ATSDR, 2019). However, from the reported studies in literature, observed concentrations in crumb rubber appear to be within limits and is reported that they do not present hazard with respect to VOCs (Gomes, et al., 2021).

Due to the known problem of synthetic turfs reaching elevated temperatures in warmer climates, and the volatility of the VOCs, a number of studies in literature focused on the analysis of the air above synthetic pitches. The chemical observed in all the studies was toluene, which remained lower than regulated limits. The studies that compared indoor vs outdoor concentrations of VOCs above the synthetic fields, have noted concentrations higher in the indoor setting (Gomes, et al., 2021).

Release of organic contaminants (PAHs)

The rubber infill also contains polyaromatic hydrocarbons (PAHs) which originate from the highly aromatic oils that are added as extender oils and from the carbon black which is added as a reinforcement filler during the production.

The US EPA has identified 16 PAHs (Table 9) as 'chemicals of concern', which are the most analysed set in the scientific literature including in the studies of crumb rubber, water leachates and air surrounding the football pitches (Gomes, et al., 2021).

In the case of tyres placed on the European market, owing to strict regulations (EU REACH) targeting the impact of PAHs on human health and environment, the highly aromatic oils have largely been replaced since 2000s (Cheng, et al., 2014). It should be noted that this might not be the case for the tyres manufactured in other parts of the world that are entering Australian market.

Carbon black, however, is still used and contributes to the PAHs in tyre rubber and PAHs remain of concern when the tyres are granulated for the infill used in the synthetic sports fields.

Table 9: Listed PAHs of concern by US EPA and carcinogenic PAHs listed by EU.

PAHs of Concern (by US EPA)		Listed Carcinogenic PAHs by EU	
NAP	naphthalene		
ACY	acenaphthylene		
ACE	acenaphthene		
FLU	fluorene		
PHN	phenanthrene		
ANC	anthracene		
FLA	fluoranthene		
PYR	pyrene		
BaA	benzo[a]anthracene	**BaA**	benzo[a]anthracene
CHY	chrysene	**CHY**	chrysene
BbF	benzo[b]fluoranthene	**BbF**	benzo[b]fluoranthene
BkF	benzo[k]fluoranthene	**BkF**	benzo[k]fluoranthene
BaP	benzo[a]pyrene	**BaP**	benzo[a]pyrene
IND	indeno[1,2,3-cd]perylene		
DBahA	dibenzo[a,h]anthracene	**DBahA**	dibenzo[a,h]anthracene
BghiP	Benzo[g,h,i]perylene		
		BeP	benzo[e]pyrene
		BjF	benzo[j]fluranthene

There are however no specific guidelines in relation to maximum PAHs contents for water leachates and air surrounding synthetic football pitches.

Table 10 summarises some of the regulations that could be relevant in the assessment of the safety of PAHs resulting from synthetic turfs in sports fields.

Table 10: Regulations on PAHs relevant in the assessment of the safety of PAHs resulting from synthetic turfs in sports fields.

PAHs limits in relevant regulations internationally	
US EPA	Identified 16 PAH as chemicals of concern, with BaP with the highest toxic potential (Gomes, et al., 2021).
EU (2010)	Restricted PAH content in extender oils to be used in the manufacturing of tires to BaP<1mg/kg and the sum of 8-carcinogenic PAHs <10mg/kg (ECHA, 2018)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals recommended that consumer products like bicycles, golf clubs, racquets, household utensils, trolleys, walking frames, clothing, diverse sportswear as well as toys should not be placed on the market if any rubber or plastic components that come into direct contact with the human skin or oral cavity contain more than 1mg/kg of any listed PAHs (BaP, BeP, BaP, CHY, BbF, BjF, BkF, DBahA – Table 9) (EU, 2013)
Limit exposure in soil	For example, Norwegian Pollution Control Authority's normative for soil pollution assessment in existing day-care centres and playgrounds is set to 2mg/kg of 16 EPA PAHs
Limits in water	Different limits set by different countries for drinking water, wastewater and rivers, lakes and costal water
Indoor air	For example, EU OSHA set a limit of 0.2 mg of PAHs per m^3 of indoor air. For outdoor air EU used BaP as a proxy and set the limit to $1ng/m^3$ (European Commission, 2009)
Outdoor air	EU set a limit of 1ng/m3 for BaP (proxy for all PAHs), while other countries have also set their own limits.

In a recent analysis of crumb rubber infill from pitches in 6 countries (European and US), Gomes et al. (2021) found that benzo[a]pyrene and zinc often exceeded the established limits by listed regulations in Table 10.

Armada et. al (2022) detected all studied PAHs, including the 8 carcinogenic ones in all samples. Almost all (except three) complied with the limit of 20 μg/g for the sum of eight carcinogenic PAHs regulated by REACH.

Gomes et el. (2021) concluded that the source of the PAHs are mostly from the high temperature used in the process for tyre production and are consequently passed to the recycled crumb rubber and that the granular size of the crumb does not impact the incidence of PAHs. Therefore, the origin of the tyres' manufacture will determine the concentration of PAHs rather than the recycling process.

It appears that some types of the coating might decrease the release of PAHs from the material's surface (Gomes, et al., 2021). The limitation of the reported studies of coating in the literature is limited to the cryogenically produced crumb rubber and not from the most common mechanical process. On the other hand, as the sports fields age, the release of PAHs decreases.

When pile blades were analysed for PAHs, 100-fold lower concentrations were detected compared to rubber infills (Gomes, et al., 2021).

PAH levels in indoor pitches were found to be higher in the surrounding air (Gomes, et al., 2021).

Other potentially harmful chemicals

In addition to PAHs, plasticizers, antioxidants, vulcanisation additives, benzothiazoles, chlorinated paraffins, polychlorinated biphenyls or alkylphenols and other were detected in the rubber crumb infills (Armada, et al., 2022).

While thermoplastic elastomers are a good alternative regarding PAH content, they contain high concentrations of plasticizers (Mitchell, 2022).

PFAS could be potentially present in the synthetic turf systems (carpet/piles, infills and shock pad). Recently reports and articles have started to emerge about detection of the chemicals. Murphy & Warner (2022) have recommended in their review that additional comprehensive studies that incorporate all components of synthetic turf are strongly needed. The focus so far has been predominantly on the infill and impact of PAHs and metals, while synthetic turfs contain many additional components that may leach harmful chemicals including PFAS.

Dispersion of microplastics into the environment

Microplastics, defined as solid particles made of non-biodegradable plastic or rubber that is 5 mm or less in size, are unintentionally formed through wear and tear or deliberately manufactured and intentionally added to products for a specific purpose.

Bertling, et al. (2021) estimated that on average about 3 tonnes of perormance infill is lost per year from the pitches examined in their study. The authors also found that the lower the density of the infill the greater the rate of loss.

Many infill materials used in synthetic turf surfaces meet the definition of micro plastic (RFL, 2020). To aid and promote good design and maintenance procedure for sports fields containing infill materials, the European Standards Committee (CEN) has provided guidance (CEN, 2020) for the design, operation and maintenance of synthetic turfs to minimise infill dispersion. The approach is to provide physical barriers preventing infills leaving the playing surface, boot cleaning, decontamination grates and drains with slit traps.

In addition to infills, the tips of the synthetic turf filament break down over time due to UV radiation and contribute to the microplastics formation (Smart Connection Consultancy, 2019). Bertling, et al. (2021) noted that the loss of fiber, which was impacted by the fiber use weight, infill type and presumably the age of the pitch, ranges from around 50 kilograms to over 1 tonne per year. Though they could not conclude to what extent the losses are attributed to turf fibre discharged as waste due to maintenance work or turf fibre remaining in the artificial turf. They stipulated that discharge via players would play an especially large role for loss of turf fibers.

Recent studies show a potential link of cancers to the synthetic turf rubber infill. In response to this, the Netherlands has announced plans to phase out all crumb rubber by 2030 (Silvester, 2021).

1.6 Challenges in repurposing, reusing, and recycling of the materials used in synthetic turfs

In NSW, EPA states that there are limited recycling options in Australia and recommends disposing of the worn-out fields to landfill (NSW EPA, 2021) following the EPA Waste Classification Guidelines (NSW EPA, 2021). Internationally, synthetic turf carpets are predominantly also either disposed to landfill or incinerated. Incineration however is not currently an option in NSW for the turf carpet. Tyres, including tyre crumb, however, are listed as an eligible fuel in an approved cement kiln (NSW EPA, 2022).

In Australia, the Tuff group has just been awarded a grant to establish the first synthetic turf recycling hub (Sustainability Victoria, 2022). The Tuff group stated that they will be able to process 4-5 tonnes of turf per hour producing the following raw materials: sand, styrene-butadiene rubber, polyethylene fibre, and polypropylene. They estimated that the plant will process approximately 7,000 tonnes of used synthetic turf each year. The details of the process are not yet publicly available, but it is understood that they will employ traditional mechanical recycling, where the components of the synthetic turf are separated based on their physical properties. Other approaches include advanced recycling.

Advanced recycling, also referred as molecular or chemical recycling, converts plastic waste into its chemical building blocks, which are used in manufacturing plastics or as a fuel resource. In advanced recycling the plastic waste is converted to monomer or new raw materials are produced by changing chemical structure of the material or substance through cracking, gasification or depolymerisation, excluding energy recovery and incineration (King, et al., 2021).

The composition of synthetic turfs with diverse materials, that include different types of plastics (thermoformed and non-thermoformed) with different melting points, and different viscosities makes recycling challenging. Owing to these properties, commonly used mechanical waste processing methods struggle to separate the polymers. Project RECITURF (AIMPLAS, 2021), funded by the Valencian Innovation Agency and led by Spanish plastics technology centre Aimplas, is developing chemical separation methods aiming to recover specific materials from synthetic turf. The process will use biological or enzymatic degradation processes for the turf (polypropylene and PET) and chemical recycling or glycolysis for the polyurethane backing. The separated materials will then be used in the mechanical recycling process.

Recycled content in synthetic turfs

Recycled tyres are used as performance infill in the synthetic turfs. This is a great circular economy initiative, however as it has been demonstrated in this report use of recycled tyres for infill can pose a hazard due to the leaching of metals and PAHs. Therefore, it is important that when recycled material is repurposed it does not have a perverse outcome.

It is also important that provenance of the material is known. As demonstrated in this report the quality of the SBR infill will strongly depend on the origin of the recycled tyres. Different regions around the world have different regulations regarding the manufacturing and use of tyres. For example, USA and Europe have stricter regulations on the safety of chemicals and components used to make vehicle tyres. As Australia imports all the tyres placed on the market, it does not have its own regulations on manufacturing of tyres. Also, Australia does not have control on the origin of the recycled tyres that are used at the end of life for the performance infill in synthetic turfs.

Carbon footprint impact of synthetic surfaces

While carbon footprint has not been the focus of this study, we noted the literature reports that a natural grass system has a much lower carbon footprint compared to synthetic turf. This is predominantly owing to the fact that grass areas act as carbon sink. It is not however always clear what natural grass maintenance has been included in the studies or if natural grass fields studied have a drainage system that includes recycled water.

When comparing different types of infill, the industry reports that when using recycled SBR for the infill, the footprint is significantly lower (50%) compared to the TPE infill, which appears to be about 40% higher than EPDM infill (Smart Connection Consultancy, 2019).

However, from an overall environmental perspective and despite a 10% increase in carbon footprint, EPDM is reported to be a good alternative material to SBR.

2. Regulations, standards, and certifications

This section briefly reviews relevant regulations, standards and certifications in relation to synthetic turf installation and operation with particular focus on materials used in synthetic turf.

2.1 Regulations for installation of synthetic turfs in NSW, Australia

The design and use of synthetic turfs on community sporting fields and any environmental impacts are assessed as part of the planning process under the *Environmental Planning and Assessment Act 1979* with local council consenting and approving, and via the *Protection of the Environment Operations Act 1997* for pollution issues caused by the installation of the synthetic turf (NSW EPA, 2021).

In addition, the disposal of the synthetic turf is regulated by *Waste Avoidance and Resource Recovery Act 2001* and *Plastic Reduction and Circular Economy Act 2021*.

NSW Plastic Reduction and Circular Economy Act 2021

The Act commenced in November 2021 and prohibits certain items and establishes a product stewardship framework for brand owners of certain products and for related purposes. (Product stewardship in Australia is discussed in more detail below.)

The objective of the Act is:

- to protect the environment and human health,
- to promote and support the principles of a circular economy by:
  - valuing resources and minimising use of virgin materials ensuring circulation in the economy
  - keeping resources in use and designing out waste, pollution and resource inefficiency
  - ecologically sustainabile and regenerative management of resources and systems
- to support material circularity through design, production, use, re-use, collection, reycling, reprocessing and end-of-life management
- ensure responsibility across their life cycle
- reduce the impact of waste on the environment and human health

The act introduces a range of staged **bans** on certain single use plastic products including lightweight plastic bags, plastic straws, stirrers and cutlery, plastic bowls/plates and takeaway food service items. This action also sets a precedent for other plastic products to be banned under this act in the future.

The act establishes a **product stewardship framework** that applies to brand owners of “regulated products” who can be required to adhere to defined product stewardship requirements and targets that will help reduce waste and encourage a more circular economy approach in the NSW economy. “Regulated products” will be identified through the regulations that are yet to be released. The Act defines product stewardship requirements that could specify the use of recycled material, product design, the longevity of the product, re-use or recovery of a product and its impact on waste management and reduction of unlawful waste disposal. The act will require “brand owners” of “regulated products” to keep records and annually report to EPA. It may specify information requirements and the requirement to prepare action plan that details how a brand owner intends to comply with the requirements or targets. The regulation is due to be exhibited late in 2022.

2.2 Regulations for chemicals used in synthetic turfs

There are no specific regulations in NSW for the presence of PAHs or heavy metals in synthetic turfs or recycled tyres that are used as an infill in the synthetic sport fields such as European Union REACH on PAHs in synthetic turf infill.

EU REACH (Registration, Evaluation, Authorization and Restrictions of Chemicals)

The EU has expanded the scope of restrictions on PAHs in granules or mulches used as infill material (in synthetic turf pitches or in loose form on playground or in sport applications) under entry 50 to Annex XVII of Regulation 1907/2006 REACH. The new restrictions will become effective on August 10, 2022. The requirement is that the sum of eight PAHs (Benzo[a]pyrene, Benzo[e]pyrene, Benzo[a]anthracene, Chrysene, Benzo[b]fluoranthene, Benzo[j]fluoranthene, Benzo[k]fluoranthene and Dibenzo[a,h]fluoranthene) is ≤ 20 mg/kg.

2.3 Standards for the materials used in synthetic turfs

Standards have been specifically developed for synthetic sport surfaces which provide specifications for design, manufacturing, installation and testing. Certifications on the requirements of the synthetic sports fields that have been developed by sporting bodies (e.g., FIFA) for different types of sports, especially at the elite level, rely on these standards. However, both certifications and standards are voluntary. Table 11 provides a few selected examples of Australian (N) and International (I) standards relevant to design, installation, testing and operation of synthetic turfs.

There appears to be only one Australian standard in relation to synthetic turf (Table 11). For design, installation and testing of synthetic turfs there are no Australian standards. Instead, International Standards listed in Table 11 are used. There are many more testing standards listed in the Certification processes applied in Australia by various sporting associations (discussed below in 2.4 Sporting bodies certifications). Again, most rely on international standards as Australian standards are not available.

Calls to adhere to specific standards might be also used in the procurement process. However, some standards are limited, do not sufficiently cover environmental aspects and are dated.

Generally standards focus on specific design parameters that were state of the art when developed. However as new materials and construction assemblies are evolving delivering desired playability and safety outcomes they might not adhere to the older standards. This was also noted by Bertling, et al. (2021).

Synthetic turfs installed and used for professional sport level need to be certified by the sport governing bodies in order to be used for international competition. The certifications call on standards to ensure the performance of the materials for sports rules and safety of players. Some of these standards are described in the table. At the community sport level play however application for synthetic turfs to be certified is voluntary and so is the use of standards.

Table 11: Selected standards relevant to the design, installation, testing and operation of synthetic turfs.

	Standard	Year	Description
N	SA TR CEN 17519:2021	2021	Surface for sports area – Synthetic turf sports facilities – Guidance on how to minimise infill dispersion into environment.
N	AS 2001.4: B02-2001	2016	Methods of testing for textiles Colourfastness test – Colourfastness to artificial light: Xenon arc fading lamp test (ISO 105 B02:1994, MOD)
I	ISO/IEC 17025	2017	General requirements for the competence of testing and calibration laboratories
I	BS EN 15330-1	2007	Surfaces for sports areas – Synthetic turf surfaces primarily designed for outdoor use – Specifications for synthetic turf.
I	BS EN 15330-2	2008	Surfaces for sports areas – Needle-punch carpets primarily designed for outdoor use – Specifications for needle-punch carpets.
I	FPREN 15330-4	2022	Surfaces for sports areas _ Synthetic turf and needle-punched surfaces primarily designed for outdoor use – Part 4: Specification for shock pads used with synthetic turf, needle-punch and textile sports surfaces
I	prEN 15330-5	2022	Surfaces for sport areas – Synthetic turf and textile sports surfaces – Part 5: Specification for infill materials
I	DIN 18035	2019	Levels of coloured pigment
I	EN 17409	2020	Surfaces for sports areas – Code of practice for the sampling of performance infills used withing synthetic turf surfaces
I	AfPS 2019:01 PAK	2019	PAH Content testing required for FIH Certification programme
I	CEN/TR 17519:2020	2020	Surfaces for sports areas – Synthetic turf sports facilities – Guidance on how to minimize infill dispersion into the environment
I	CEN/TS 16384:2012	2012	Synthetic sport systems – Leaching test
I	ASTM D5603-01	2015	Standard Classification for Rubber Compounding Materials – Recycled Vulcanizate Particular Rubber

2.4 Sporting bodies certifications

International sporting bodies that use synthetic turfs for international competition have developed standards for synthetic sport fields to ensure the quality of play and safety of players. The certification process normally includes verification of the materials used in the construction of the field and verification of the constructed field for performance. The certification is awarded for a period and needs to be renewed at the end of that period. Certifications include periodical checks of the certified fields checking for field performance and appropriate field maintenance. Listed below are certifications for the sports that use synthetic turfs in Australia, with brief high-level assessments of testing for the chemicals. As the certification is likely to be only applied at the elite level of sport, community synthetic turfs are not likely to be covered by the certification process even though some of the certifications have been specifically developed for the community level of play.

FIFA Quality and FIFA Quality Pro

With the goal for the synthetic turf to replicate the playing qualities of good quality natural grass, provide a playing environment that will not increase the risk of injury of players and is of adequate durability, FIFA developed a rigorous test program for Football Turfs in 2001. The program (Figure 3) assesses the ball-surface interaction, player-surface interaction, and durability of products. The program offers two certifications: FIFA Quality Pro – for elite level and FIFA Quality for community. The program includes two phase testings. In the first phase, laboratory tests are performed assessing suitability for football and other material quality criteria before the turf is installed. In the second phase, field tests are performed on the fully installed and ready to play pitches. To ensure appropriate maintenance of the pitches, FIFA carries out quality checks on randomly selected pitches helping operators use and maintain them correctly. If repair work is necessary, the manufacturer is informed.

Figure 3: FIFA Program approval process steps and related documents and parties. (FIFA, 2022)

The constituent components of the system, submitted by the manufacturer for laboratory testing need to be tested by an accredited laboratory following the procedures outlined in the Test methods manual (FIFA, 2022). The test methods include testing for polymeric infills for PAH content as per the latest EU REACH Regulation requirements and infill toxicology of heavy metals.

Details for the whole program including the certified methods required are described in the Test requirements manual (FIFA, 2022).

While the laboratory tests aim to determine the weathering of the material, heat, UV stabiliser content, and decitex (linear density) of yarns, the tests of the installed field are intended to test the performance of the field during the play.

The artificial weathering test tests pile yarn and polymeric infill under UV. However, the test looks for visual and physical changes and not chemical reactions that might occur under tested conditions. Additionally, a TGA (thermogravimetric analysis) is used to determine the ratio of organic to inorganic material present in the synthetic infills. The procedure differs based on the type of infill used: SBR or EPDM, TPE and other polymers. Similarly, the heat test only tests for temperature change. The Wear and splash test inform on the wear and compacting of the infill. Loss of UV stabiliser over time can be tested by comparing the value to the original laboratory tested sample.

FIH Quality Programme for Hockey Turf

The FIH Quality Programme provides industry standards and products, ensuring they are available and that the field has been designed and built to the correct standards. It certifies:

- **HOCKEY TURFS**: Tested products for playability and safety – they are assessed for 40 different properties including sports performance, player welfare, durability and toxicology.
- **SPECIALIST FIELD BUILDERS**: accredited specialist contractors as Preferred Suppliers and Certified Field Builders.
- **FIELD CERTIFICATION**: fields that have been independently tested and have shown to comply with FIH Hockey Turf and Field Standards get the certification.

- **APPROVED FIELD EQUIPMENT**: FIH Approved goals, rebound boards, team benches and technical official's booths are independently tested for quality and safety.

Field specific requirements are specified for each of the 5 Category fields (from global to national, community and multiuse). Specifications include the category of hockey turf and not the materials used. The components' characteristics are listed and are required to be sourced from an Approved Supplier. For each component are listed characteristics and test methods standards required to test them. Standards that test for materials are: pile polymer and carpet fibre polymer characterisation (using FIFA Test Method 22) and polymer composition of the polymeric infills (using FIFA Test Method 11). In addition, the standard requires testing for toxicology, carcinogenic PAHs specifically. They need to comply with REACH Regulation requirements, unless the non-EU country has their own.

World Athletics Certification

The certification program aims to ensure that all synthetic surface products, facilities, implements and equipment market for use in athletics competitions conform to World Athletics specification. The certification does not include a health and safety test or other international, regional or national regulatory test. The test includes physical tests and visual inspections, such as evenness, thickness, shock adsorption, vertical deformation, friction, tensile properties, colour and drainage. The focus is purely on the performance of the products rather than testing for material composition or hazardous substances as part of this certification scheme.

World Rugby Regulation 22 (World Rugby, 2022)

Requirements of Regulation 22 require the manufacturer and facility owner to perform the certification. The manufacturer is responsible for the product to be successfully laboratory tested. Once the field is installed, field testing commences and is repeated every two years. If the field is Regulation 22 complainant, it will likely meet the FIFA certification as well.

The regulation takes into account the environmental impacts with specific focus on microplastics and dispersion into the environment. For the field to be certified it is required to have installed mitigation measures specified in the Regulation 22 (Assessed using methods in CEN/TR 17519).

NRL Rugby League Standard (NRL, 2014) and NRL Performance and Construction Standards 2021 (NRL, 2021)

This certification is based on BS EN 13330-1 and aligned with FIFA Certification and IRB Regulation 22 whenever possible. The certification process includes three stages:

Stage 1- product type approval – the synthetic turf is laboratory tested for performance, durability and material qualities.

Stage 2 – initial facility testing and certification – following construction the pitch is tested to verify the synthetic turf surface has been installed correctly and is providing the anticipated levels of performance.

Stage 3 – pitch recertification – the pitch is re-tested through its life to demonstrate it is still providing a satisfactory and safe playing environment.

As there are limited Australian standards, European and other specific global standards are relied on, for example the European Standards Committee, International Standards Organisation and FIFA test procedures.

In the latest Standards edition (NRL, 2021), environmental and toxicology properties are also required to be tested. The standards require the synthetic turf carpet to comply with the REACH regulations Annex XVII Entry 50 (EU, 2013), performance infill REACH restriction requirement of the European Chemical Agency (20 mg/kg of the REACH 8-PAHs) (ECHA, 2018), and to minimise the impact of microplastics, the field design needs to comply with ASTR 17519:2020 (CEN, 2020).

AFL Cricket Australia Synthetic Turf Certification System (AFL/CA, 2018)

In the first stage, certified products are subject to laboratory tests assessing durability, joint strength, resistance to weathering, ball roll and bounce, hardness, critical fall height, traction and abrasion.

In the second stage, the installed oval must meet the criteria of “fit for play”, which occurs after the oval has been installed and played for a month or 160 hours of play.

Materials in pile yarn are characterised to assess if they replicate manufacturer specifications and the infill material is analysed for the ratio of organic to inorganic materials present. The main focus of the tests is for physical properties rather than chemical composition.

2.5 Other certifications

In addition to sport’s bodies certifications, there are also industry and government certifications. Most of the certifications rely on standards for construction and testing. For example, German government and industry have developed **RAL-GZ 944** – Artificial Turf System for Outside Sports Facility certification, which requires products to be tested according to the existing standards (e.g. EN 15330-1, DIN 18035). This quality assurance tests the entire synthetic turf structure:

- the flooring system and
- installed products are spot-checked on site using random sampling tests.

2.6 Product Environmental Footprints

European Commission proposed the Product Environmental Footprint (PEF) as a common way to measure environmental performance (EU Commission Recommendation 2021/2279). PEF use EU recommended Life Cycle Assessment (LCA) based methods to quantify the environmental impacts of products (goods and services).

ESTC, the trade organisation for synthetic turf industry in the Europe, Middle East and Africa has been developing category rules for PEF assessment for synthetic turf sports and landscape surfaces. The assessment of the environmental footprint is applicable for the entire synthetic turf life cycle. The rules will cover

- performance criteria for a sport system and landscaping application,
- product classification,
- representative products,
- system boundary,
- life cycle stages
- impact categories.

3. Product stewardship in Australia

3.1 What is Product Stewardship

Product stewardship is an approach to managing the environmental and social impacts of products and materials at different stages in their production, use and disposal. It acknowledges that those involved in producing, selling, using, and disposing of products have a shared responsibility to ensure that those products or materials are managed in a way that reduces their impact on the environment and on human health and safety throughout their life cycle. Product Stewardship includes Extended Producer Responsibility (EPR) that was defined by the OECD as “an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of a product’s life cycle”, especially for the take-back, recycling, and final disposal of the product (OECD, 2016).

Product stewardship initiatives can either be collective schemes where multiple businesses putting similar products on the market work collaboratively on delivering product stewardship solutions, or individual business initiatives led by a single business.

Currently there are about 55 collective schemes and many more individual business initiatives. In the case of collective schemes there are 32 active national and state-based schemes and 17 schemes in development. Packaging and electrical and electronic products are the most common product classes in focus. Plastics is also a major area of focus. Two relevant examples are discussed below.

Australian Government Legislation on Product Stewardship

The *Recycling and Waste Reduction Act 2020* and the *Product Stewardship Act 2011* that it repeals provides a framework to manage the environmental and health and safety impacts of products, and substances contained within products throughout the life cycle. The Act covers voluntary, co-regulatory and mandatory product stewardship arrangements and is administered by the Department of Climate Change, Energy, the Environment and Water (Australian Government DCCEEW, 2022).

There is one mandatory initiative the Product Stewardship for Oil Program (addressing machine lubricant oil). There are two national co-regulatory schemes, the National Television and Computer Recycling Scheme (NTCRS) for televisions and computers and the National Environment Protection Measure for Used Packaging (NEPM UPM). Under these national co-regulatory schemes, there are individual government approved arrangements including Ecycle Solutions and TechCollect under the NTCRS, and the Australian Packaging Covenant Organisation (APCO) under the NEPM UPM. The majority of initiatives are voluntary industry led schemes that includes government accredited industry led voluntary schemes. The accredited initiatives are MobileMuster, Tyre Product Stewardship Scheme, Big bag recovery, Fairview aluminium cladding scheme and APCO. There are many more voluntary schemes without accreditation for example Paintback, drumMuster and B-cycle.

Minister’s Priority List

In accordance with the Recycling and Waste Reduction Act 2020, each year the Minister is required to publish a priority product list that identifies products and materials considered to be most in need of a product stewardship approach (Australian Government DCCEEW, 2022). This may include the Minister deciding to implement regulatory measures where industry action has not been taken. This mechanism is intended to accelerate product stewardship activity and give certainty to the community and industry about what the Australian Government is considering for regulation under the *Recycling and Waste Reduction Act 2020*. The process involves public consultation whereby product/ product class nominations are invited for consideration to be included for the next year’s priority list.

Collaboration with state and territory governments – pathways to scheme establishment

Historically the Australian government has collaborated with state and territory governments on national priority product stewardship issues. Recent experience in the case of paint and batteries demonstrates likely timeframes in establishing national product stewardship initiatives of more than 10 years.

One key mechanism for coordination is through the Meeting of Environmental Ministers (MEM). A recent example is for the case of batteries and photovoltaic panels, whereby Australia's Environment Ministers agreed in 2018 to develop new product stewardship schemes to ensure safe management. This year saw the establishment of B-cycle, a national industry led scheme for batteries. Batteries took at least a decade to get to this point with support along the way, for instance, from the Queensland government that led battery collection trials for power tools and rechargeable batteries.

In NSW, the *NSW Plastic Reduction and Circular Economy Act 2021* (described in Section 2) provides a framework to support product stewardship activities for 'regulated products'. This includes requiring brand owners to meet product stewardship requirements around data collection and reporting as well as financial responsibilities.

3.2 Relevant existing product stewardship schemes – principles applicable to the field

Tyre Product Stewardship Scheme

The Tyre Stewardship Voluntary Scheme provides an ACCC authorised, industry framework to effectively reduce the environmental, health and safety impacts of tyres that have reached the end of life in Australia. The end-of-life tyres and tyre-derived products are used in applications such as road surfacing, soft fall playground surfacing, brake pads, industrial and commercial flooring, explosives, or in civil engineering and for fuels for energy recovery. The scheme is funded by tyre importers and automotive manufacturers.

Export of waste tyres are also regulated under *Recycling and Waste Reduction Act 2020* and *Recycling and Waste Reduction (Export – Waste Tyres) Rules 2021.* From 1 December 2021, whole baled tyres or tyres in pieces larger than 150 mm can no longer be exported. With a waste export licence tyres that have been processed into shreds or crumb (<150 mm) for use as tyre derived fuel, tyres for retread verified by Tyre Stewardship Australia's foreign end market program, tyres for re-use, tyres processed into shreds, crumb, buffings or granules can be exported.

From this year, it offers a new initiative to accredit recyclers, where Australian end of life tyres are collected and processed in Australia and placed on the market as tyre crumb. Thus, this scheme could play a role in influencing how tyre crumb is used in the context of synthetic turfs.

Tyre Product Stewardship Australia recently published a study on the health and safety and environment impacts of the tyre particles. They concluded that artificial turfs have been studied extensively and despite ongoing contention related to environmental transport of particles, the literature only pointed to a minor risk towards the environment and human health (Mitchell, 2022). However, the report identifies knowledge gaps regarding microplastic and tyre and road wear particles' pollution and long-term environmental impact studies. The report also notes applicability of studies to the Australian context and assumes analogous tyre materials.

Stewardship for Resilient Flooring

The Australian government has supported the Australian Resilient Flooring Association (ARFA) through the National Product Stewardship Investment Fund to develop a product stewardship scheme for floor covering products. The objective of the initiative is to divert floor covering products such as vinyl, linoleum, and rubber from landfill. Although synthetic turf is not directly in scope for this new initiative there will likely be relevant findings from this initiative, including the development of relevant reverse logistic solutions and reprocessing technology development (Australian Government, 2022).

3.3 Material passport mechanisms for composition and provenance

Material passport mechanisms could be used to monitor the provenance of the materials along the whole value chain of the synthetic turfs. This would be particularly important when recycled materials with potential hazardous and/or toxic chemicals are involved. As it has been demonstrated in the literature and reported in this report, the concentrations of PAHs in rubber infill depends on the tyre manufacturing process. Considering the difference in regulatory requirements around the globe, tyres will be manufactured with different levels of PAHs arising and consequently installed in the synthetic turfs.

Material passports could include the properties of material being passed along the supply chain and assigned a value according to the properties and prominence.

Certifications could also be used to understand the safety and provenance of materials used in the construction of synthetic turfs but also to ensure that these fields are maintained properly.

Approaches taken in other sectors

Provenance verification – use of scientific testing services to determine provenance. For example, SourceCertain (SourceCertain, 2022) determines origins of the supply chain using laboratory testing, databases and forensic science.

Authentication platforms – use of blockchain technology to identify origin, ownership and characteristics of a product. For example, the Everledger Platform (Everledger, 2022) uses blockchain technology to provide transparency in global supply chains.

3.4 Development of new sustainable products

Biobased synthetic turf (SYNLawn, 2017)

Polyethylene can be produced from a sugar cane (SYNLawn) that is sustainably grown under environmental, social and industrial practices. The synthetic turf is combined with soy-based (EnviroLoc) backing technology making it a completely biobased synthetic turf.

4. Knowledge gaps in chemical composition of materials used in synthetic turfs

This report identified a number of important gaps in the current state of knowledge regarding the chemical composition of synthetic turfs. To address these gaps and increase transparency of information regarding chemical composition the following overarching principles and actions are proposed with the intention to drive improvements in performance and safety.

Principles and actions

- **Fostering circular economy principles with implications for material safety**

  The implementation of circular economy principles ensuring that products are designed to last and hazardous materials that may be problematic in use or at the end of life are avoided. Considering end of life, the waste hierarchy should be followed by prioritising re-use, followed by re-purposing and recycling. While in principle this should deliver a desirable outcome, end of life options should also be assessed to ensure there are no perverse outcomes.

- **Developing new materials and components for the environment**

  There is potential to expand the scope of innovation and development of new materials beyond performance and playability to include environmental and social aspects as well, and to explore options for bio-based materials.

- **Characterising all toxins in the system**

  Further analysis of the material components in the synthetic turfs is needed not only from the players' safety perspectives but also from the environmental point of view. There is a disagreement in literature regarding the safety of some of the chemicals, especially PAHs. US EPA has recently released a research report characterising synthetic turf fields using recycled tyre crumb rubber and there is ongoing work characterising player exposure that has been delayed due to covid. This report is anticipated to be released soon and will provide multi-year data on informing future management approaches (US EPA, 2022).

- **Product stewardship approach**

  Product stewardship approach should be evaluated to reduce the environmental and social impacts across the whole product lifecycle. Product stewardship actions focused on production could include design requirements and improved supply chain practices. Information requirements providing material provenance relevant to disposal and recycling could be introduced. Regulatory tools at the NSW and Australian government levels could support such product stewardship approaches.

- **Providing material provenance**

  The material passport concept is an approach for providing greater information on provenance of materials. Such approaches are increasingly important in the context of the circular economy to avoid the potential risk of circulating hazardous materials in new product or material lifecycles. Technologies such as blockchain or tagging could be explored to implement this concept.

- **Addressing gaps in certifications**

  Comprehensive certifications could be required that focus on performance and maintenance practices. Such approaches should be considered for all applications from elite sports to community sport, and for private and business settings.

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Appendix 6

Environmental Impact of Synthetic Turf: A Life Cycle Analysis (LCA) Review and Circular Economy Perspective

Environmental Impact of Synthetic Turf: A Life Cycle Analysis (LCA) Review and Circular Economy Perspective

Independent Experts Advice

August 2022

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Disclaimer

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Executive Summary

The University of Sydney (USYD) through its Waste Transformation Research Hub (WTRH) was commissioned by the Office of the NSW Chief Scientist and Engineer (OCSE) to provide expert review and advice on the Life Cycle Assessment (LCA) of turf surfaces, aiming to identify overall trends in the environmental impact of products and to critically assess gaps in knowledge, methodology, and data surrounding the LCA of turf. This report contains the expert review, followed by a discussion on strategies around Circular Economy (CE) solutions for the emerging Synthetic Turf (ST) industry.

Section 1 explains the need to review the environmental impact of current turf, outlining the main aim of the report, which is to provide a review of the available scientific knowledge on ST LCA and CE, and to use the findings to guide the future of the ST industry in NSW. ***Section 2*** describes the methodology chosen to compare publicly available LCAs. The results are extracted from each LCA, where a relative difference is calculated between different scenarios. This allows a comparison of the different LCA findings, without the need for excessive data streamlining. A total of 8 different LCAs were reviewed. The key findings of this review are highlighted in ***Section 3***, where the technical results and discussion of the review are provided in ***Sections 6 and 7***. Lastly, ***Section 8*** discusses different strategies to make the ST supply chain more circular.

The findings and recommendations are summarised in Table 1, while the CE graphical strategy is outlined in Table 2, Figure 1, and Figure 2, in the following pages.

Table 1: Summary of finding and recommendations

Category	Key finding	Recommendations
LCA results and trends	Most LCAs agree with the premise that ST implementation leads to lower maintenance, resulting in lower water consumption, eutrophication impact, and maintenance energy requirement. However, ST has a higher global warming impact due to virgin plastic production, given the use of fossil fuels in their manufacturing processes. This impact can be reduced by using recycled materials, or increasing the usage rate of the turf surface, thereby modifying the cost/benefit ratio. Nonetheless, the LCA methodology does not consider some other important impacts, such as due to leaching of PAHs, microplastic pollution, and the urban heat island effect. In contrast, Natural Turf (NT) has a lower global warming impact and may act as a carbon sink, but since it requires constant growing and water use, it results in a higher eutrophication impact. Moreover, water consumption requirements may be the determining factor in turf selection. However, it is important to note that NT water use data is geo-dependent due to varying weather, soils, and other conditions that impact its growth. Hence, the data collected may not be applicable for future scenarios and does not translate geographically.	This finding highlights the variability between LCA studies and how the framework adopted can impact the result. Hence, LCAs should be conducted on a case-by-case basis, and their findings are not always translatable. It is also important to note that LCA is not a perfect tool, the result is as "good" as the input data.
LCA framework – Functional Unit	Including usability time (aka: usage time, playtime, consumer benefits, hours of use, etc.) in the functional unit, may skew the results towards preferring ST. Some LCAs argue that STs provide higher usability time as they do not need a growing phase or create muddy surfaces during rainy conditions. Employing usability time is a valid strategy. However, it is important to assess whether ST does have a higher usability time to justify this assumption.	It is recommended that relevant agencies in NSW Government collect sufficient information related to turf type and its usage time, normalising the data against location (climate condition) and sport type. With this information, LCA assessors can have the confidence to assume whether ST has a higher usability or not.
LCA framework – System boundary	There is significant diversity in system boundary definitions amongst turf LCA. An incomplete system boundary may omit certain stages of the life cycle that could contribute significantly to the environment. Some LCA studies do not include material transport into the field, a clear turf replacement strategy, or proper EOL management. It is speculated that lack of data availability may have influenced the system boundary of the reported LCAs.	The full recommendations are provided in Table 12 (section 6.2.2). In short, a turf LCA framework should consider including transport, replacement strategy within its useful life, and EOL that reflects real life data in their system boundary. Most importantly, LCAs must be transparent about their system boundary and data sources. It is important to note as well that a ST LCA category rule may be published at the end of 2022. (flemigESTC, 2022a).

Category	Key finding	Recommendations
LCA framework – Other	There is a limited number of LCAs for the authors to confidently conclude whether a specific framework is the best practice for turf LCA. Obtaining valid input data appears to be the most challenging part of turf LCA. Some studies combined data from various sources, which may not be valid for ST products, while NT growing data varies depending on the weather. The lack of data for ST, along with the location-based variability of data for NT, complicate the analysis and comparison of turf LCAs. Thus, many studies tend to adopt drastic assumptions to verify their source data. LCA can comprehensively provide a critical information of environmental impact if executed properly.	If turf LCA is expected to be standardised in NSW, it is recommended for the NSW Government to consult with Australian LCA database providers and discuss whether the necessary data is available in Australia. Moreover, councils should be transparent about their turf consumption and maintenance data. These actions may assist in the creation of a comprehensive turf database. For LCA assessors, it is wise to review multiple data sets for the same turf product. This step might eliminate biases and potentially normalise the data. LCA assessors should be practical about what they can achieve from the available dataset. Feeding the system boundary with external data that is not true for the local context may not produce a useful finding. Such action would require a valid justification. Furthermore, LCA is only one tool in a feasibility study. Hence, it is wise to complement it with other assessments (wastewater, cost, microplastic, etc.), depending on the specific needs. Other life cycle extension techniques that can assist in better understanding of social, ecological, and environmental impacts to inform future design approaches are: Eco-LCA, Life Cycle Costing Analysis (LCCA), Economic Input Output (EIO) LCA, and Social-LCA.
Circular Economy – Materials input	Some ST materials and designs do align with the CE perspective, such as biobased turf from sugarcane, using treated olive stones as infill, designing a cooler ST with a water reservoir, eliminating the need for infill, and adding sensors to improve the lifespan of ST. However, advances in other aspects of ST, such as adopting a complicated plastic blend or installing a complex shock pad, may hinder the CE shift as these may complicate the recycling process and consume more materials.	Councils should review sustainable materials and prioritise recycled material for ST. At the same time, they should consider how the different material options can impact recycling and EOL practices. This impact should be included in the feasibility study. If possible, councils may conduct an LCA or other assessments for the different ST products and implement the ST based on their LCA findings.
Circular Economy – Business Model	Improving longevity and transforming business practices are equally crucial in CE. A transformation can happen by implementing a leasing practice, where councils transfer the responsibility over the product to the supplier, becoming responsible for the installation, maintenance, and EOL. This will encourage the supplier to educate the user in maintenance and best practice, since having a long turf lifespan is in their interest.	It is unclear whether any sport-grade turf supplier has adopted the lease business model. Councils should consult with the ST provider to discuss whether this is an option for them. If such practice is unavailable, councils should choose a supplier that has a clear "service-after-sales" practice. This may help to educate the users on best practices, which may improve ST longevity.

Category	Key finding	Recommendations
Circular Economy – EOL	Despite existing recycling practices, ST recycling is still riddled with challenges, given that they only operate with a small capacity centred around Europe. ST material separation is costly and complicated, producing a poor-quality recycled material that is only suitable for incineration or downcycling. In an ideal CE scenario, materials should be recycled back into the equivalent product or at a higher functionality. Current efforts exist in chemical recycling and standardisation of the recycling practice	To assist the ST recycling industry, councils should develop clear EOL strategies during the planning stage. They should consider adopting infill free systems, practice the best maintenance to improve ST lifespan, reuse shock pads and ST for other purposes, and demand a clear EOL strategy from the manufacturer. At the same time, Government should regulate the ST EOL, by controlling the waste export and landfilling practice for this material. There is also a need to establish a sufficient capacity for ST recycling in Australia that meets the local needs, while supporting the research in chemical recycling.

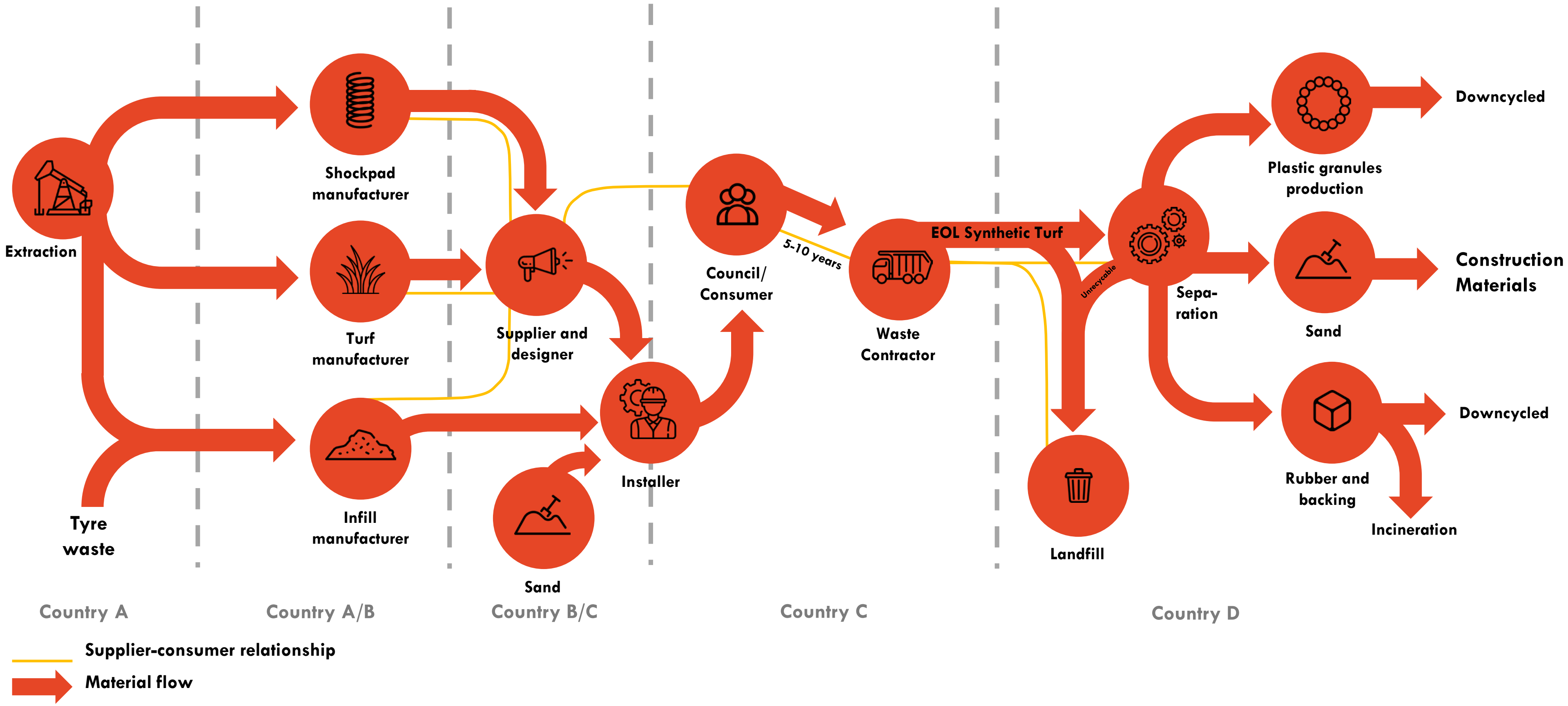

Figure 1: Current "Linear Economy" model of synthetic turf supply chain.

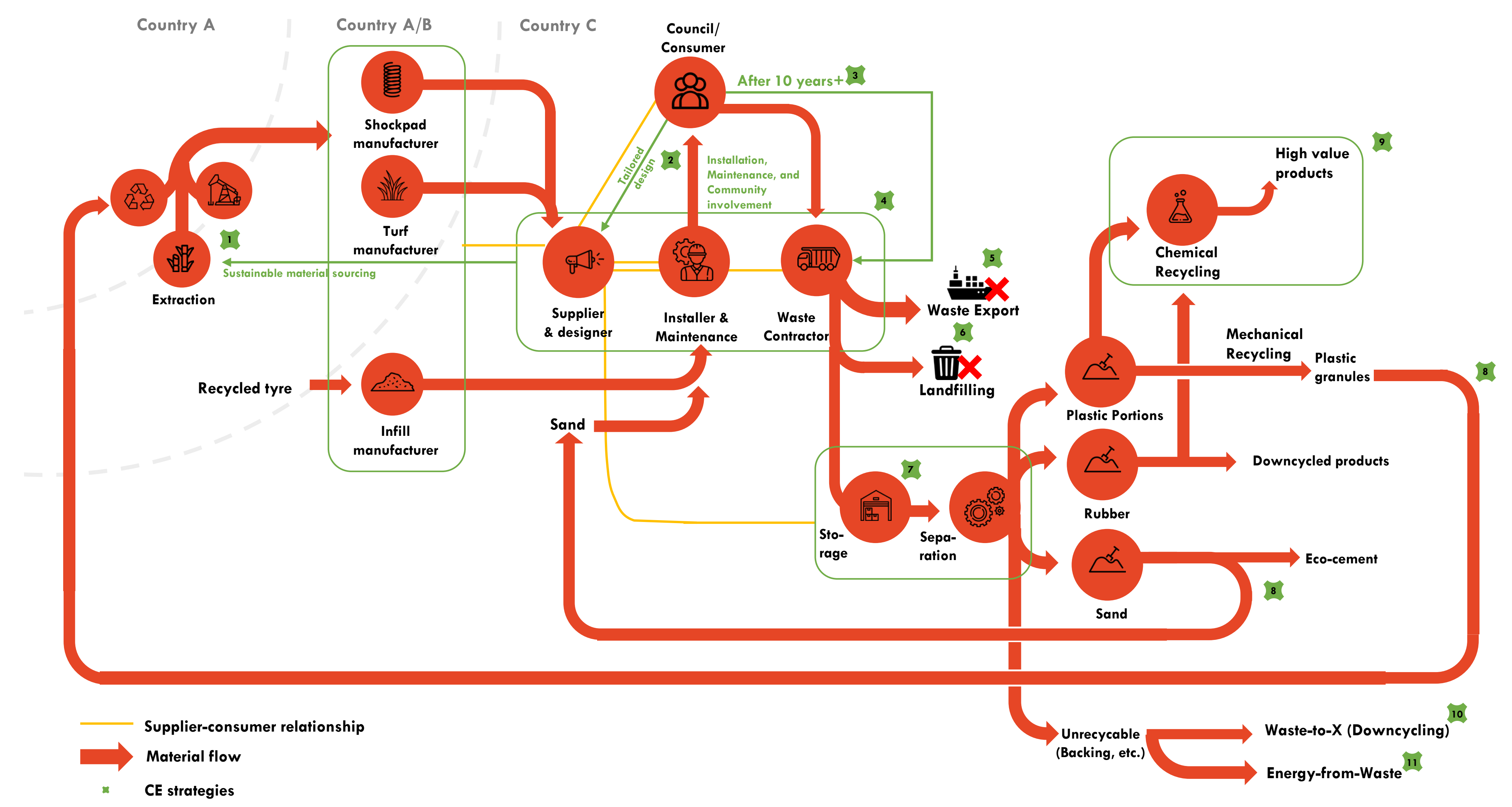

Figure 2: Towards circular business model for the synthetic turf industry

Table 2: Summary of potential CE strategies for ST

No	Strategy	Description
1	Sustainable material sourcing	Consider regenerative material (biomass) or prioritised recycled material (from other products with higher functionality, downcycling).
2	Tailored design	Consumer to consult with the supplier to enable a tailored design to minimise unnecessary material consumption
3	Improving longevity	By choosing a supplier that has a strong service-after-sales, users can be aware of proper maintenance, which results in a longer product lifespan.
4	Extended Producer Responsibility (EPR)	The supplier is responsible for product maintenance, installation, and EOL. This means instead of the consumer contacting a third party for EOL cost, the service is included throughout the product's life cost. This business model can be done through a service model or ownership model. This aligns with improving longevity as a longer lifespan means a lower cost for the supplier.
5	Regulate waste export	Waste export should be avoided for this material to mitigate unregulated EOL practices. Waste export is only encouraged when ST is imported to a country with a better and proven ST recycling infrastructure, e.g. FIFA send ST to be recycled in Denmark (State of Green, 2017).
6	Regulate landfilling practice	High gate fees and subsidies for recycling would encourage business leaders to redirect waste material into a recycling facility.
7	Regulate storage capacity	Storage capacity should be regulated to avoid stockpiling practices.
8	Recycle material to equal value	In a circular economy, the material is recycled into a product with similar functionality.
9	Recycle material into higher value	In the future, chemical recycling may be preferred since this pathway is arguably more resilient to market demand due to its versatile material production.
10	Waste-to-X	Converting the material into other products.
11	Energy-from-waste	Although this is not classed as circular economy, such strategy still aligns with waste management hierarchy and is arguably better than landfilling.

Contents

Abbreviations

CAGR	Compound Annual Growth Rate
NSW	New South Wales
ST	Synthetic Turf
NT	Natural Turf
FIFA	International Federation of Association Football
OCSE	Office Chief Scientist & Engineer
CE	Circular Economy
ESTC	Europe, Middle East, and Africa Synthetic Turf Council
EOL	End of Life
EPR	Extender Producer Responsibility
LCA	Life Cycle Assessment
IC	Impact Category
ISO	International Organisation for Standardisation
EFW	Energy from Waste
p.a.	per annum
UHI	Urban Heat Island
Chemicals	
GHG	Greenhouse gases
VOC	Volatile Organic Carbon
PAHs	Polycyclic aromatic hydrocarbons
POPs	Persistent Organic Pollutants
PE	Polyethylene
HDPE	High Density Polyethylene
LCA impact categories	
AD	Abiotic depletion
AP	Acidification Potential
EP	Eutrophication potential
GHG	Greenhouse gases
GWP	Global Warming Potential
HH	Human Health
HTC	Human toxicity Carcinogen
HTNC	Human toxicity non-carcinogen
IR	Ionising radiation
MR	Mineral Resource
ODP	Ozone Depletion Potential
PEC	Primary Energy Consumption
PM	Particulate matter
POCP	Photochemical Ozone creation potential
RMC	Raw Material Consumption
SWG	Solid Waste Generation
TP	Toxicity Potential
WE	Water Emission

1 Introduction

Worldwide, various governing bodies are rapidly installing synthetic/artificial turf. The synthetic turf market is expected to grow to $7 billion by 2025 (at CAGR of 6.84% from 2020 to 2025) (Global News Wire, 2022).

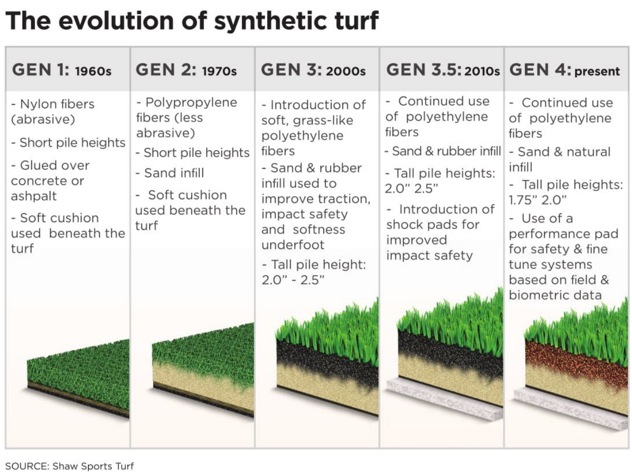

Figure 3: The evolution of synthetic turf (Pare, 2019; Shaw Sport Turf, 2022)

In short, synthetic turf is a grass surface made of human-made fibre – usually nylon or polyethylene blend (Pare, 2019) – that is installed to mimic natural grass for sporting and commercial uses. Current synthetic turfs have a tall pile height, complete with shock pads and infill (composed mainly of sand and rubber), which are claimed to mimic natural grass even more than the previous design (Pare, 2019). Figure 1 describes the evolution of synthetic turf. Synthetic turf has become a lucrative option in terms of cost-saving features and quality consistency. However, concerns arise around its environmental impact, especially due to its artificial origin.

Table 3: Pros and Cons of Synthetic vs Natural turf (from the environmental perspective).

	Pros	Cons
Synthetic turf	- Water conservation - Uses recycled tyres that otherwise go to landfill - Longer useful life - Available at any time anywhere	- Potential run off pollutants - Require backing and infill - Require maintenance in the form of cleaning, conditioning, and replacement. - Odour build up - Made of petroleum-based chemicals
Natural turf	- No potential pollutant runoff (in terms of human-made polymers) - Acts as carbon sink	- Require specific climate to grow - Significant water usage in the growing and maintenance stage - Require constant maintenance (mowing, fertiliser, and watering) - Eutrophication potential - Less useful life i.e., constant replacement

Thus, this report aims to review the available scientific knowledge on Life Cycle Assessment studies of synthetic turf. The findings of this review can potentially be used to guide policy, circular economy strategies, and research directions for synthetic turf in NSW.

2 Review Methodology

There have been several studies reported that investigate the potential environmental impact of synthetic turf. These studies have varying objectives and assessment techniques, ranging from leaching potential (Verschoor, 2007) to air quality impact (Lim & Walker, 2009).

To fully understand the environmental impact of synthetic turf, this report reviews Life-Cycle-Analyses (LCAs) that compare synthetic turf with other alternatives. The result of this LCA review is then assessed against other environmental studies to shed further insights. Lastly, consultations with industry and researchers are presented to further verify our findings.

2.1 LCA comparisons

LCA is a standardised technique for assessing the environmental impacts throughout the life cycle of certain products, processes, or services (Finkbeiner et al., 2006), where the life cycle is defined in terms of a system boundary. For detailed definitions of functional unit and system boundary, as used in the context of a LCA, please refer to Sections 6.2.1 & 6.2.2, respectively. By leaning on this technique, this report aims to assess the environmental impact of synthetic turf in comparison to that of natural turf (base scenario). Because of this objective, the review is limited to LCA studies that compare various turf products.

Although there is an ISO framework to govern the LCA methodology, the method still allows room for interpretation, which may lead to different results (Laurent et al., 2014). Furthermore, the diverse system boundaries, data sources, assumptions and scenarios produce complexity in reviewing different LCA studies.

Hence, we adopt a comparison technique that is outlined by Istrate et al. (2020). This method compares the environmental impact of synthetic turf to its respective base scenario by calculating a relative difference. This allows reviewers to compare the result of different LCA studies without excessive data streamlining. From this, we can estimate the trend of synthetic turf environmental impact across different studies and analyse the causation and possible outliers. Figure 4 illustrates this method. Table 4 list the details of the LCA study used for this review.

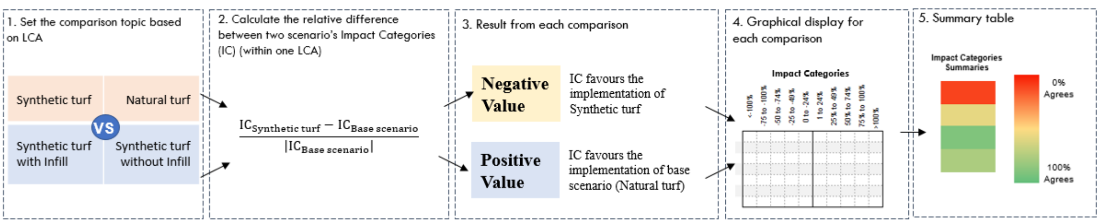

Figure 4 steps to produces relative differences in each study which is used to estimate trends.

Table 4: Summary of LCA studies reviewed for comparison

Author, Year, and Affiliation	Functional unit Location	LCA tools (Model & method) and data origin	System boundary and EOL	Impact Categories	Scenarios	Comments
Adachi et al. (2016) UCLA	1 m^2 for 15 years California, USA	Online tool EIOLCA Input originated from various source (See table 1 in the document)	NT: Production (Turf, fertilizer, and seeds), power generation, water and solar energy ST: Production (Rubber, blade, mesh), power generation, and water EOL: do not take into consideration EOL	Water and cost	Sc1 Sod (Natural grass) Sc2 Synthetic Turf (recycled tyre, polyethylene, and polyester fabric)	- Do not follow any LCA standard - Provide sensitivity analysis
Uhlman (2013) BASF Chemical company	Functional Unit: "Costumer Benefits (CB)" or 75,000 ft^2 for 600 hrs/year over average of 20-year time frame. Conditions above varies between turf selection USA, unspecified state	Did not specify tool Input originated from various sources (USA and Germany) (See table 11 in the document)	ST: Production (Yarn, backing, infill, base, and drainage), transport, installation, maintenance, disposal, or recycling NT: Production (Seed, topsoil mulch, fertilizer, field paint, and base), transport, installation, maintenance, return to the natural state EOL: NT removed at 20 years, while for ST is assumed that the required infrastructure to recycle plastic blades is readily available.	PEC, RMC, GHG, POCP, ODP, AP, WE, SWG, TP, Land use, Work accident, risk potential, and cost.	Sc1 PureGrass ® (Nylon, no infill) Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill) Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill) Sc4 Natural grass (available 600 hrs/year) Sc5 Natural grass (available 432 hrs/year) Sc6 Natural grass (available 360 hrs/year) Sc7 Natural grass (available 300 hrs/year) Sc8 Natural grass (available 200 hrs/year) Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	- All ST is by AstroTruf ® - All ST is completed with polyester woven, polyurethane precoat, and drainage - Would argue the Best LCA for synthetic turf out there. It considers playtime, synthetic turf durability, and useful year.
Cumming (2019) Hort Innovation Infotech Research	1 m^2 for 5-10 years Across Australia, claim it involved by 30 natural turf growing sites.	Open LCA with Eco Invent Database Data collected from industry Claim to follow ISO 14025	NT: Growing and harvesting, transport, installation, and maintenance (Mowing and fertiliser used) EOL: Turf return to the biosphere	GWP, ODP, AP, EP, POCP, AD, HTC, HTNC, Water use, land use, freshwater toxicity	Sc1 Natural turf (1 Year) Sc2 Natural turf (for 5 years) Sc3 Natural turf (for 10 years)	- Only assess natural turf (one scenario), not what we are after here.
Itten et al. (2021) ZHAW Institute of natural resource science for the City of Zurich	1 hour usage for sport (soccer) Zurich Switzerland	Data collected locally ISO 14040/14044	N/A, Full Report is in German	GHG, IR, EP (Freshwater, marine, terrestrial), MR, HH, PEC, Eco-toxicity, land use, and air pollutants	Sc1 Natural Turf without drainage layer (480 Hrs usage) Sc2 Natural turf with drainage (800 Hrs usage) Sc3 Hybrid turf, reinforced (1000 hr) Sc4 Artificial turf without plastic or granules infill (16000 hr) Sc Artificial turf with plastic infill (16000 hr)	- Unspecified disposal strategy and ST. - Full report is in German - From The German report, ST is composed of 7.5% PP, 40% PE, 25% Nylon, and 27.5% Latex
Magnusson and Mácsik (2017) Lulea University, Sweden	Time of artificial turf allowed to play football for a year in a football size of 7881 m^2 for 10 years. Sweden	Data were estimated to mimic real field in Sweden, collected from various sources (See table 3 in the document) Claim to follow ILCD Handbook 2012	ST: Primary energy resource for material extraction, production, construction, use and maintenance, and disposal (landfill or incineration) EOL: Landfill or incineration but did not assess it within the different infill materials.	GHG emission Energy use	Sc1 Synthetic turf with recycled tyre infill Sc2 Synthetic turf with Thermoplastic elastomers infill Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill Sc4 Synthetic turf with recycled EPDM infill	- Compares the different infill materials for synthetic turf production, with no assessment on the natural turf. - Also assess infill leaching.
Meil and Bushi (2007) Athena Sustainable Material institute, Canada	9,000 m^2 for 10 years Ontario, Canada	LCA done in SimaPro 7 with Ecoinvent library, along with various other sources. (See page 6 in the document)	NT: Transport, Production (PE, Thioback Pro Backing, PU, Rubber granules, PVC piping), bonding, maintenance, and disposal ST: Grass seed, plant matter production, transport, natural grass carbon sequestration and maintenance EOL: Recycling, with GHG savings based on ICF consulting report (No source found)	Greenhouse gases emission (GHG)	Sc1 Natural grass Sc2 Synthetic turf (Made of Thioback Pro backing material (USA), rubber granule infill, Polyethylene turf, and PVC drainage piping)	- Only compares global warming impact - The functional unit is the same for both. In other studies, we notice that they take into consideration active playtime.
Russo et al. (2022) University of Foggia, Italy	1 soccer field the size of 7140 m^2 with 10 useful years Italy	Gabi, with database: Sphera Dabatase, (From Plastic Europen) and Eco invent.	NT- Cradle to grave: excavation, soil preparation, irrigation system, installation, maintenance, and return to biomass ST: Production (plastic, infill, and shock pad), maintenance, and disposal of plastic material EOL: Claim to have a mix strategy of recycling and landfill for ST, however it is not specified what strategy in place to achieve this.	GWP (fossil fuel, biogenic) ODP, HTC, HTNC, AP, PM, IR, POCP, EP (Freshwater, marine, terrestrial, water use, land use, mineral use, ecotoxicity for freshwater,	Sc1 Natural turf Sc2 Artificial/Synthetic turf: Shock pad of 88% used tyres, adhesive, PE-HD and PP artificial turf, and used-tyres for infill materials	- Discuss from CE perspective, with some recommendations to improve both ST and NT
Säberg (2021) Linkoping University, Sweden	8214 m^2 in accordance with FIFA usage. Sweden, across different areas.	No LCA tools, data collected independently and The Ecoinvent database and Swedish Football association	NT: Grass production, grass growing, harvesting, transport, maintenance, and disposal ST: Production (Carpet (PP, PE, PU), Rubber or Cork infill), maintenance, and disposal EOL: Landfilling	Water usage CO_2 Emitted	Sc1 Synthetic turf (total, without infill) Sc2.1 Synthetic turf + Cork infill w landfill Sc2.2 Synthetic turf + Cork infill w incineration Sc3.1 Synthetic turf + Recycled tyre infill w landfill Sc3.2 Synthetic turf + Recycled tyre infill w incineration Sc4 Natural turf	- The result is discussed based on the regions, how their climate can adapt to NT, and the proximity to the waterway. - EOL Incineration is assumed to be CO_2 savings than landfilling, through energy production

3 Key Takeaways

From the available and reviewed body of knowledge, it is possible arrive at conclusions based on the available LCA data. Results and full analysis are presented in sections 5 and 6

3.1 Takeaway I: Synthetic Turf (ST)

1. Most LCAs agree with the premise of ST implementation being preferable. Opting for ST reduces water and resource consumption, which also reduces the eutrophication impact and pollutants emitted during the maintenance stage.
2. However, ST requires a higher energy consumption and generates more greenhouse gases (GHG). This is due to the requirement of virgin plastic material production.
3. The impact of GHG can be reduced by (1) using recycled materials as infill (recycled tyres) and blades or (2) if ST is proven to have longer usage time than natural grass, as this contributes to a lower cost/benefit ratio. Some researchers argue that due to the higher durability of ST, there is potential for ST to be used more intensely than natural turf.
4. Other environmental concerns about ST that may have not been captured by LCA are:
    1) Recycled tyres may contribute to the leaching of VOCs, heavy metals, and PAHs.
    2) Wear and tear that contributes to microplastic pollution.
    3) Use of liquid softener and disinfectants for maintenance
    4) Potential environmental impact owing to the Urban Heat Island effect.

3.2 Takeaway II: On Natural turf (NT)

1. NT has a lower GHG and energy requirements to be produced, despite requiring constant maintenance throughout its life cycle. NT may also act as a carbon sink, although it is important to consider the EOL of clippings. If clippings are being landfilled and converted into methane, the assumption of NT being a carbon sink may be inaccurate.
2. Most studies that conduct NT versus ST cost comparisons do not find substantial lifecycle cost differences between the two implementations. However, if ST has a higher usability time and is being used more intensely than NT, this translates to a lower cost/benefit ratio for ST, hence increasing its return on investment.
3. NT require constant watering throughout their useful life, which can be challenging for a dry area. Improper management of NT in an urban area may lead to higher eutrophication impact, but more studies are required to confirm this. Best practice on NT management exist (Sydney Water, 2011).
4. NT growing and maintenance requirements are influenced by local climate, soil conditions, and other factor that influence the turf growth. Hence, NT data is not always valid for every future scenario and does not translate geographically.

3.3 Takeaway III: LCA framework for turf products

Full discussion is presented in section 6.2

3.3.1 On Functional Unit

Some studies include usage time/usability as their functional unit. This standardises the environmental impact of the turf to the amount the usage time associated with certain activity/sport. This is useful because different scenarios (i.e., the different turf products, different locations with varying sunlight hours, etc.) may relate to different capabilities to offer usable hours. This assumption sets the tone for the environmental impact, modifying the result depending on the ability of the product to offer usable hours.

Including usability time is a valid strategy, but it is important to assess whether ST has a higher usability time than NT for its users. This can be done by reviewing sufficient data to investigate whether there is a significant difference in usage time between ST and NT for the same activity and same weather conditions.

Some recommendations are:

1. The relevant NSW Government agencies collect data from local councils and sports organisations to review their:
    a. location (and possibly climate condition) and the type of turf.
    b. hours/number of activities on the turf,
    c. type of sports, number of athletes, and their category (children, teenagers, or adults)
    d. How often the turf is being replaced

   By collecting this information, assessors can confidently determine the correct functional unit for a specific activity. In the case that the survey found that for a specific sport/activity both ST and NT have the same usability time, the LCA can resort to surface area (i.e., in m^2) as its functional unit. Sport Turf Institute (2009) provide more elaborate details in how to measure optimal use of a sport field.
2. If usability time is included in the functional unit and scenarios, the assessor should provide clear evidence that the usage time between the two turf products is different.
3. Sports Turf Institute has reviewed 300 sports turfs from 18 councils in Australia. They created a database that standardised turf performance in the face of climate and activity variance (Holborn, 2009; Roche et al., 2010; Turf Finder, 2022). The database is claimed to be available to the participating councils. This database will be a useful information for functional unit determination, and even possibly the LCA objective, that is assessing the different scenarios (e.g., climate, sports activities, surface type, etc.). similarly, Neylan and Nickson (2019) assessed four different playing surface usable hours throughout different activities and weather conditions. It is recommended that NSW Government discuss possible data sharing with participating councils or with the organisation.

3.3.2 On System Boundary

The system boundary is open to the interpretation of the assessor. However, an incomplete system boundary can omit stages of the life cycle that may contribute significantly to environmental impact. From this review, it was possible to observe that a significant number of studies do not have a comprehensive system boundary, with questionable assumptions such as lack of turf replacement, omission of transportation, and invalid EOL management. It is speculated that unavailability of data may have influenced the choice of LCA system boundaries.

From an academic research perspective, there is a lack of LCA that assess proper EOL, and how different management, material, and design might influence this result.

Full technical LCA advice is available in Table 12 (section 6.2.2). In short:

1. LCAs should reference the origin for ST composition, manufacturing process, and energy sources for production. Consultation with manufacturer is highly recommended.
2. Proper transport of material in and out of the field should be considered.
3. Evidence should be provided that the turf will not need any replacement within its useful life. If replacement is needed, outline the renovation process and consider whether the replacement period will be the same for different turf products.
4. NT data (growing and maintenance) varies on the climate and geography. Hence, LCA needs to outline the decision behind data selection or any data treatment (averaging, analysis, etc.) done on the NT data sets.
5. Proper EOL strategy for turf products should be considered, i.e., one that is based on real life EOL management, and its efficacy should also be considered.

3.3.3 On Data Origin, study motivation, and other assumptions.

In the research community, researchers often tailor LCAs for a specific industry, establishing a unique best practice for each industry. Unfortunately, there is not a sufficiently large number of turf LCAs to be able to confidently conclude whether a specific framework is the best practice. Within the available LCAs, there is a diverse variability of data origin and objectives.

Some studies combine data from various independent studies, which are later used accordingly, depending on the turf composition. While this method is a valid strategy, assessors should proceed cautiously as these data may not be valid for every turf blend. Moreover, for NT, the data is only true locally and during the specific weather conditions when the data is collected.

If turf LCA is expected to be the standard for NSW's environmental impact assessment, it is advised that the relevant NSW Government agency consults with the LCA database provider and assess whether such database is available in Australia. Meanwhile, councils should be transparent about their local turf consumption and maintenance data, enabling collaboration for a more comprehensive turf database.

Some advice for LCA assessors:

1. The assessor should review two or more data sets for the same turf product under different operating conditions (climate, activity, etc.). This step might help eliminate biases and potentially normalise the data. If there are significant discrepancies between the data sets, assessors should take an extra step to analyse the data before feeding it into LCA.
2. Ideally, when comparing ST and NT, both data sets should be collected within proximity and the turf used for similar activities.
3. LCA assessors should be practical about what they can achieve from the available dataset. Feeding the system boundaries with external data that is not true for the local context will not produce a useful finding. Excessive streamlining would require justification. Data inaccessibility should be highlighted along with all the assumptions.
4. When collecting data from manufacturer/industry (e.g., ST performance or composition), assessors should consider whether an independent analysis is required to confirm the manufacturer's claims.

3.3.4 The (near) future of turf LCA

As ST uptake is expected to increase, the environmental impact of ST might be further scrutinised. Hence, a proper and standardised LCA is expected. EMEA Synthetic Turf Council (ESTC) is currently curating a category rule for ST products (ESTC, 2022a). Category rule is a methodological guidance for assessors to follow; such guidance is expected to standardise the LCA method across diverse conditions (European Commission, 2011). This may improve the consistency and overall reproducibility of ST LCAs. The upcoming report is claimed to provide category rules for product environmental footprint of ST for sport and recreational activity. The report is expected to be published by December 2022 (ESTC, 2022a).

Relating this to NSW, such category rules are expected to be transferable, particularly for establishing boundary conditions and a functional unit. However, it is still important to carefully assess the assumptions and databases, especially considering Australia's stark differences to EMEA in (1) distance from the manufacturer, (2) climate condition, (3) preferred sport activities, (4) available EOL infrastructure and management practice, and (5) regulatory differences in rubber crumbs and other materials.

3.3.5 Final notes

LCA is a comprehensive method that, when executed properly, can provide a complete understanding of a product's environmental impact. For ST, extra attention is needed during the data collection and scenario creation. Assessors should ensure that there are no excessive assumptions that may potentially skew the outcome. If a full dataset collection is unfeasible, assessors should consider a targeted life-cycle study, such as water and/or energy consumption, prioritising accuracy by reducing complexity.

On the cost note, if Life Cycle Costing Analysis (LCCA) is to be conducted, such analysis may be more feasible than LCA. Transaction records that are digitally stored can be easily collected, treated, and used for LCCA. This can also provide insights into maintenance cost variability throughout seasons and different activities, which can be taken as a preliminary analysis and a gateway for LCA.

Overall, cost and environment are only some aspects of the decision-making process for turf implementation. A comprehensive guide should also consider health, safety, performance, and feasibility of the project. Although reviewing turf selection criteria is outside of the scope of this report, some useful references are outlined here:

1. City of Melville (2011) assess the feasibility of ST implementation. The assessment is mainly around cost and financial impact, with minimal regard to the environment apart from its water savings feature.
2. Victoria State Government (2011) A technical guide for planning, selection, installation, and replacement strategy for ST across multiple sport, it considers the life-cycle costing, planning and constructor' selection, and surface evaluation model.
3. Football NSW (2015) claim to be a guide for ST selection, considering the safety, testing, and capital investment required.
4. Talbot et al. (2019), A four stage decision making guideline, namely, estimating demand, considering options, cost analysis, and procurement
5. AECOM Australia (2020), assess the environmental impact of ST implementation, such as landscape, air quality, and socio-economic impact.
6. Government of Western Australia (2021) provide a multistep decision-making guide that consider turf demand, environmental impact, social and health impact.

It is apparent that some of these "guidelines" do not have a clear strategy for the ST EOL. Thus, the next section discusses the CE aspect of ST industry, and how current practice can be aligned to them.

4 Emerging trends for Circular Economy

CE is a holistic framework that transforms the supply chain to tackle and minimise environmental, social, and economic impact by eliminating waste, circulating product at the highest value, and using regenerative materials (Ellen MacArthur Foundation, 2022). Various approaches and strategies exist within the CE. Kalmykova et al. (2018) reviewed 100 different case studies of CE implementation and categorised them as 45 distinct strategies implemented in 9 different stages of the supply chain. From this review, a selection of applicable strategies and how they may be relevant for the synthetic turf industry are summarised in Table 5.

Table 5: Selected CE strategies from Kalmykova et al. (2018) and possible implementations for ST. Note further research may be required to investigate the feasibility of each strategy.

CE Strategy	For ST product
	1. Material Sourcing
Energy production/Energy autonomy	Make sure manufacturing process has minimal environmental impact.
Diversity and cross-sector linkages	Utilising waste material from other sectors.
Material substitution	Priorities recycled material.
Taxation	Virgin material taxation.
LCA	Assess the most beneficial material.
Functional recycling	Making sure ST is recycled back as ST
High quality recycling	Chemical recycling to produce feedstock chemical with minimal contaminant, producing raw material again.
Industrial symbiosis	Making sure by-product from ST recycling and production is being reused in another manufacturing process.
	2. Design
Customisation	Product tailored made for specific sport/activity, reducing unnecessary material and over production.
Design for disassembly/recycling	Consider eliminating the use of adhesive and complicated plastic blend & additives that impact recycling.
Design for modularity	Make sure infill can be easily replaced and surface can be fixed.
Reduction of harmful materials	Consider the need for utilising materials contaminated materials, and frequently sample recycled material that goes into ST production.
	3. Manufacturing
Energy efficiency	Use renewable energy, use an energy efficient process.
Adaptable manufacturing	Use locally source material to avoid transport.
	4. Distribution and sales
Redistribute and resell	Establish a market to make sure that ST is recycled, and material is reused, not landfilled or stockpiled.
	5. Consumption and use

CE Strategy	For ST product
Community Involvement	Make sure the owner and community aware of the replacement strategy and how to prolong the ST product.
Eco-labelling	A certification system that guarantees that the ST material has pass the test for minimal contamination and future environmental impact.
Product labelling	A transparent information that provides consumer (council) to be aware of the EOL and composition of the ST.
Socially responsible consumption	Consider whether ST implementation is necessary in the first place.
6. Collection and disposal	
Extended Producer Responsibility (EPR)	Manufacturer guarantee a sustainable EOL for the product. possibly creating a subscription/leasing contract arrangement.
Incentivized recycling	Choose ST that has been proven to be easily recycled with a clear EOL direction.
Separation	Establish a clear separation of biological cycle from technical cycle. if hybrid turf is used, establish a clear method to separate them.
Logistics	Make sure recycling is accessible and consumer friendly.
7. Recycling and recovery	
By product use	Use the EOL ST as raw material for different products.
Downcycling	Use the EOL ST as raw material for products with lower quality or less functional.
Substance recovery	Recover the sand infill, or shock pad to eliminate production of new materials.
Energy recovery	Separate high heating value materials and convert it into usable energy (e.g., incineration, gasification, etc.)
8. Remanufacturing	
Refurbishment	Certain part of the turf will require replacement sooner than the others (due to higher foot traffic). Hence defective turf should be able to be replaced without sacrificing the entire surface.
Upgrading, maintenance, and repair	Choose supplier that has a clear service after sales to improve ST's longevity.

Considering the diversity of approaches that can be implemented to catalyse the CE for ST, this section focuses on reviewing synthetic turf technological advancements, along with a brief discussion around management strategy that can improve longevity and further facilitate technology to support ST for the circular economy.

Figure 5 depicts the current linear supply chain of ST. From this, the CE strategy was curated and shown in Figure 6. The detail of potential CE strategies is outlined in Table 6.

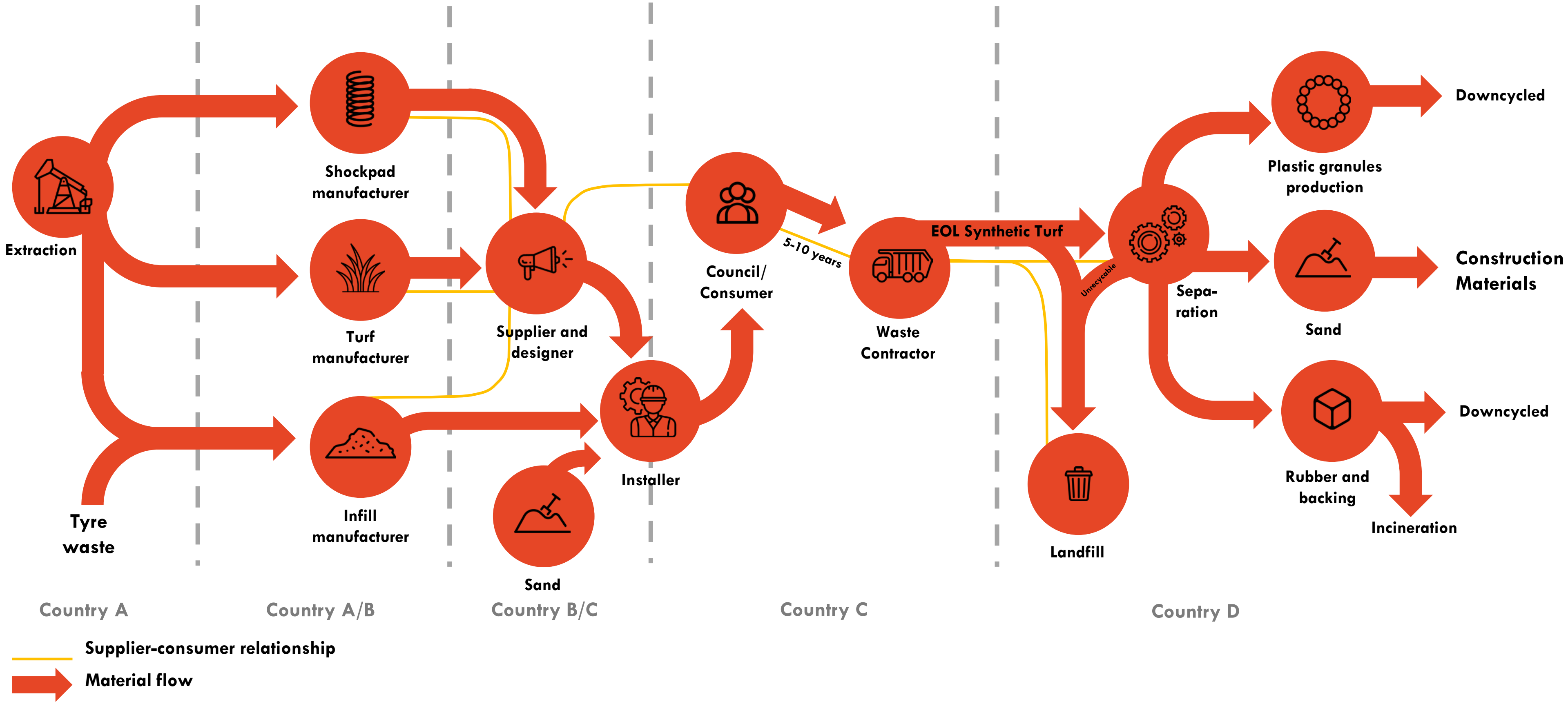

Figure 5: Current "Linear Economy" model of synthetic turf supply chain, modified from Total Energies (2022) complemented with current recycling practice based on Formaturf (2022)

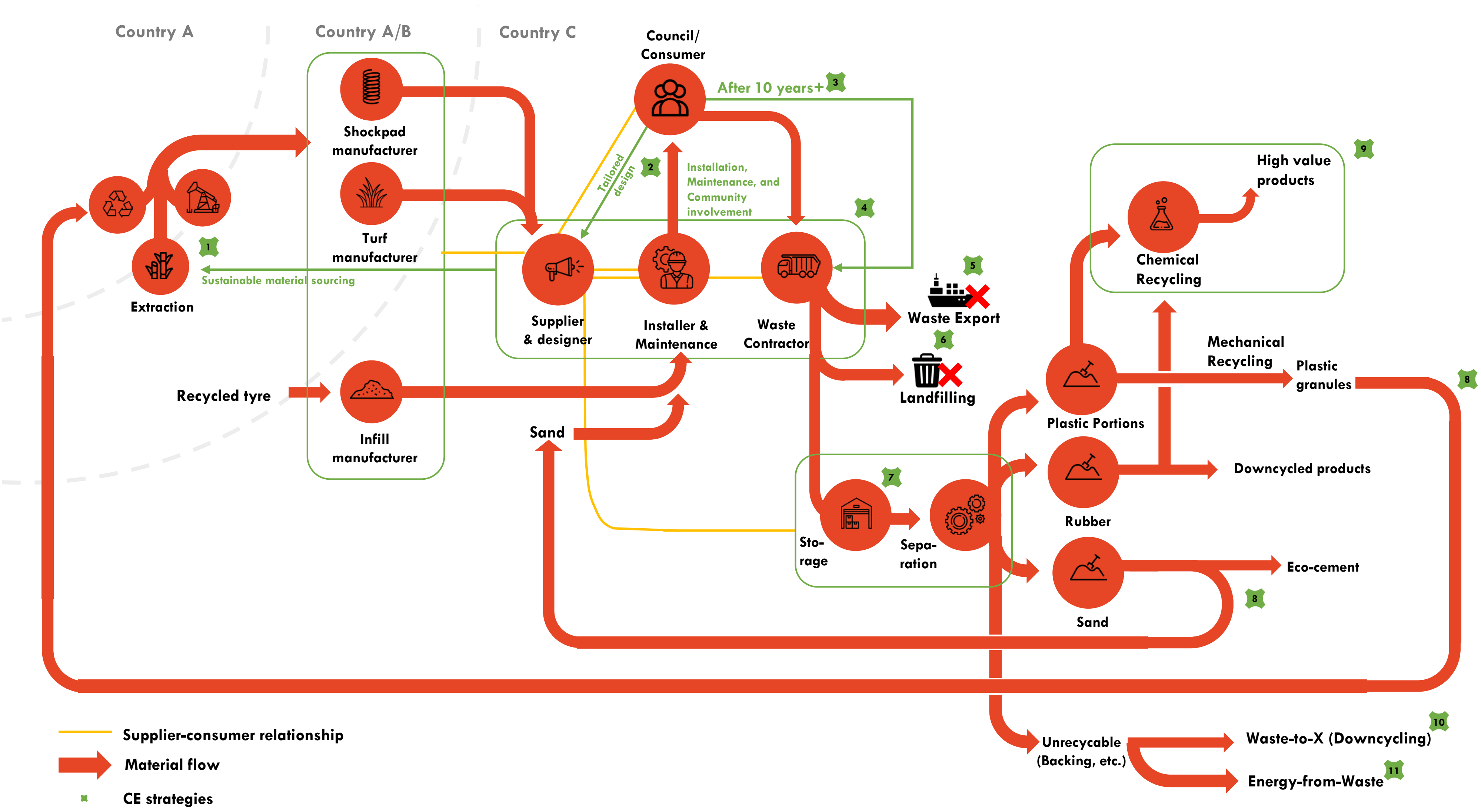

Figure 6: Towards circular business model for the synthetic turf industry

Table 6: Summary of potential CE strategies for ST

No	Strategy	Description
1	Sustainable material sourcing	Consider regenerative material (biomass) or prioritised recycled material (from other products with higher functionality, downcycling).
2	Tailored design	Consumer to consult with the supplier to enable a tailored design to minimise unnecessary material consumption
3	Improving longevity	By choosing a supplier that has a strong service-after-sales, users can be aware of proper maintenance, which resulted in a longer product lifespan.
4	Extended Producer Responsibility (EPR)	The supplier is responsible for product maintenance, installation, and EOL. This means instead of the consumer contacting a third party for EOL cost, the service is included throughout the product's life cost. This business model can be done through a service model or ownership model. This aligns with improving longevity as a longer lifespan mean a lower cost for supplier.
5	Regulate waste export	Waste export should be avoided for this material to mitigate unregulated EOL practices. Waste export is only encouraged when ST is imported to a country with a better and proven ST recycling infrastructure. (e.g. Fifa send ST to be recycled in Denmark (State of Green, 2017))
6	Regulate landfilling practice	High gate fees and subsidies for recycling would encourage business leaders to redirect waste material into a recycling facility.
7	Regulate storage capacity	Storage capacity should be regulated to avoid stockpiling practice.
8	Recycle material to equal value	In a circular economy, the material is recycled into a product with similar functionality.
9	Recycle material into higher value	In the future, chemical recycling may be preferred since this pathway is arguably more resilient to market demand due to its versatile material production.
10	Waste-to-X	Converting the material into other products.
11	Energy-from-waste	Although this is not a circular economy, such strategy still aligns with waste management hierarchy and is arguably better than landfilling.

4.1 New materials

Advancement in turf design for CE is influenced by performance improvements, heat reduction, health impacts and sustainability (Athletic Business, 2017). The concern is that increased deployment of ST will require more extraction of raw materials and further support the linear economy. However, this can be mitigated during material selection by (1) eliminating unnecessary material, (2) improving the recycled material, and (3) using regenerative sources (biomass). Other strategies for the development of new ST materials and their correlation with CE are outlined in Table 7.

Advancements around performance are possible by adding shock-pads and using different plastic blends (Uhlman, 2013). As regards health concerns, a review of infills has been carried out (Cheng et al., 2014), where six different infill materials were evaluated and compared with the traditional rubber crumbs. Other concerns such as odour and bacterial growth are addressed through maintenance and cleaning. Relating these advancements with CE, utilising complex design and plastic blends may negatively impact the recycling process. More analysis is required for a more informed decision, as material selection may significantly impact the recycling process.

Overall, there are some sustainable ST options that align with CE, and these options should be taken into account during the decision-making process. Again, LCA may be the suitable tool in decision making, and a clearer judgement can be drawn if LCA is complemented with cost and health assessment.

4.2 Business Model

Apart from production and EOL, improving longevity and transforming business practices are equally crucial in CE. These latter strategies may reduce the overall requirement of materials and create a robust business model focusing on consumer benefits. ST suppliers should educate their consumers on best maintenance practices, especially for sports activities, which means councils should seek out businesses that have a strong "service-after-sales" practice, providing a consistent review of the turf. If the business were to provide such a service, the "service as a product" concept can be taken further to shift the overall product's responsibility to the producer/seller rather than the consumer (EPR). This would transform the consumer-supplier relationship (See Figure 5 & Figure 6)

In EPR, consumers do not "own" the product. Instead, the supplier leases the product and takes full responsibility for its installation, usage, and EOL. This may encourage the supplier to educate the user on best practices to prolong the turf's lifespan, ensuring the best performance for the consumer. The cost can be evaluated by the subscription method, where the installation and EOL cost is spread-out throughout its "expected lifetime" guaranteed by the supplier.

Government can play a role as a facilitator by only choosing the businesses that provide "Service-after-sales" and demand more supplier action in maintenance and EOL. Meanwhile, councils should consult with turf providers and evaluate whether the leasing cost model is within their interest, some this model may reduce the need for capital cost while ensuring optimum performance.

A similar scheme has been demonstrated on packaging products and electronics. Shooshtarian et al. (2021) review various regulatory practices for construction and demolition waste, including recommendations to actualise EPR in Australia, namely:

1. Clear product and material documentation.
2. Choosing products that is designed for disassembly with a clear EOL.
3. Making EPR mandatory rather than voluntarily, determining responsibility at the construction stage.
4. Considering all stakeholders' input prior to construction.

Nevertheless, it is unclear whether any sport grade turf supplier has implemented such a business model. Furthermore, some issues may arise from EPR/leasing model. Shifting responsibility to the manufacturer means that the public may have a limited control over the ST EOL, this may result in a dishonest EOL practice.

4.3 Recycling technologies

The current ST industry is arguably still very linear, despite the existing recycling infrastructure, material is often stockpiled and unrecycled. On top of that, the direction of the recycled material is often downcycled or converted into energy (Rambøll, 2020). The current challenges of ST recycling are:

- Plastic blend and backing separation is often complicated (Pilkington, 2921).
- Most processes only focus on separation and do not specify the material being taken up into other products, i.e., lack of traceability (Rambøll, 2020).
- Most plastic produced from the recycling process is downcycled, while the rubber part of it is converted into energy (Rambøll, 2020).
- The currently operating recycling facility will not be able to keep up with the incoming turf material, leading to stockpiling (Thompson, 2019). ST recycling practice is only at a small scale and predominantly in Europe (Smart Connection Consultancy, 2021).
- ST recycling requires clear economic feasibility. A facility needs to prove that the mixed and contaminated plastic, can be effectively cleaned and converted into pellets for a downstream market (Cox et al., 2018).

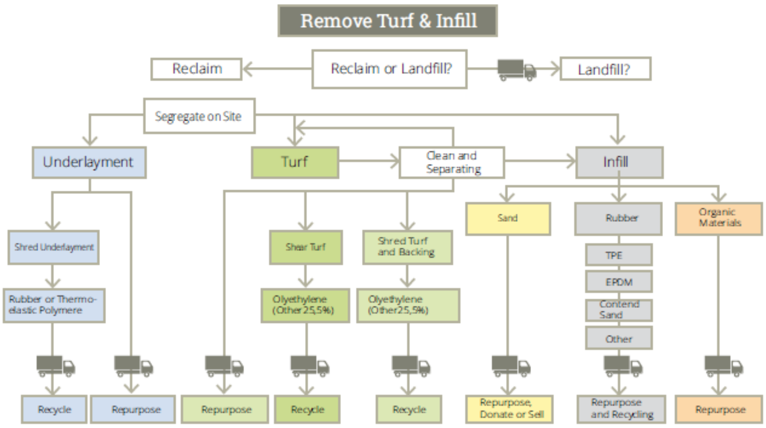

Figure 7: Current pathway for ST reclaiming and Recycling (Cox et al., 2018)

While a recycling pathway does exist (Figure 7), in an ideal CE, all recycled material should be re-used for its equivalent or at a higher product functionality, Figure 6 shows the recycling pathway for an ideal CE framework, where the ST waste is dealt locally and recycled into its equivalent products. Note that the rubber portion is still being downcycled, this is because this material has a unique market and technological barrier. Rubber crumb infill separation and cleaning are costly, and the recovered rubber crumb often does not have the same quality as virgin rubber production, limiting the market option. However, research is underway to manage this issue (Louis Berge, 2016). This agrees with a review by Rambøll (2020), where out of 7 ST recycling plant in Europe, only 1 facility claim that they convert the rubber material into other products (rubber mat), but they also reported that some portion of it may be converted into fuel (Refuse Derived Fuel). The rest of the facility landfills or incinerates their rubber portion.

EOL strategy should be formulated during the decision-making stage, including EOL in the cost assessment, LCA, and feasibility study. Such assessments can be executed by the council or ST supplier. At a higher level, the government can demand a clear waste management plan and/or chain of custody certification for turf material (Cox et al., 2018). Some changes that can be made right now to assist the future of ST recycling are (Cox et al., 2018):

1. Adopt infill free system, infill represents >90% of turf and avoiding these will significantly reduce requirements in rubber treatment down the road.
2. Consult with suppliers and manufacturers to prolong turf lifespan.
3. Improve shock-pad design to mitigate the need for replacement
4. Reusing ST from sports grade turf into recreational if within lifespan.
5. Avoid problematic blends and chemicals from going into ST in the first place.
6. Demand a clear EOL guide from the manufacturer.
7. Follow plastic recycling best practices for the ST blades.
8. If possible, choose biodegradable materials that can be composted and returned to earth sustainably (cork infill and/or bio-based plastic) (Senbis Sustainable Product, 2020; Sportsfield, 2021).

4.3.1 Waste-to-X

Waste-to-X is a process that convert waste materials into different products. This can be an alternative option or the transitional technology before the ST recycling industry fully matures, eliminating landfilling by converting EOL ST into a different product. Some possible Waste-to-X pathways are:

1. Incineration ash (After an EFW process) transformed into construction material (ARPA-E, 2022).
2. Green Ceramics or tile production (SMaRT, 2022).

4.3.2 Plastic portions

The plastic portion of the ST aligns with the advancement and policy around plastic waste (Circular Plastics Australia, 2022; NSW Government, 2021).

If infrastructure and technology to process mixed and contaminated plastic exist, this infrastructure can also assist ST EOL problems. Many believe the future of plastic waste is chemical recycling pathways (Jiang et al., 2022; Koshti et al., 2018; Ragaert et al., 2017), such as:

1. Thermal pathway
    a. Hydrothermal
    b. Hydrolysis
    c. Pyrolysis
    d. Gasification
2. Chemical pathway
    a. Ammonolysis
    b. Solvolysis
    c. Glycolysis
    d. Methanolysis
3. Biological pathway
    a. Fungi
    b. Bacteria
    c. Isolated enzyme

Table 7: Summary of new turf products.

New Material/ design	Product/ companies	Advancement/ description	Alignment with CE	Comment	Ref
Biobased blades	Endoturf All Seasons Synthetic turf	Australian companies claim to produce ST from sugarcane. Sugarcane is fermented to produce ethanol and later synthesised into ethylene gas, and then polyethylene beads, and then plastic yarn before turning into ST.	Using biobased material mean that it can be returned to earth after its EOL, and can be sourced regeneratively	Not sure if it has me the sport usage standard	All Seasons Synthetic turf (2021); Endoturf
Biobased infill	Bio-powder	Malta based company that uses treated olive stone as ST infill granules	Using biobased material mean that it can be returned to earth after its EOL, and can be sourced regeneratively	Not sure if it has met the sport usage standard	BioPowder (2022)
Cooling turf	Tcool Envirofill	Cooling turf is not a novel technology. ST has been proven to cause the heat island effect. Reduction in temperature can be done by adding water reservoir, or formulating a specific infill, such as coated sand (acrylic), zeolite, or mixed with hemp.	Improving its temperature can reduce heat risk, and potentially increase the playtime during hot weather; hence, higher consumer benefits.	Studies have been done on this type of turf products (Petrass et al., 2015b), but more studies is required to establish whether it does improve usability. The use of certain material may also increase health risk (Zeolite or acrylic coating).	Bresee (2021)
Enriched turf	Pureti, Domo Sports Grass	Water-bonded titanium dioxide acts as a photocatalyst to reduce organic carbon and NOx from the air, claiming to improve overall air quality.	Increasing air quality and pollution algin with minimising environmental impact strategy.	The company claim it has met the 'strict' regulation to bring TiO_2 to EU market.	Domo Sports Grass
Non-infill product	TenCate grass	Instead of infill, the ST has a thatch layer of dense fibres. The company mentioned that the product has been in development by working closely with sports clubs.	Material reduction	The company outline the different feel of natural grass to no infill turf.	TenCate Grass (2022)
"Smart" – Sport field	FieldTurf Australia Astroturf	Not a new ST material, but a design addition. By adding sensors on the lights/users, the data collected can be monitored to estimate the turf quality and potential maintenance required.	Improving longevity by design.	It is unclear if such software has been implemented.	Astroturf ; FieldTurf Australia (2022)

Table 8: Overview of recycling process.

Company/ Affiliation	Region	Recycling type	Technical description	Status	Ref
Reciturf	Spain Europe	Chemical recycling and Enzymatic degradation	Aim to develop a new recycling process that uses a combination of biological enzyme and chemical recycling. Material separation is done through mechanical recycling	Currently on research	European Union (2021); ReciTurf (2020)
Tuff group	Victoria Australia	Unclear, possibly mechanical	Technical detail is not provided The separation and recycling process is unspecified, what product to be produces is also unspecified.	Construction, expected to process 4 to 5 tonne of synthetic turf per hour, 7680 p.a.	Daricilli (2021); Sustainability Victoria (2022)
GBN	Netherlands Europe	Mechanical recycling	ST is separated into turf and rubber/sand (infill). turf goes into shredding and cutting into plastic pellets. Sand and rubbers are separated for construction material. Unclear market uptake of plastic and rubber material, while sand is used for construction	Commence early 2022, operating at 200,000 tonne p.a.	Rambøll (2020)
KBR	Germany Europe	Separation	Separation of turf from backing and sand, where the material is used	25 tonne per month of ST	Rambøll (2020)
Re-match	Denmark Europe	Mechanical recycling	ST is shredded and separated into plastic PE, backing, rubber sand, and sand. PE is transformed into fibre for other production, the backing is used for energy recovery, rubber is used for mat production, and sand is used for construction.	30,000 tonne per year, and planning on expansion	Rambøll (2020)
Vink	Netherlands Europe	Mechanical recycling	ST is separated from infill where turf is separated into PE and mixture while sand is separated using wet flocculants. PE is “repurposed” while sand is for concrete production.	100,000 ton per year	Rambøll (2020)
Formaturf	Germany Europe	Mechanical recycling	ST is separated, where the plastic portion is pelletised, and the infill is separated into rubber and sand. The company claim that rubber granules, sand, and plastic are reused for turf production. alternatively, they used for construction or other product	Capacity is unclear	Formaturf (2022); Polytan (2021)

4.4 Circular Outlook

CE and life thinking should be part of any feasibility study. The shift into a more circular ST can be done by:

1. Improving consumer awareness of the product's EOL strategy and service-after-sales, possibly choosing a supplier that has a guaranteed lifespan and more sustainable material sourcing.
2. For councils, feasibility and costing assessment should include EOL strategy They should consider turf supplier that has a strong "Service-after-sales" as best maintenance practice may improve the turf lifespan. If possible, councils should consult with industry and potentially create a leasing model that can be economically sound for their circumstances. Nevertheless, such business model is untested for ST.
3. Policymakers should regulate EOL waste classification and demand a clear strategy from councils and ST manufacturer, while regulates the landfilling and export practice of ST materials. This can be done by making local recycling cheaper and higher landfilling gate-fee.
4. Despite advancement in plastic chemical recycling, ST still requires mechanical separation, hence, it is necessary to establish this infrastructure. Moreover, with current knowledge in chemical recycling, it is unlikely that the technology will be mature and ready for upscaling by the time ST waste needs to be treated, thus it is imperative to implement CE strategy at every stage of the supply chain.
5. Often, best practice and guideline for ST EOL is unclear, resulting in councils passing the responsibility to the contractor without a clear recycling direction, which resulted in ST being stockpiled, incinerated, or exported

5 LCA Review Result

Table 9: Comparison list for Natural turf Vs Synthetic Turf

Study	Alternative Scenario	Base Scenario	Code
Adachi et al. (2016)	Sc2 Synthetic Turf (recycled tyre, polyethylene, and polyester fabric)	Sc1 Sod (Natural grass)	STNT1
Uhlman (2013)	Sc1 PureGrass ® (Nylon, no infill)	Sc4 Natural grass (available 600 hrs/year)	STNT2.1
	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	Sc4 Natural grass (available 600 hrs/year)	STNT2.2
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	Sc4 Natural grass (available 600 hrs/year)	STNT2.3
	Sc1 PureGrass ® (Nylon, no infill)	Sc6 Natural grass (available 360 hrs/year)	STNT2.4
	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	Sc6 Natural grass (available 360 hrs/year)	STNT2.5
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	Sc6 Natural grass (available 360 hrs/year)	STNT2.6
	Sc1 PureGrass ® (Nylon, no infill)	Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	STNT2.7
	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	STNT2.8
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	STNT2.9
Itten et al. (2021)	Sc3 Hybrid turf, reinforced (1000 hr)	Sc1 Natural Turf without drainage layer (480 Hrs usage)	STNT3.1
	Sc4 Artificial turf without plastic or granules infill (16000 hr)	Sc1 Natural Turf without drainage layer (480 Hrs usage)	STNT3.2
	Sc5 Artificial turf with plastic infill (16000 hr)	Sc1 Natural Turf without drainage layer (480 Hrs usage)	STNT3.3
	Sc3 Hybrid turf, reinforced (1000 hr)	Sc2 Natural turf with drainage (800 Hrs usage)	STNT3.4
	Sc4 Artificial turf without plastic or granules infill (16000 hr)	Sc2 Natural turf with drainage (800 Hrs usage)	STNT3.5
	Sc5 Artificial turf with plastic infill (16000 hr)	Sc2 Natural turf with drainage (800 Hrs usage)	STNT3.6
Meil and Bushi (2007)	Sc2 Synthetic turf (Made of Thioback Pro backing material (USA), rubber granule infill, Polyethylene turf, and PVC drainage piping)	Sc1 Natural grass	STNT4
Russo et al. (2022)	Sc2 Artificial/Synthetic turf: Shock pad of 88% used tyres, adhesive, PE-HD and PP artificial turf, and used-tyres for infill materials	Sc1 Natural turf	STNT5
Säberg (2021)	Sc2.1 Synthetic turf + Cork infill w landfill	Sc4 Natural turf	STNT6.1
	Sc2.2 Synthetic turf + Cork infill w incineration	Sc4 Natural turf	STNT6.2
	Sc3.1 Synthetic turf + Recycled tyre infill w landfill	Sc4 Natural turf	STNT6.3
	Sc3.2 Synthetic turf + Recycled tyre infill w incineration	Sc4 Natural turf	STNT6.4

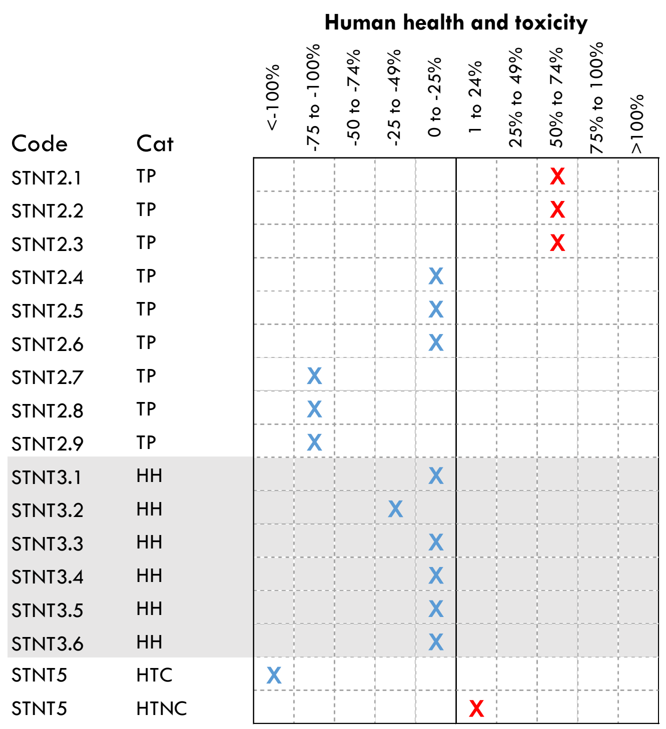

Figure 8: Graphical summary of relative differences between Natural turf (red) and Synthetic turf (blue), where each shade represents one LCA. The X position favours the side they are on, i.e., it identifies lower relative impact. TP: Toxicity Potential, HH: Human Health, HTC: human toxicity carcinogen, HTNC: Human toxicity non-carcinogen.

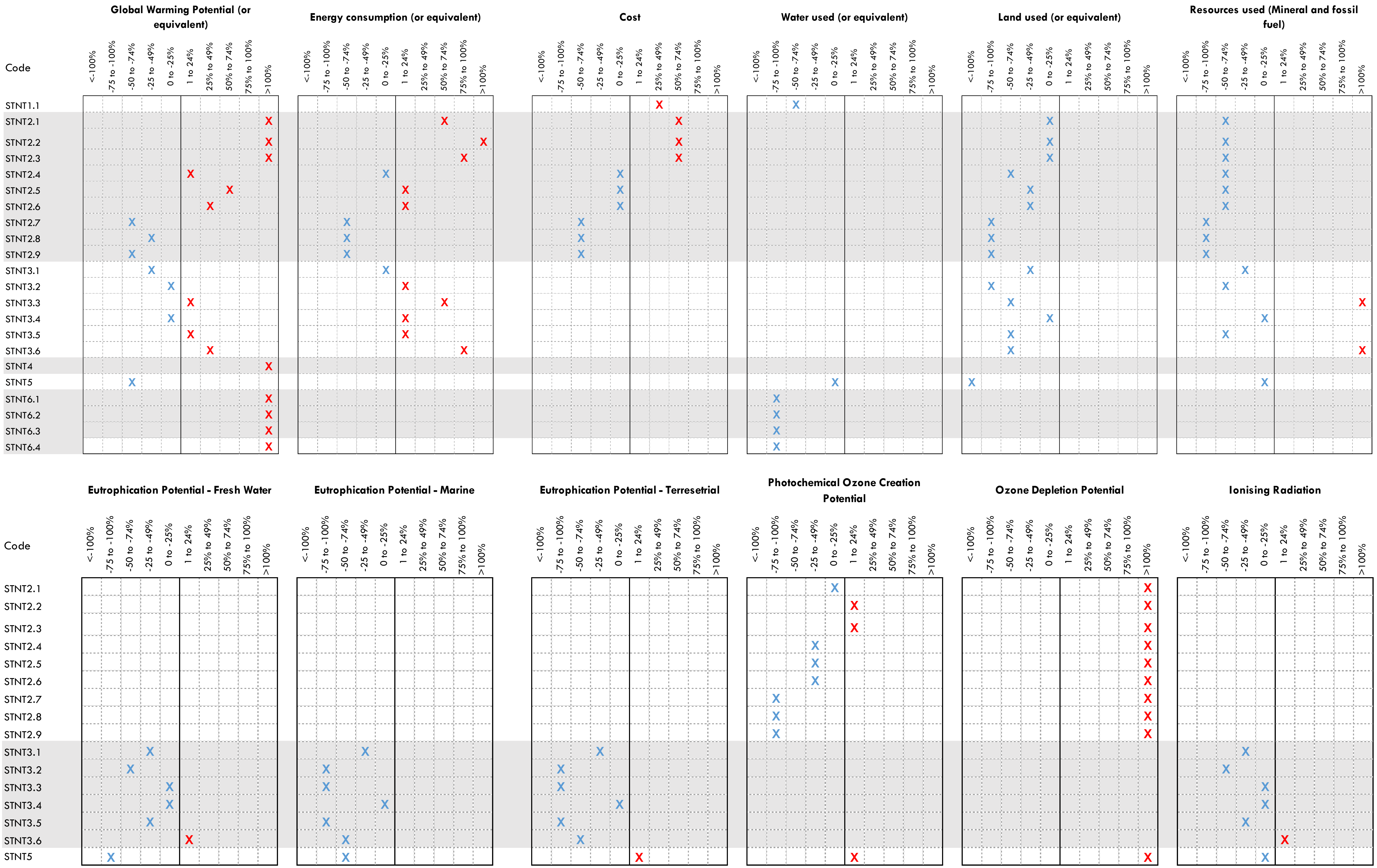

Figure 9: Graphical summary of relative differences between Natural turf (red) and Synthetic turf (blue), where each shade represents one LCA. The X position favours the side they are on, i.e., it identifies lower relative impact.

Table 10: Comparison list for Synthetic turf vs Synthetic turf

Study	Alternative Scenario	Base Scenario	Code	Comparison on
Uhlman (2013)	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	Sc1 PureGrass ® (Nylon, no infill)	STST1.1	Infill or no infill
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	Sc1 PureGrass ® (Nylon, no infill)	STST1.2	Infill or no infill
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	STST1.3	Full PE vs Nylon blend
Itten et al. (2021)	Sc5 Artificial turf with plastic infill (16000 hr)	Sc4 Artificial turf without plastic or granules infill (16000 hr)	STST2.1	Infill or no infill
	Sc3 Hybrid turf, reinforced (1000 hr)	Sc4 Artificial turf without plastic or granules infill (16000 hr)	STST2.2	Infill or no infill
	Sc5 Artificial turf with plastic infill (16000 hr)	Sc3 Hybrid turf, reinforced (1000 hr)	STST2.3	Hybrid vs Full ST
Magnusson and Mácsik (2017)	Sc2 Synthetic turf with Thermoplastic elastomers infill	Sc1 Synthetic turf with recycled tyre infill	STST3.1	Virgin infill vs recycled infill
	Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill	Sc1 Synthetic turf with recycled tyre infill	STST3.2	Virgin infill vs recycled infill
	Sc2 Synthetic turf with Thermoplastic elastomers infill	Sc4 Synthetic turf with recycled EPDM infill	STST3.3	Virgin infill vs recycled infill
	Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill	Sc4 Synthetic turf with recycled EPDM infill	STST3.4	Virgin infill vs recycled infill
Säberg (2021)	Sc3.1 Synthetic turf + Recycled tyre infill w landfill	Sc2.1 Synthetic turf + Cork infill w landfill	STST4.1	Recycled tyre infill vs cork infill
	Sc3.2 Synthetic turf + Recycled tyre infill w incineration	Sc2.2 Synthetic turf + Cork infill w incineration	STST4.2	Recycled tyre infill vs cork infill

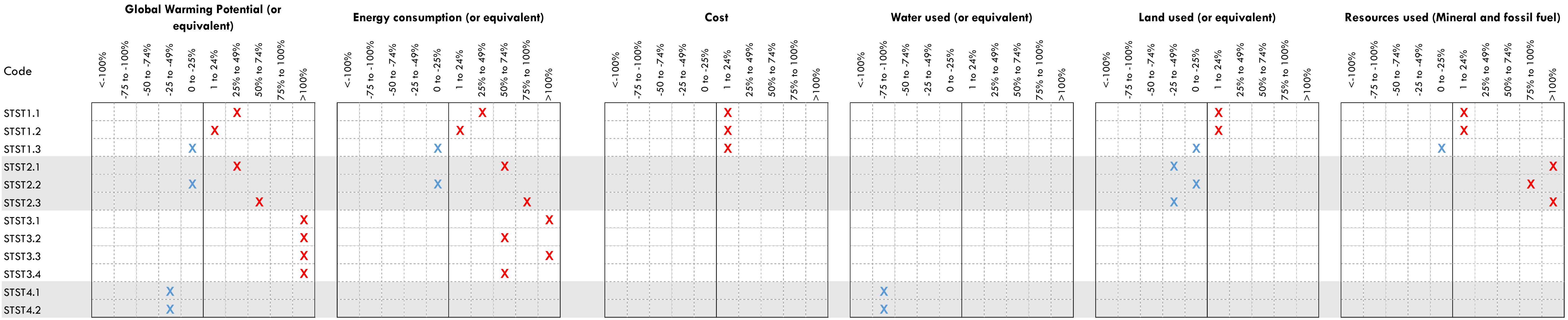

Figure 10:: Graphical summary of relative differences between Synthetic turf base scenario (red) and Synthetic turf Alternative (blue), where each shade represents one LCA. The X position favours the side they are on, i.e., it identifies lower relative impact.

6 LCA Review Discussion

6.1 LCA Environmental Discussion & More

On global warming impact, emission of non-biogenic carbon (fossil fuel) usually comes from energy consumption during the production (growing for NT and plastic manufacturing for ST and chemical) and maintenance (NT fertiliser production and chemicals for ST maintenances).

Most LCA concluded that synthetic turf would generate more global warming impact, caused by the virgin plastic material manufacturing step (STNT2, STNT3, STNT4, STNT6). However, some LCA were able to demonstrate the importance of used hours (usability time) to the overall impact. ST is arguably more durable; ergo, it will have more usability time than NT (Jenicek & Rodriguez, 2019). If the comparison is made between the same used hour, NT has a lower global warming impact than ST (STNT2.1-2.6; STNT3.5 & 3.6). However, if the usage time of NT is significantly reduced (~70-75%), NT would have a higher global warming impact (Itten et al., 2021; Uhlman, 2013) (STNT2.7-2.9, STNT3.1 & 3.2). Hence, it is important to consider whether ST installation can lead to more playtime/usability time.

Material and design choice also play a role in the impact, (1) choosing a less energy intensive material, (e.g., adding nylon blend, STNT2.9) or (2) using a hybrid design (mix of NT and ST, STNT3.1& 3.4) and (3) the elimination of infill material (STNT2.7 and STNT3.2) would reduce the overall environmental impact. These strategies should be considered during the planning stage. In the future, LCA around biobased ST can be executed and compared to traditional ST.

STNT5 (Russo et al., 2022) is an outlier, it is the only study that found that NT produced more global warming impact than ST. The study did not provide a clear explanation for such result; however, we were able to observe that the impact is predominantly happened during the NT production stage, where they reported to use 15 m^3 of water for 10.8 m^2 of NT (1.39 m^3/m^2), in comparison, Uhlman (2013) use 112 gal/1000 ft^2 (0.0046 m^3/m^2).

Moreover, natural turf may act as a carbon sink, absorbing CO_2 from the air; but it is important to consider the destination of the grass clippings. If the clipping is landfilled and ends up converted into methane, the idea of NT being a carbon sink may be irrelevant. Nevertheless, this impact is probably insignificant in comparison to the usage of fertiliser and energy during maintenance practice. Section 6.2 discusses the system boundaries and the LCA technique in general.

Beyond LCA, any human-caused urban development, including the installation of ST, may increase surface temperature, which can lead to the phenomenon called Urban Heat Island (UHI) (US EPA, 2022b). ST has the ability to retain heat, increasing ground temperature and creating UHI (Jenicek & Rodriguez, 2019). Some researchers have flagged the impact of ST on surface temperature, with concerns around heat related risk (Abraham, 2019; Jim, 2017).

The impact of ST on increasing ground temperature is not a novel concern, with studies as early as 1971 (Buskirk et al., 1971). Modern tools, such as modelling (Yaghoobian et al., 2010) and satellite imaging (Mantas & Xian, 2021) have confirmed this phenomenon as well. For a more advanced ST, Petrass (2015) studied the heat impact from Coolgrass® ST in Victoria, Australia. They conclude that the installation of this ST resulted in lower surface temperature than typical ST, but other variables (e.g., humidity, wind etc.) still play an important role in the surface temperature (Petrass et al., 2015a). Other design such as using water Retentive ST (Tebakari et al., 2010) or the use of subsurface water storage units (van Huijgevoort & Cirkel, 2021) may mitigate the UHI impact. Regardless, in most circumstances, ST will have a higher surface temperature than NT. Villacanas (2016) studied various ST materials and found that styrene rubber with fibrillated fibres produces the highest temperature (Villacañas et al., 2016). Similarly, another study compared various ST's infill materials and concluded that styrene rubber produces the highest heat surface (Petrass et al., 2014).

One study took it further, arguing that ST's ability to increase ground temperature, might also increase the heating of the atmosphere (Golden, 2021). Nevertheless, the study agrees that this contribution is minimal, and the study did not consider whether ST is a major UHI contributor, considering the effect is caused largely by concrete buildings (US EPA, 2022b).

Shi (2022) developed a thermal suitability index, essentially a scoring system to measure whether ST is fit to be used by considering user activity, weather conditions, and solar radiation (Shi & Jim, 2022). If heat related risk is a concern, further studies could be undertaken.

To summarise, while Golden (2022) argues that ST improves UHI and global warming potential, USA EPA explained that UHI does not cause global warming (US EPA, 2022a). From the reviewed studies, heat risk varies geographically and should be addressed through local context. For ST and their general UHI potential contribution to global warming, more studies are required to verify this theory.

On energy consumption, a similar trend was observed, the usability (used hour) of the turf can improve the impact of energy consumption. Lower energy consumption is present when (1) ST is being used more than NT (STNT2.6-2.9, but this is not always the case. In STNT3.2 & 3.3, where more ST had higher usage time, it still ends up in higher energy consumption than NT). The omission of infill (STNT 2.4) and hybrid design (STNT3.1) can also reduce the overall energy consumption, but this is not as impactful as usability hours. In general, it is safe to conclude that NT will require more energy consumption than ST.

On cost, it is important to note that that cost is usually not part of LCA, but it can be easily integrated, such as Life Cycle Costing Analysis (LCCA) or economic-input-output-LCA (EIO-LCA). Only two studies include cost analysis in their LCA. Adachi et al. (2016) (STNT1.1) found that for 1 m^2 of turf, NT is 40% lower in cost than ST, with the largest expenditure coming from backing the production of ST. Again, Uhlman (2013) demonstrate that ST can be cheaper when the consumer benefits is considered, that is the usability time of ST. This finding is backed up by Jenicek and Rodriguez (2019), who conducted a review on LCCA for ST vs NT, and argue the need to consider "Cost-Benefit" situations, reflecting the number of activities that can take place within the turf area, and whether more activities can be done when ST is installed.

In short, it can be said that for ST, there is a high capital cost (production and installation). Meanwhile, for NT, there is a high operational cost (fertiliser and water). However, the result can be influenced by the source of the LCA data, assumptions (e.g., replacement period and maintenance), and whether the study considers the "Cost-benefits"/usability time.

A discussion of LCA extensions and their techniques is provided in section 6.2.

On land and water use, all the reviewed LCA agrees that NT used more land and water resources than ST. ST only requires watering in a form of cleaning and does not require large land space for growing. While the result seems obvious, this demonstrates the ability of LCA to assess the overall life cycle impact for these variables, as it is often one of the crucial decision-making criteria depending on the geographical location.

Water usage is controlled by the local climate. Säberg (2021) discusses the potential water saved during the rainy season. They believe that it is best to have NT close to a waterway, in Southern Sweden, close to the area where NT is being produced, while Northern Sweden should resort to ST. Water usage optimisation for NT is not a new concept. Multiple organisations have published best practices for natural turf, including Sydney Water, Lawn Solution Australian, and the Union of European Football Association (UEFA). (Law Solution Australia, 2017; Sydney Water, 2011; UEFA, 2018)

Furthermore, it is possible to control NT irrigation, The US Army Engineering Research and Development Centre (ERDC) mention the need to encourage the installation of water efficient materials and employ certified irrigation system (Jenicek & Rodriguez, 2019).

Like the previous impact category, this LCA finding is bound to its assumptions and data origins. The main reasoning behind opting for ST is their water saving feature. Thus, people that conducted these LCA may have been motivated to compare two scenarios in a dry area that require significant human-made irrigation, pre-emptively selecting LCA conditions where NT require significant watering condition. Nevertheless, this theory is untested, and more field analysis is required, for example, a study that focuses on NT and ST in different climate condition.

On resources used, this category describes the mixed consumption of minerals, soil, metals, and oil, and includes water for Uhlman (2013) (STNT2). Overall, most LCA found that NT requires more resources than ST. NT requires constant feed of fertiliser and medium. The only case where ST requires more resources is when a virgin plastic material is manufactured and used for ST infill, as per STNT3.3 & 3.6 (Itten et al., 2021).

On Eutrophication Potential (EP), only two studies reported the eutrophication impact of turf installation (Itten et al., 2021; Russo et al., 2022). Both studies assess the EP to freshwater, marine, and terrestrial (soil or other mediums). Most comparisons found that

NT has a higher EP than ST, resulting from the constant consumption of fertiliser during the maintenance and production stage. However, two outliers were identified. STNT 3.6 reported higher EP-freshwater for ST, this is possibly caused by the utilisation of drainage pipe in the NT, the exact result cannot be deduced from the study, since we were unable to obtain the full document in English. STNT5 reported higher EP-terrestrial for ST, it is also unclear what causing this result; however, we were able to observe that this result happens during to construction/manufacturing stage. It is speculated that a certain unreported solid waste that has a high EP leaks out into the environment during ST manufacturing.

Beyond LCA, some researchers raised the concern that the improper management of NT in urban areas may lead to a higher EP in stormwater and waterways (Compost for Soils, 2011; Reubold, 2017; Virginia Tech, 2022), while others argue that a properly managed NT might reduce nutrient leakage and even act as nutrient retention area (Hochmuth et al., 2012; Petrovic & Easton, 2005).

In short, pinpointing the exact cause of EP in an urban area can be challenging. For precautionary reasons, best management practice for fertiliser, complementary to the water usage guideline, can mitigate potential impact. Nevertheless, these days, eutrophication management strategies and controls are available (Chislock et al., 2013).

On Photochemical ozone creation potential (POCP), this impact category measures the potential of volatile organic pollutants to produces ground level ozone (summer smog or photochemical smog). Only two studies review this impact category. Uhlman (2013) argues that POCP predominantly originated from the diesel engine combustion used for NT fertilizer transport and mowing. where their study found that most comparison favours ST for POCP as it does not require constant mowing and transport of material into the field. However, it can be said that ST and NT have a minimal difference in their POCP when both products have the same usability time (STNT 21.-2.3 & STNT3.6) and becomes exaggerated when NT has a lower usability time (STNT2.4-2.9)

On Ozone depletion potential, only two LCA compare the ODP, and they both agrees that ST produces more ODP than NT, possibly from the usage of certain chemical that has an ODP during the plastic manufacturing. Nevertheless, this impact is extremely insignificant as it only accounts to less than 1% of the overall emission during the life cycle (Uhlman, 2013).

On Ionising radiation (IR), this impact category assesses the potential impact on ecosystem and human health that is caused by the emission of radionuclides atoms, usually resulting from the nuclear power in the grid energy mix. Only two studies assess this impact (Russo et al., 2022; Uhlman, 2013), and both find that ST has a lower IR impact. It is unclear what causes this result, as neither study discloses their grid electricity origin. However, from the study by Russo et al. (2022), it is possible to investigate this further as the origin of their database is provided (Sphera and Ecoinvent). Nonetheless, due to the niche nature of this impact category, this was not investigated further.

On human health and toxicity impact, LCA studies often include human health impacts. It is important to acknowledge that the result is simply a quantification of emissions and their general effect on human health between different scenarios, i.e., it does not consider what specific human health impact it will generate. Hence, this part will compare how the LCA method and assumptions arrive at the result. We need to stress that a more specific health review is required.

Three LCAs consider the Human health impact of ST. Essentially, these studies found that ST has a lower impact when compared to NT. this is caused by ST's lower maintenance requirement. ST is considered an inert material. ST do not use fertiliser and diesel engines (for transport and mowing), eliminating the emission exposure to users, ergo a lower human health impact. However, ST has a higher impact during the manufacturing stage (Itten et al., 2021; Russo et al., 2022; Uhlman, 2013). Again, Uhlman (2013) demonstrate that the impact can be reduced when ST has a higher usability time than NT.

The takeaway from this section Is (1) how LCA is being framed (in this case its functional unit) can influence the result, and (2) LCA data is limited to traditional emissions, and due to ST's inert properties and the lack of maintenance, some studies arrive conclude that it has a lower human health impact than NT.

On infill selection, Figure 10 highlights the different ST products and their implication on the environmental impacts. Not using infill will reduces the global warming impact (STST1.1, 1.2, 2.1, 2.2,) and when infill is desired, using recycled material (plastic or tyre) will reduce the environmental impact as it does not require more manufacturing of virgin material (STST 3.1-3.4), even when the infill is biomass (cork infill) (STST4.1 & 4.2).

6.2 Comment on LCA technique and assumptions

From Section 4.1, it is evident that the way LCA is framed can impact the result. LCA appears as a holistic tool that measures everything in a product's life cycle and includes every environmental impact. Nevertheless, LCA is largely influenced by its execution and available information. Standards for LCA do exist (Finkbeiner et al., 2006), however, it is impractical to create a singular "correct" technique for LCA across different industries, products, and services. Changes need to be made and analysis needs to be tailored to each study, accounting for the feasibility and objective.

The limitations of LCA for synthetic turf is described below, Table 11 showing the full SWOT analysis.

1. LCA outcomes are as good as the input data, if certain data is unavailable (e.g., the fertiliser leak into the environment, plastic emissions, etc.) it will be not quantified.
2. If a system boundary is incomplete, it may omit the life cycle stage that contributes significantly.
3. LCA focuses on a macro material flow throughout the life cycle, while small material flowrate is often ignored. In contrast, there is a concern about the small number of organic pollutants and microplastics leaching from ST.
4. There is not enough comprehensive LCA on ST vs NT that gives the authors confidence that a certain technique can be considered "best practice".

Thus, this section aims to review the current and available LCA on the turf industry, focusing on their techniques and compare it to LCA guide and best practices (Klöpffer & Grahl, 2014; Renouf et al., 2015). Other suitable techniques and the extension of LCA are discussed in section 6.2.4

Table 11:SWOT analysis on using LCA for turf products

Strength	Weakness
- Ability to consider the full life cycle. - Identify "hotspot" stage in the product's life cycle. - Make confidences, data drive decision.	- Some impact categories can be irrelevant, while lacking others. - Result may be skewed by functional unit. - Require extensive and detail data collection. - Incomplete system boundary. - Focus on the macro material flow.
Opportunities	**Threat**
- Integration with cost and social extension - Have a standardised & tailored LCA technique for turf products - Assess environmental impact that is often missed by other assessment.	- Standard (ISO14044) is not being followed. - pre-emptively selected data that favour certain scenario. - Data quality and sensitivity analysis often omitted. - False assumption that negatively impact the result.

6.2.1 Functional unit

Functional unit is described as a quantified description of a product's performance that is appropriate within the a product's life cycle (Weidema et al., 2004). Table 13 reviews available turf LCA and discusses their reasoning. For the ST industry, we notice some studies included the "Consumer Benefits" or "Usability time" (Itten et al., 2021; Magnusson & Mácsik, 2017; Uhlman, 2013), essentially using usage time as a functional unit, while their scenarios (the different turf products) have different availability.

The reasoning behind this is that some researchers argue ST can be used more than NT, due to its durability and rainproof condition. However, these studies do not consider that there are some circumstances where ST cannot be used, for example, when the surface temperature of synthetic turf is too hot.

Considering usability time as a consumer benefit is a valid approach, however, it is important to review enough data across different conditions, to make a valid judgement on the suitable functional unit. This is important because the functional unit is effectively setting the tone for the rest of the LCA. It is recommended that relevant Government agencies collect data from the local council and sports organisation to review their:

1. location (and possibly climate condition) and the type of turf.
2. hours/number of activities on the turf,
3. type of sports, number of athletes, and their category (kids, teenager, or adult)
4. The turf's maintenance regime and replacement strategy.

The result of this survey should tell us whether different turf products does have a different ability to offer usage-time/playtime for the same sport/activity. This will give LCA assessor confidence to benchmark certain activities as a functional unit in terms of hours used. Activity specific analysis is also endorsed by (Jenicek & Rodriguez, 2019) where they try to assess the cost-benefit installation of synthetic turf.

If the survey found that for a certain sport, different type of turf has the same playtime hour, then the LCA can resort with size as its functional unit. If usability time is included in the functional unit and scenarios, the assessor should provide clear evidence that the usage time between various turf products is different.

Sports Turf Institute has reviewed 300 sports turfs from 18 councils in Australia. They created a database that standardised turf performance in the face of climate and activity variance (Holborn, 2009; Roche et al., 2010; Turf Finder, 2022). The database is claimed to be available to the participating councils. This database will be a useful information for functional unit determination, and even possibly the LCA objective, that is assessing the different scenarios (e.g., climate, sports activities, surface type, etc.). Similarly, Neylan and Nickson (2019) assessed four different playing surface usable hours throughout different activities and weather conditions (Neylan & Nickson, 2019). It is recommended for NSW Government to discuss possible data sharing with participating councils or with the organisation.

6.2.2 System boundary and other assumptions

The system boundary is the delimitation for which the product's supply chain is included in the LCA study. This limit is established by the assessors based on the study's objective. Figure 10 shows some examples of system boundaries from the turf LCA. Table 14 compares the system boundary from various turf LCA, the diversity in system boundary is bound to create some result variance. Moreover, the data used for these LCA is context dependent, meaning the locally collected information cannot be translated into different scenarios.

The system boundary and assumptions (often the data's origin and treatment) can significantly influence the outcome. From Table 14, we were able to observe that a substantial number of studies do not have a comprehensive system boundary, with questionable assumptions such as no turf replacement, omission of transportation, and invalid EOL management. It is speculated that data inaccessibility may have influenced the LCA's system boundaries.

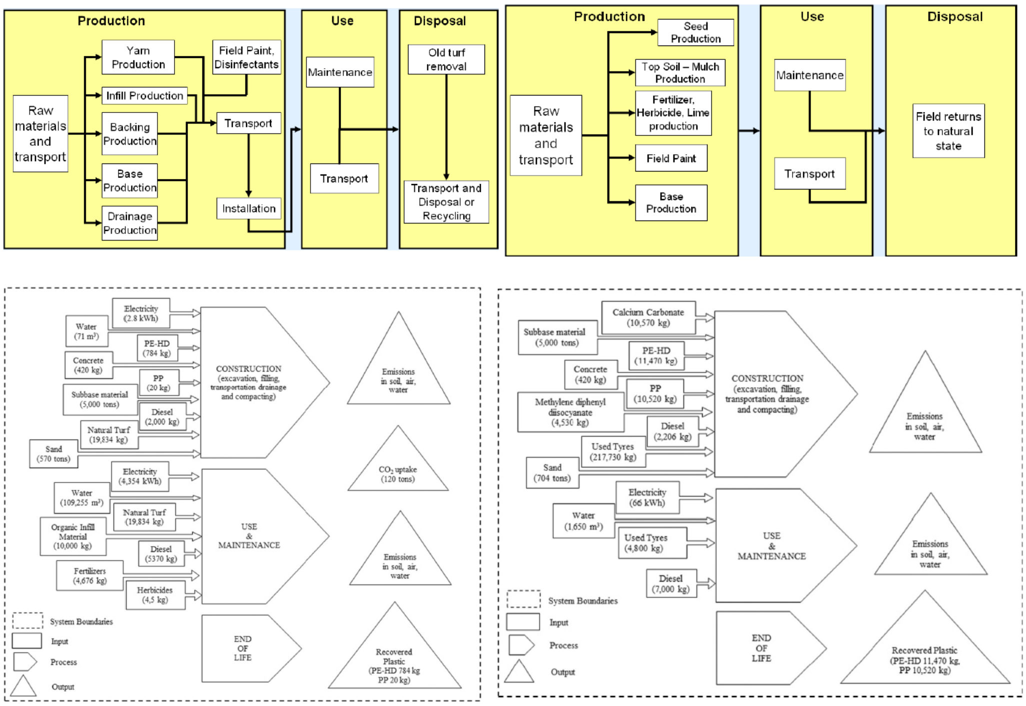

Figure 11: System boundaries for ST (Left) and NT (right) for (Uhlman, 2013)(top) and (Russo et al., 2022)(bottom)

For the NSW context, if the LCA method is expected to be the standard, an assessment of available databases or future collections is needed. Hort Innovation have collected such data for NT for Australia (Cumming, 2019). Meanwhile, councils should be transparent about their local turf consumption and maintenance data, enabling collaborations for a more comprehensive turf database.

From the research perspective, there is a lack of LCA that comprehensively considers the turf EOL, and how different management, design, and materials can impact the EOL (see Table 14). Moreover, most studies also do not have a comprehensive system boundary, hence, Table 12 provides some technical advice for future LCA assessors.

Table 12: Technical advice for LCA assessor.

Product	Stage	Recommendations
ST	Pro-Duction	- ST true composition/blend is often unknown; thus, assessors should provide references for their assumptions, or consult with the industry. - Highlight the database being used, possibly consult with the industry to confirm that the database used is suitable for the specific ST. - If information is gathered from the manufacturer, provide ST company and product's name. - Outline the energy source for manufacturing. - Include drainage (piping), backing, and infill composition.
ST	Main-tenance	- Transport considerations, encompassing the distance from the raw material extraction, manufacturer, seller, and lastly the field. - Include watering and any chemicals used to maintain ST, including the transport of these chemicals into the field. - Outline the origins of the data.

Product	Stage	Recommendations
		- Provide surveys or evidence that within the useful year, the ST will not need any replacement. If replacement is needed, outline the renovation process and whether the replacement period is the same for other turf products.
ST	EOL	- Need to consult with the manufacturer, or a local council on their local strategies before adopting a specific EOL for the LCA. - Should be able to provide evidence that the adopted EOL strategy is suitable for that ST products, and whether infrastructure exists to accommodate this assumption. - If recycling or EFW is being adopted, the data origin and emissions activity for this EOL treatment should be provided preferably from an active plant. - If landfilling is being adopted, the distance to the landfill should be calculated, including any process to pre-treat the ST before landfilling.
NT	Pro-Duction	- Describe the location of the turf growing phase, water, and chemical consumption. - Need to highlight the energy source (diesel, grid, etc.). - Include transport of chemicals into the growing site, and possibly the local climate as well (for data comparison with other growing locations).
NT	Main-tenance	- Need to review the maintenance consumption data across different seasons to ensure which best data set used for LCA. - Include watering and any chemicals used to maintain NT, including the transport of these chemicals into the field. - Include the maintenance practices, and any equipment used. - Provide survey or evidence that within the useful year, the NT will not need any replacement. If replacement needed, outline the renovation process and whether the replacement period is the same for other turf products.
NT	EOL	- Consider the volume of grass clippings produced, their landfilling destination, and the distances.
ST & NT	Other	- It is understood that material input-output varies throughout seasons, conditions, type of turf, and function. Thus, the LCA assessor needs to explain their assumptions and reasoning for selecting the data set (whether it is by averaging the available data, or simply citing one database/source) - Need to maintain a high level of transparency in their methodology, data origin, data processing/treatment, and assumptions.

6.2.3 Data origin, quality, and study motivation

In the research community, researchers often tailor LCA for a specific industry, establishing a unique best practice for each industry (examples: Waste management (Iqbal et al., 2020), Wastewater treatment (Corominas et al., 2020), and agriculture (Notarnicola et al., 2015)). Unfortunately, there is not enough turf LCA for us to be able to confidently conclude whether a certain framework is the best practice. Hence, we resort to investigating each LCA motivation to review whether some biases may arise from the study motivations to the way the data is being collected.

From Table 15, we review turf LCA motivation, affiliation, and data origin. As expected, there is a massive diversity in the data origin. Some studies combine data from various independent studies, which are later used depending on the turf composition. While this method is a valid strategy, assessors should proceed cautiously as these data may not be valid for every turf blend. Moreover, for NT, the data is only true locally and during specific weather conditions when the data is collected.

Some advice for future assessors is provided as follows:

1. During LCA data collection, the assessor should review two or more data sets for the same turf product under different operating conditions (climate, activity, etc.). This step might help eliminate biases and potentially normalise the data. If significant variance arises, assessors should take an extra step to analyse the data before using it for LCA.
2. Ideally, when comparing ST and NT, both data sets should be collected within proximity and used for similar activities.
3. LCA assessors should be practical about what they can achieve from the available dataset. Feeding the system boundaries with external data that is not true for the local context will not produce a useful finding. Excessive streamlining would require justification. Data unavailability should be highlighted, along with all of the assumptions.
4. When collecting data from manufacturer/industry, such as the composition of ST, consider whether an independent analysis is required to confirm the manufacturer's claims.

When executed properly, LCA is a comprehensive method that can provide a complete understanding of the environmental impact of a product. For ST, extra care should be given to the data collection and scenario creation stages. Assessors should ensure that there are no excessive assumptions that may potentially skew the outcome. If a full data set collection is unfeasible, assessors should consider a targeted life-cycle study, such as water and/or energy consumption, prioritising accuracy by reducing complexity.

In the future, as ST uptake is expected to increase, the environmental impact of ST might be further scrutinised; hence, a proper and standardised LCA is expected. EMEA Synthetic Turf Council (ESTC) is currently curating a category rule for ST products (ESTC, 2022a). Category rule is a methodological guidance for assessors to follow, such guidance is expected to standardise the LCA method across diverse conditions (European Commission, 2011). This may improve the consistency of studies and their overall reproducibility. The upcoming report is claimed to provide a category rule for product environmental footprint of ST for sport and recreational activity. The report is expected to be published by December 2022 (ESTC, 2022a).

Relating this to NSW, some elements of this category rule are expected to be transferable especially in establishing boundary conditions and the functional unit. However, it is still important to examine their assumptions and databases, especially considering Australia’s stark differences to EMEA in (1) distance from the manufacturer, (2) climate condition, (3) preferred sport activities, (4) available EOL infrastructure and management practice, and (5) regulatory standards for rubber crumbs and other materials.

Table 13: Summary of functional units used in turf LCA reviewed.

Study	Functional unit	Reasons for choosing this unit	The functional unit implication on LCA & Comment
Adachi et al. (2016)	1 m^2	Not clear, other than to standardise the two scenarios.	The study does not include many impact categories. The result is simply per m^2
Uhlman (2013)	Functional Unit: "Costumer Benefits (CB)" or 75,000 ft^2 for **600 hrs/year** over average of 20-year time frame.	The 600 hrs/year is based on ST ability to handle 200 events (3 hours each) a year, where such information is collected from Synthetic Turf Council (Synthetic turf council)	NT has a similar environmental impact to ST for the same usage time, but a higher impact than ST if it has a lower usage time. They demonstrate that there are less environmental impact and more benefits to ST if it's being used more than NT. However, they do not specify the scenario where this is the case.
Cumming (2019)	1 m^2 for 5-10 years	Not clear, other than to standardise the different scenarios.	None, the study only assesses natural turf.
Itten et al. (2021)	**1 hour usage** for sport (soccer)	The LCA is for a soccer field, where they also argue that ST can be used more than NT, which resulted in different annual usage hours.	It is unclear how they concluded the annual usage hour for various turf products, this differences eventually affected the environmental impact. Note: the full report is in German.
Magnusson and Mácsik (2017)	**Time of artificial turf used** to play football for a year in a football size of 7881 m^2 for 10 years.	The author used this functional unit in agreement with Fleming (2011), where they theorised the best practice for turf products analysis.	The LCA did not compare different turf products, they compared different infill material for ST. Because of this, the study can be done with only assessing the dimension (m^2 or kg), since it is unclear if different infill cause different playtime.
Meil and Bushi (2007)	9,000 m^2 for 10 years	The size of the field they're assessing.	Only assess CO_2, mainly concern about how to be carbon neutral.
Russo et al. (2022)	1 soccer field the size of 7140 m^2 with 10 useful years	The use of soccer field is because that this is the objective of the study. The 10 years useful years was based on circular economy strategy (Wolf et al., 2016)	None, there is only two scenarios, hence judgement cannot be drawn.
Säberg (2021)	8214 m^2 in accordance with FIFA usage	Based on the Swedish football association, where they also specify that the turf should be able to handle 1040 hrs/year, but usage time is not considered.	None, there is only two scenarios, hence judgement cannot be drawn.

Table 14: Summary of system boundaries from the different turf LCA reviewed (N/A: Not available information/not included).

Study	Type	Productions	Energy source	Usage phase Useful year	Installation & maintenance	Replacement strategy	Transport	EOL	Other Assumption	Sensitivity analysis
Adachi et al. (2016)	NT	Water, soil, fertiliser, energy, potassium chloride, and energy	Oil and coal	15	Water and fertilizer	None, turf is assumed to last for 15 years	N/A	N/A	EOL is assumed to be negligible	±10% of base value to assess changes in water consumption.
Uhlman (2013)	NT	Seed, topsoil (mulch), fertilizer, herbicide lime, field paint, sand cap based, and watering (initial and regular)	Gasoline for transport and mowing. No energy specified during production	20	Water, fertilizer, lime, top dressing, herbicide, insecticide, fungicide, mowing, sand replacement, field painting	No additional replacement, however, it is noted that NT need replacement after 10 years	Material travels for 250 km for installation, and 100 km for EOL and maintenance	Removed and returned to biosphere.	NT carbon sequestration ability is included. Transport efficiency of 2.7 MJ/ton/km.	Conduct data quality assessment. Mention that NT data is context dependent.
Cumming (2019)	NT	Water, Nitrogen, Phosphorus, Potassium, Agriculture chemicals, and lime	Electricity (unspecified origin but speculated to use eco-invent database) and diesel. For maintenance, petrol	5-10	Mowing, watering, fertiliser, nitrogen phosphorus additives and agriculture chemicals	Did not consider replacement but assess multiple NT lifespan (ranging from 1-10 years) as comparison scenarios.	Diesel and LPG per m² of NT (instead of distance)	EOL was not considered as "NT EOL is not a problem"	NT carbon sequestration ability is included	N/A
Meil and Bushi (2007)	NT	Grass seed production and organic matter	Only in the form of transport	10	Irrigation and mowing	N/A	Unspecified distance but included in form of GHG. only during installation	N/A	NT carbon sequestration ability is included	Uncertainty estimated by combining the available data
Russo et al. (2022)	NT	Natural turf Maxi-roll, watering, and fertiliser	Energy (unspecified origin but speculated to use eco-invent & Sphera database) and diesel. For diesel.	10	Excavation, sand, concrete, watering, fertiliser, organic infill, mulching, herbicide, an	For 10 years, the turf replacement impact will be 10% of the total surface every year	Transport only during installation (3600 km)	Removed and returned to biosphere.	NT carbon sequestration ability is included	Data quality is scored
Säberg (2021)	NT	Growing (soil flattening, fertiliser, water) and harvesting.	Petrol, electricity heat, and diesel	10	Watering	N/A	Only during installation and EOL, distance not specified	Removed and returned to biosphere.	N/A	Mentioned sensitivity but no assessment was conducted
Adachi et al. (2016)	ST	Rubber manufacturing (recycled tyre), blade manufacturing (polyethylene and water), and mesh manufacturing (polyester fabric, fiberglass, and adhesive) and energy	Oil and coal	15	Water	None, turf is assumed to last for 15 years	N/A	N/A	EOL is assumed to be negligible	±10% of base value to assess changes in water consumption.
Uhlman (2013)	ST	Yarn, infill (crumb tyre), backing (polyester and polyurethane), urethane adhesive, base (aggregate, wood nail, etc.) and drainage pipe (HDPE)	For production, grid energy (unspecified origin) and diesel	20	Watering, field paint, disinfected, fabric softener, and crumb rubber	Unclear if there are replacement, however, it is noted that ST need replacement after 9-10 years	Material travels for 250 km for installation, and 100 km for EOL and maintenance	It assumed "recycling infrastructure was available, and only small portion of ST is landfilled". – unclear how much portion that is recycled.	Transport efficiency of 2.7 MJ/ton/km.	Claimed that no critical uncertainties found.
Magnusson and Mácsik (2017)	ST	Turf production, infill production, drainage pipes, geotextile, shocking pad system, sand, and soil.	Unspecified, impact factor is presented as energy consumption	10	Crumb infill replacement	N/A	Lorry travel for 1000 km one way for material installation and another 1000 for maintenance	Incineration for turf, and rock layers removal	Turf composition, and lorry energy efficiency is assumed	N/A
Meil and Bushi (2007)	ST	Polyethylene, backing production, polyurethane, rubber granules, PVC piping, and topsoil	Unspecified, represented as the amount of GHG emitted.	10	ST maintenance, unspecified (estimated to be 30% of NT maintenance)	N/A	Truck and shipping travel from various places ranging from 21-6700 km, only during installation	100% recycling, unspecified technique. represented in the form of GHG emitted.	Data collected from eco-invent library	Uncertainty estimated by combining the available data, with some data uncertainty as high as 32%
Russo et al. (2022)	ST	Shock pad, adhesive, artificial turf (Polyethylene and polypropylene), and used tyre	Energy (unspecified origin but speculated to use eco-invent & Sphera database) and diesel. For maintenance, electricity	10	Excavation, sand, concrete, watering, and rubber infill.	For 10 years, the turf replacement impact will be 10% of the total surface every year	Transport only during installation (3600 km)	Removed, transported, and landfilled	N/A	Data quality is scored
Säberg (2021)	ST	Polyethylene, Polypropylene, Polyurethane,	Natural gas oil, coal and diesel	10	Energy	N/A	Only during installation and EOL, distance not specified	Landfill and incineration	Only assess water and CO_2 emitted.	Mentioned sensitivity but no assessment was conducted

Itten et al. (2021) is not included as the full document was not available in English.

Table 15: Summary of motivation and data origins for turf LCA reviewed.

Study	Objective/Motivation	Document Type	Study affiliation, funding, and/or support	Data origin/database	Comment
Adachi et al. (2016)	To assess water usage of NT in the wake of the California draught, by normalising data to m^2	Unspecified type of report	Authors are from UCLA without specified funders.	Data is collected across EOILCA database, and various references study ranging from 2005-2016	The data is processed through EIOLCA (online tool). Data not from the same source.
Uhlman (2013)	To compare the overall environmental impact of synthetic turf versus a natural turf	Eco-efficiency report	By BASF chemical company verified by NSF international	NT data collected from the University of Tennessee Knoxville publication, while ST data is collected from Astroturf ® & Sports Turf Management Associations	ST data relies from manufacturer instead of real field treatment, meaning there is a high possibility that the turf does not undergo the same activity, while being compared against the same "costumer benefits"
Cumming (2019)	To assess NT impact on the environment by considering natural resource management	LCA report	By Hort Innovation with Infotech research (Australia)	Data collected from 30-40 turf growers across Australia, where the median and average is estimated	Consider various data set and average them out.
Itten et al. (2021)	To analyse carbon footprint of City of Zurich citizens	LCA report for City of Zurich	By Zurich University of Applied Science	Data were collected with the sport field experts within the City of Zurich, no further detail.	While they mentioned that the LCA input is based on the City of Zurich, the usage hours is estimation/theoretical
Magnusson and Mácsik (2017)	To assess the energy used and GHG from ST with various infill.	Journal paper	The study is within a project that financially supported by Swedish Transport Administration	Data (energy use and GHG emission) is broken down according to each component, from literature ranging from 2001-2015	Not true ST data, rather it is a material environmental impact and estimated according to each turf composition.
Meil and Bushi (2007)	To analyse the GHG from ST vs NT for Upper Canada College.	Report	By Athena Sustainable Materials institute (non-profit)	Data collected from databases (Ecoinvent, Franklin, etc.) and other report (FIFA, ICF consulting, etc.)	Not true local data, data is gathered despite various operating conditions.
Russo et al. (2022)	To analyse the environmental footprint for soccer field made of ST and NT	Journal paper	By the University of Foggia without specified financial support.	Using database Sphera, Plastic Europe, and Ecoinvent. While watering data's origin is unspecified.	Consider the different watering requirement during different seasons.
Säberg (2021)	To assess the global warming potential and water consumption for FIFA certified ST and local NT	Master thesis	By the Linkoping University, without specified financial support.	Using database Ecoinvent, complement with survey from Swedish Football Association, NT and ST suppliers.	Real local data collected through interview/survey. However, they only manage to assess water consumption and GHG.

6.2.4 Extension

This part explores other types of assessment that incorporate life cycle thinking.

6.2.4.1 Life Cycle Cost Analysis (LCCA) and Economic-Input-Output-LCA (EIO-LCA)

LCCA is a process that evaluates the cost of a product over its lifetime within multiple stages of the supply chain (InnProBio, 2020). Moreover, EIO-LCA is a quantification technique that measures each sector's environmental impact and its interrelationship with other sectors in the economy (Carnegie Mellon University, 2018). EIO-LCA combines the economic information with resource flow and its impact on the environment (West Coast Climate).

For example, Jenicek and Rodriguez (2019) review various LCCA and conducted a cost analysis on ST vs NT by estimating the cost of each ST component and comparing them to usage time (cost-benefit analysis). They found that it is not always cheaper to install ST, but the study did not conduct enough surveys on the usage time; hence, it was unable to conclude whether the most benefit can be extracted from the ST installation. Another LCCA analysis according to the amount of game is by Polyturf (n.d.).

Like LCA, it is important to collect sufficient data to prove that more activities can be done with one surface type over another (e.g., ST vs NT and vice-versa). Otherwise, the study is skewed into certain products without substantial evidence of their usability. Cost analysis review is possibly needed to investigate the method variance, along with assessment of how different studies measure the "cost-benefit" impact. Some useful references that consider costing in their analyses are:

1. Jenicek and Rodriguez (2019) – review different LCCA for turf surfaces
2. Victoria State Government (2011) provide steps on life-cycle-costing for various sports on ST.
3. Football NSW (2015) analysed the capital investment required.
4. Talbot et al. (2019) provide the life-cycle-costing step for ST.
5. Sheppard (2020) estimate the costing require for ST.

6.2.4.2 Social LCA (S-LCA)

Social-LCA quantifies the potential positive and negative social and socio-economic outcomes of certain products or services throughout their lifecycle (Benoît-Norris et al., 2011). S-LCA relies on social audits and in person surveys to collect data from various stakeholder and how it impacts the impact categories (human rights, working conditions, health and safety, etc.). Other social assessment techniques, such as social acceptance through social license can also be implemented (Gunningham et al., 2004).

6.2.4.3 Ecological LCA (Eco-LCA)

Ecological LCA is a LCA that focuses on direct and indirect ecological impacts and its surrounding ecosystem (Singh & Bakshi, 2009). For turf, such a study can be useful in understanding and addressing concerns over potential biodiversity loss and disruption to the ecosystem. While this study hasn't been executed on syntenic turf, some studies have assessed the ecological impact of ST implementation. Opting for ST over NT does eliminate the ecological function, but it is unclear how it impacts the broader ecosystems and its biodiversity (Lavender et al., 2017; Lozano & Ferguson, 2021).

6.2.5 Other Environmental Concerns

The LCA results are only "as good as" the data inputted into the system, meaning pollutants that are not recorded (e.g., because of their microscopic quantity or because they are undetected) will simply not be quantified nor assessed.

Thus, this section evaluates some potential pollutants that may need investigation in light of available literature. The goal of this section is not to fully map the body of knowledge for potential pollutants coming from ST, but rather to navigate the ST environmental assessment, providing insight into a possible direction for future environmental investigation. More extensive external review for these pollutants is required.

6.2.5.1 Microplastics

Microplastics are defined as plastic fragments (< 5 mm in size), usually the product of wear and tear, that escape into the environment. Microplastics are still emerging pollutants, with more studies required to assess their real long-term impact (Kole et al., 2017).

While it is cost effective and environmentally friendly to use recycled rubber as ST infill, some studies argue that recycled tyre can be a problematic source of microplastics (Armada et al., 2022). However, Russo et al. (2022) reviewed available studies on microplastics from infill materials and concluded that microplastics from infill pose minimal damage to the environment and humans. They note also that various organisations are currently investigating the impact of infill material on microplastic emissions.

Herz (2022) describes some maintenance practices that can mitigate the microplastic discharge from reaching the environment. In the future, it is possible to have a dedicated unit to address the microplastic unit. Technology advances should also assist this purpose. A methodology to assess microplastic wear and tear is currently under development and expected to be standardised by the end of 2022 (ESTC, 2022b). Microplastic vacuuming technologies have been demonstrated for beaches (Hoola One, 2022), and filtration cyclonic units for fields are being explored. Microplastic filtering technology is available for faucets (Jern, 2021) and washing machines (Electrolux Group, 2022).

6.2.5.2 Persistent Organic Pollutants (POPs) and Volatile Organic Carbons (VOCs)

POPs are carbon based chemical structures that do not breakdown in the environment. They can accumulate in tissue, causing side effects on humans and the environment. For turf products, the rubber crumb is believed to be a source of Polycyclic Aromatic Hydrocarbon (PAHs, a type of POPs). Cheng et al. (2014) reviewed various studies that measured the content of PAHs and VOCs for several ST fields and noted that various studies found an elevation of PAH and VOC content over synthetic turf. A more recent study by Armada et al. (2022) assessed 91 ST infill samples and found that rubber crumb infill has a higher PAH content, including some species considered carcinogenic.

6.2.5.3 Other chemicals

Many LCAs do not assess the chemicals required for maintenance, or additives in the products. Some potential pollutants are:

1. ***Heavy metals*** leaching is usually part of LCA, but if such data is not available, recorded or inputted into the LCA, it will not be quantified in the assessment. Rubber crumbs that contain heavy metals may have the potential to leach it into waterways and the surrounding soil (Cheng et al., 2014)
2. ***Additives*** used for ST (e.g., pigment, plasticiser, etc.) may have the potential to leach into the environment, however their environmental impact is unclear.
3. ***Fabric softener, field painting, and disinfectant*** are common for ST maintenances; however, their environmental impact is unclear.

7 Conclusion

This report has reviewed 8 LCA studies focused on turf surfaces. In general, most of the LCA findings reviewed agree with the premise of ST implementation being the preferred option. Opting for ST reduces maintenance (water, mowing, etc.) requirements, but it increases the impacts of global warming potential due to virgin plastic manufacturing. However, these LCA results are influenced by the framework employed, namely the functional unit, boundary condition, assumptions, and the origin of the data inputted into the LCA. Based on these findings, technical advice is provided on the LCA framework for future assessors. Limitations surrounding the LCA method is also discussed, such as inability to capture the impact of specific micropollutants. Beyond the insights gained from LCAs, possible strategies are also provided to make the ST industry more circular. Critically, there is a lack of a circular business model and recycling facilities. Government entities should endorse industries that are proactive in the shift towards CE while simultaneously supporting the construction of ST recycling facilities.

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9 Appendix 1: LCA Comparison and Calculation

(Adachi et al., 2016)	Impact category	Water use	Cost
Table 3-6	Unit	Gal/m2	$/m2
	Sc1 Sod (Natural Grass)	6926	53.41
	Sc2 Synthetic turf	1926	75.29

(Uhlman, 2013)	Impact category	PEC	RMC	GHG	POCP	ODP	AP	WE	SWG	Land use	TP	Work accident	Risk Potential	Cost
Figure 8-23	Unit	MJ/CB	kg-Ag-Eq/CB	g-CO2-Eq/CB	kg-Ethylene-Eq/CB	g-CFC-11-Eq/CB	g-SO2-Eq/CB	L of water/CB	kg-MSW-Eq/CB	m2a/CB	TP-score/CB	Scoring/CB	Scoring/CB	$/CB
	Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	413	5.56E+08	8.46E+05	110	4.18E+06	5.56E+07	1.02E+05	4.48E+04	0.19	0.9	0.89	1482046
	Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	445	7.15E+08	1.09E+06	260	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	0.20	1	0.93	1530740
	Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	436	6.78E+08	1.03E+06	220	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	0.20	0.96	0.91	1548070
	Sc4 Natural grass (available 600 hrs/year)	7.81E+06	905	2.57E+08	9.78E+05	5	2.34E+06	2.38E+07	4.98E+04	5.68E+04	0.12	0.16	0.31	960663
	Sc5 Natural grass (available 432 hrs/year)	1.11E+07	1149	3.78E+08	1.34E+06	5	3.48E+06	3.33E+07	6.77E+04	7.75E+04	0.11	0.21	0.35	1337681
	Sc6 Natural grass (available 360 hrs/year)	1.34E+07	1393	4.54E+08	1.67E+06	5	4.44E+06	3.98E+07	8.16E+04	9.42E+04	0.24	0.25	0.38	1608154
	Sc7 Natural grass (available 300 hrs/year)	1.64E+07	1693	5.64E+08	2.01E+06	5	5.47E+06	4.84E+07	9.72E+04	1.14E+05	0.32	0.3	0.42	1934014
	Sc8 Natural grass (available 200 hrs/year)	2.59E+07	2579	9.26E+08	3.12E+06	5	9.07E+06	7.31E+07	1.48E+05	1.71E+05	0.57	0.48	0.56	2920054
	Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	3.62E+07	3423	1.35E+09	4.28E+06	5	1.32E+07	9.99E+07	1.98E+05	2.32E+05	0.90	0.62	0.71	3918783

(Cumming, 2019)	Impact category	GWP	ODP	AP	EP	POCP	AD	Water use	Land use	PEC	Fresh water toxicity	HTC	HTNC
Page 22	Unit	kg CO2eq	kg CFC11eq	kg SO2eq	kg PO4 eq	kg C2H4eq	kg Sbeq	m3	m2	MJ	PAF.m3.day	cases	cases
	Sc1 Natural turf (1 Year)	-0.00948	7.44E-05	0.006254	0.046331	0.000255	6.15E-05	6.33E-01	2.67E+00	1.89E+01	9.33E-03	5.77E-11	1.80E-11
	Sc2 Natural turf (for 5 years)	0.51956	1.49E-05	0.003322	0.01108	1.30E-04	3.34E-05	0.1825	0.534	7.584	0.00289	3.38E-11	6.24E-12
	Sc3 Natural turf (for 10 years)	0.58569	7.46E-06	0.002956	0.006667	0.000114	2.98E-05	0.12625	0.267	3.792	0.002085	3.08E-11	4.78E-12

(Itten, Stucki, & Glauser, 2021)	Impact category	GHG	Air Pollutants	IR	EP-freshwater	EP-Marine	EP-Terrestrial	Land use	MR	HH	Ecotoxicity	PEC
Fig S.1	Unit											
	Sc1 Natural Turf without drainage layer (480 Hrs usage)	85.6	100	100	100	100	100	100	46	100	100	62
	Sc2 Natural turf with drainage (800 Hrs usage)	67.7	82	77	75	66	67	63	31	97	60	53
	Sc3 Hybrid turf, reinforced (1000 hr)	62.2	71	67	69	55	57	55	25	90	46	53
	Sc4 Artificial turf without plastic or granules infill (16000 hr)	68.5	29	44	41	15	15	23	14	75	5	64
	Sc5 Artificial turf with plastic infill (16000 hr)	100.0	44	91	92	17	18	29	100	85	10	100

(Magnusson & Mácsik, 2017)	Impact category	GHG-construction	GHG-Maintenance	GHG total	Energy use - construction	Energy use - maintenance	Energy use
Fig 3-5	Unit	1 ton of CO2 Eq	1ton of CO2 Eq	1 ton of CO2 Eq	1000 MJ Eq	1000 MJ Eq	1000 MJ Eq
	Sc1 Synthetic turf with recycled tyre infill	10.1	10.2	20.3	568	576	1144.4
	Sc2 Synthetic turf with Thermoplastic elastomers infill	167.7	97.1	264.7	4704	2706	7410.0
	Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill	55.1	44.9	100.0	1099	886	1984.7
	Sc4 Synthetic turf with recycled EPDM infill	13.6	10.0	23.5	722	570	1292.6

Data collected only when it is diverges between different scenario e.g. in the infill alternatives

(Meil & Bushi, 2007)	Impact category	GHG
Table 3-4	Unit	1 ton of CO2 Eq
	Sc1 Natural grass	-16.9
	Sc2 Synthetic turf	55.6

(Russo, Cappelletti, & Nicoletti, 2022)	Impact category	GWP Fossil+biogenic	GWP Fossil	GWP Biogenic	GWP land use change	ODP	HTC	HTNC	AP	PM	Ecotoxicity for freshwater	IR	POCP	EP-terrestrial	EP-freshwater	EP-Marine	Landuse	Water use	Fossil and minerla use
Fig 3-5	Unit	kgof CO2 Eq	kgof CO2 Eq	kgof CO2 Eq	kgof CO2 Eq	kg-CFC-11 Eq	USEtox	USEtox	Mold of H+ Eq	kg PM2.5 Eq	USEtox	U-235 Eq	kg-NMVOC Eq	Mole N Eq	Kg P eq				
	Sc1 Natural turf	5.13E+05	2.08E+05	-1.02E+01	1.61E+03	1.82E-04	7.97E-04	1.35E-01	1.56E+03	1.60E+03	4.42E+04	1.71E+04	1.34E+03	6.16E+03	1.23E+01	2.21E+02	2.39E+03	8.11E+03	5.53E-01
	Sc2 Artificial/Synthetic turf:	1.98E+05	8.16E+04	-1.18E+01	1.75E+03	3.26E-02	-1.84E-04	1.62E-01	1.60E+03	1.81E+02	4.65E+04	1.57E+04	1.43E+03	6.54E+03	3.86E-01	7.55E+01	-1.23E+04	7.70E+03	4.49E-01

(Söberg, 2021)	Impact category	GWP-production	Water use - Production	Water-Use phase	GWP -usephase	GWP disposal	GWP total	Water use total
Fig 11-15	Unit	CO2 Eq	m3	m3	CO2 Eq	CO2 Eq	CO2 Eq	m3
	Sc1 Synthetic turf (total, without infill)	20093	16	-	-	-		
	Sc2.1 Synthetic turf + Cork infill w landfill	30990	2272	42	860	1481	33331	2314
	Sc2.2 Synthetic turf + Cork infill w incineration	30990	2272	42	860	21	31871	2314
	Sc3.1 Synthetic turf + Recycled tyre infill w landfill	20101	16	5	656	1478	22235	21
	Sc3.2 Synthetic turf + Recycled tyre infill w incineration	20101	16	5	656	18	20775	21
	Sc4 Natural turf	2919	11500	5600	4227	13	7159	17100

(Adachi et al., 2016)			Water use	Cost
			Gal/m2	$/m2

		Sc1 Sod (Natural grass)	6926	53.41
		Sc2 Synthetic Turf (recycled tyre, polyethylene, and polyester fabric)	1926	75.29
	STNT1.1		-72%	41%

(Uhlman, 2013)			PEC	RMC	GHG	POCP	ODP	AP	WE	SWG	Land use	TP	Work accident	Risk Potential	Cost
			MJ/CB	kg-Ag-Eq/CB	g-CO2-Eq/CB	kg-Ethyelne-Eq/CB	g-CFC-11-Eq/CB	g-SO2-Eq/CB	L of water/CB	kg-MSW-Eq/CB	m2a/CB	TP-score/CB	Scoring/CB	Scoring/CB	$/CB
		Sc4 Natural grass (available 600 hrs/year)	7.81E+06	9.05E+02	2.57E+08	9.78E+05	5.00E+00	2.34E+06	2.38E+07	4.98E+04	5.68E+04	1.21E-01	1.60E-01	3.10E-01	9.61E+05
		Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	4.13E+02	5.56E+08	8.46E+05	1.10E+02	4.18E+06	5.56E+07	1.02E+05	4.48E+04	1.90E-01	9.00E-01	8.90E-01	1.48E+06
	STNT2.1		53%	-54%	117%	-13%	2100%	79%	134%	105%	-21%	57%	463%	187%	54%
		Sc4 Natural grass (available 600 hrs/year)	7.81E+06	9.05E+02	2.57E+08	9.78E+05	5.00E+00	2.34E+06	2.38E+07	4.98E+04	5.68E+04	1.21E-01	1.60E-01	3.10E-01	9.61E+05
		Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	4.45E+02	7.15E+08	1.09E+06	2.60E+02	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	1.95E-01	1.00E+00	9.30E-01	1.53E+06
	STNT2.2		102%	-51%	179%	11%	5100%	210%	184%	-494%	-5%	61%	525%	200%	59%
		Sc4 Natural grass (available 600 hrs/year)	7.81E+06	9.05E+02	2.57E+08	9.78E+05	5.00E+00	2.34E+06	2.38E+07	4.98E+04	5.68E+04	1.21E-01	1.60E-01	3.10E-01	9.61E+05
		Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	4.36E+02	6.78E+08	1.03E+06	2.20E+02	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	1.95E-01	9.60E-01	9.10E-01	1.55E+06
	STNT2.3		83%	-52%	164%	5%	4300%	176%	168%	-327%	-8%	61%	500%	194%	61%
		Sc6 Natural grass (available 360 hrs/year)	1.34E+07	1.39E+03	4.54E+08	1.67E+06	5.00E+00	4.44E+06	3.98E+07	8.16E+04	9.42E+04	2.37E-01	2.50E-01	3.80E-01	1.61E+06
		Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	4.13E+02	5.56E+08	8.46E+05	1.10E+02	4.18E+06	5.56E+07	1.02E+05	4.48E+04	1.90E-01	9.00E-01	8.90E-01	1.48E+06
	STNT2.4		-11%	-70%	22%	-49%	2100%	-6%	40%	25%	-52%	-20%	260%	134%	-8%
		Sc6 Natural grass (available 360 hrs/year)	1.34E+07	1.39E+03	4.54E+08	1.67E+06	5.00E+00	4.44E+06	3.98E+07	8.16E+04	9.42E+04	2.37E-01	2.50E-01	3.80E-01	1.61E+06
		Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	4.45E+02	7.15E+08	1.09E+06	2.60E+02	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	1.95E-01	1.00E+00	9.30E-01	1.53E+06
	STNT2.5		18%	-68%	57%	-35%	5100%	63%	70%	-340%	-43%	-18%	300%	145%	-5%
		Sc6 Natural grass (available 360 hrs/year)	1.34E+07	1.39E+03	4.54E+08	1.67E+06	5.00E+00	4.44E+06	3.98E+07	8.16E+04	9.42E+04	2.37E-01	2.50E-01	3.80E-01	1.61E+06
		Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	4.36E+02	6.78E+08	1.03E+06	2.20E+02	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	1.95E-01	9.60E-01	9.10E-01	1.55E+06
	STNT2.6		7%	-69%	49%	-38%	4300%	45%	60%	-238%	-45%	-18%	284%	139%	-4%
		Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	3.62E+07	3.42E+03	1.35E+09	4.28E+06	5.00E+00	1.32E+07	9.99E+07	1.98E+05	2.32E+05	9.02E-01	6.20E-01	7.10E-01	3.92E+06
		Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	4.13E+02	5.56E+08	8.46E+05	1.10E+02	4.18E+06	5.56E+07	1.02E+05	4.48E+04	1.90E-01	9.00E-01	8.90E-01	1.48E+06
	STNT2.7		-67%	-88%	-59%	-80%	2100%	-68%	-44%	-49%	-81%	-79%	45%	25%	-62%
		Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	3.62E+07	3.42E+03	1.35E+09	4.28E+06	5.00E+00	1.32E+07	9.99E+07	1.98E+05	2.32E+05	9.02E-01	6.20E-01	7.10E-01	3.92E+06
		Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	4.45E+02	7.15E+08	1.09E+06	2.60E+02	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	1.95E-01	1.00E+00	9.30E-01	1.53E+06
	STNT2.8		-56%	-87%	-47%	-75%	5100%	-45%	-32%	-199%	-77%	-78%	61%	31%	-61%
		Sc9 Natural grass (available 150 hrs/year, 75% reduction of usage compared to synthetic turf)	3.62E+07	3.42E+03	1.35E+09	4.28E+06	5.00E+00	1.32E+07	9.99E+07	1.98E+05	2.32E+05	9.02E-01	6.20E-01	7.10E-01	3.92E+06
		Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	4.36E+02	6.78E+08	1.03E+06	2.20E+02	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	1.95E-01	9.60E-01	9.10E-01	1.55E+06
	STNT2.9		-60%	-87%	-49.64%	-76%	4300%	-51%	-36%	-157%	-78%	-78%	55%	28%	-60%

(Itten, Stucki, & Glauser, 2021)													
			GHG	Air Pollutants	IR	EP-freshwater	EP-Marine	EP-Terrestrial	Land use	MR	HH	Ecotoxicity	PEC
		Sc1 Natural Turf without drainage layer (480 Hrs usage)	85.56547619	100	100	100	100	100	100	46.28879892	100	100	62.43169399
		Sc3 Hybrid turf, reinforced (1000 hr)	62.20238095	71.44992526	66.81957187	68.7593423	54.83425414	57.3388203	54.82573727	25.23616734	90.23323615	46.18644068	53.27868852
	STNT3.1		-27%	-29%	-33%	-31%	-45%	-43%	-45%	-45%	-10%	-54%	-15%
		Sc1 Natural Turf without drainage layer (480 Hrs usage)	85.56547619	100	100	100	100	100	100	46.28879892	100	100	62.43169399
		Sc4 Artificial turf without plastic or granules infill (16000 hr)	68.45238095	29.29745889	44.03669725	41.40508221	15.05524862	14.54046639	56.70241287	13.90013495	75.36443149	5	64.3442623
	STNT3.2		-20%	-71%	-56%	-59%	-85%	-85%	-43%	-70%	-25%	-95%	3%
		Sc1 Natural Turf without drainage layer (480 Hrs usage)	85.56547619	100	100	100	100	100	100	46.28879892	100	100	62.43169399
		Sc5 Artificial turf with plastic infill (16000 hr)	100	43.79671151	91.13149847	91.77877429	16.85082873	17.83264746	29.35656836	100	84.83965015	5	100
	STNT3.6		17%	-56%	-9%	-8%	-83%	-82%	-71%	116%	-15%	-95%	60%
		Sc2 Natural turf with drainage (800 Hrs usage)	67.70833333	82.06278027	77.37003058	74.88789238	65.60773481	67.21536351	62.60053619	31.0391363	96.93877551	59.88700565	52.86885246
		Sc3 Hybrid turf, reinforced (1000 hr)	62.20238095	71.44992526	66.81957187	68.7593423	54.83425414	57.3388203	54.82573727	25.23616734	90.23323615	46.18644068	53.27868852
	STNT3.3		-8%	-13%	-14%	-8%	-16%	-15%	-12%	-19%	-7%	-23%	1%
		Sc2 Natural turf with drainage (800 Hrs usage)	67.70833333	82.06278027	77.37003058	74.88789238	65.60773481	67.21536351	62.60053619	31.0391363	96.93877551	59.88700565	52.86885246
		Sc4 Artificial turf without plastic or granules infill (16000 hr)	68.45238095	29.29745889	44.03669725	41.40508221	15.05524862	14.54046639	56.70241287	13.90013495	75.36443149	5	64.3442623
	STNT3.4		1%	-64%	-43%	-45%	-77%	-78%	-9%	-55%	-22%	-92%	22%
		Sc2 Natural turf with drainage (800 Hrs usage)	67.70833333	82.06278027	77.37003058	74.88789238	65.60773481	67.21536351	62.60053619	31.0391363	96.93877551	59.88700565	52.86885246
		Sc5 Artificial turf with plastic infill (16000 hr)	100	43.79671151	91.13149847	91.77877429	16.85082873	17.83264746	29.35656836	100	84.83965015	5	100
	STNT3.5		48%	-47%	18%	23%	-74%	-73%	-53%	222%	-12%	-92%	89%

(Meil & Bushi, 2007)			GHG
			1 ton of CO2 Eq
		Sc1 Natural grass	-16.9
		Sc2 Synthetic turf (Made of Thioback Pro backing material (USA), rubber granule infill, Polyethylene turf, and PVC drainage piping)	55.6
	STNT4		429%

(Russo, Cappelletti, & Nicoletti, 2022)			GWP Fossil+biogenic	GWP Fossil	GWP Biogenic	GWP land use change	ODP	HTC	HTNC	AP	PM	Ecotoxicity for freshwater	IR	POCP	EP-terrestrial	EP-freshwater	EP-Marine	Landuse	Water use	Fossil and minerla use
			kgof CO2 Eq	kgof CO2 Eq	kgof CO2 Eq	kgof CO2 Eq	kg-CFC-11 Eq	USEtox	USEtox	Mold of H+ Eq	kg PM2.5 Eq	USEtox	U-235 Eq	kg-NMVOC Eq	Mole N Eq	Kg P eq		0	0	0
		Sc1 Natural turf	512988.79	208396.14	-10.16	1605.117	0.00018205	0.0007973	0.13500163	1559.42	181.236	1994484.5	17117.6	1342.01	6160.1	12.299326	220.5	2390.324	8111.61	0.5529884
		Sc2 Artificial/Synthetic turf:	198196.14	81598.81	-11.84	1747.59	0.0325864	-0.0001844	0.1624523	1604.4	180.83	46482	15675.3	1433.5	6541.5	0.3858	75.52	-12255.81	7702.61	0.44935
	STNT5		-61%	-61%	-17%	9%	17800%	-123%	20%	3%	0%	-98%	-8%	7%	6%	-97%	-66%	-613%	-5%	-19%

(Säberg, 2021)			GWP total	Water use total
			CO2 Eq	m3
		Sc4 Natural turf	7159	17100
	STNT6.1	Sc2.1 Synthetic turf + Cork infill w landfill	33331	2314
			366%	-86%
		Sc4 Natural turf	7159	17100
		Sc2.2 Synthetic turf + Cork infill w incineration	31871	2314
	STNT6.2		345%	-86%
		Sc4 Natural turf	7159	17100
		Sc3.1 Synthetic turf + Recycled tyre infill w landfill	22235	21
	STNT6.3		211%	-100%
		Sc4 Natural turf	7159	17100
		Sc3.2 Synthetic turf + Recycled tyre infill w incineration	20775	21
	STNT6.4		190%	-100%

(Uhlman, 2013)			PEC	RMC	GHG	POCP	ODP	AP	WE	SWG	Land use	TP	Work accident	Risk Potential	Cost
			MJ/CB	kg-Ag-Eq/CB	g-CO2-Eq/CB	kg-Ethyelne-Eq/CB	g-CFC-11-Eq/CB	g-SO2-Eq/CB	L of water/CB	kg-MSW-Eq/CB	m2a/CB	TP-score/CB	Scoring/CB	Scoring/CB	$/CB
		Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	4.13E+02	5.56E+08	8.46E+05	1.10E+02	4.18E+06	5.56E+07	1.02E+05	4.48E+04	1.90E-01	9.00E-01	8.90E-01	1.48E+06
		Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	4.45E+02	7.15E+08	1.09E+06	2.60E+02	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	1.95E-01	1.00E+00	9.30E-01	1.53E+06
	STST1.1		32%	8%	29%	28%	136%	73%	22%	-293%	21%	3%	11%	4%	3%

		Sc1 PureGrass ® (Nylon, no infill)	1.19E+07	4.13E+02	5.56E+08	8.46E+05	1.10E+02	4.18E+06	5.56E+07	1.02E+05	4.48E+04	1.90E-01	9.00E-01	8.90E-01	1.48E+06
		Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	4.36E+02	6.78E+08	1.03E+06	2.20E+02	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	1.95E-01	9.60E-01	9.10E-01	1.55E+06
	STST1.2		20%	6%	22%	22%	100%	54%	15%	-211%	16%	3%	7%	2%	4%
		Sc2 Gameday Grass MT (Polyethylene, with rubber crumb infill)	1.58E+07	4.45E+02	7.15E+08	1.09E+06	2.60E+02	7.24E+06	6.77E+07	-1.96E+05	5.40E+04	1.95E-01	1.00E+00	9.30E-01	1.53E+06
		Sc3 Gameday Grass 3D MT (67% Polyethylene and 28% Nylon, with rubber crumb infill)	1.43E+07	4.36E+02	6.78E+08	1.03E+06	2.20E+02	6.45E+06	6.39E+07	-1.13E+05	5.21E+04	1.95E-01	9.60E-01	9.10E-01	1.55E+06
	STST1.3		-9%	-2%	-5%	-5%	-15%	-11%	-6%	42%	-4%	0%	-4%	-2%	1%

			GHG	Air Pollutants	IR	EP-freshwater	EP-Marine	EP-Terrestrial	Land use	MR	HH	Ecotoxicity	PEC
(Itten, Stucki, & Glauser, 2021)		Sc4 Artificial turf without plastic or granules infill (16000 hr)	68.45238095	29.29745889	44.03669725	41.40508221	15.05524862	14.54046639	56.70241287	13.90013495	75.36443149	5	64.3442623
		Sc5 Artificial turf with plastic infill (16000 hr)	100	43.79671151	91.13149847	91.77877429	16.85082873	17.83264746	29.35656836	100	84.83965015	5	100
	STST2.1		46%	49%	107%	122%	12%	23%	-48%	619%	13%	0%	55%
		Sc4 Artificial turf without plastic or granules infill (16000 hr)	68.45238095	29.29745889	44.03669725	41.40508221	15.05524862	14.54046639	56.70241287	13.90013495	75.36443149	5	64.3442623
		Sc3 Hybrid turf, reinforced (1000 hr)	62.20238095	71.44992526	66.81957187	68.7593423	54.83425414	57.3388203	54.82573727	25.23616734	90.23323615	46.18644068	53.27868852
	STST2.2		-9%	144%	52%	66%	264%	294%	-3%	82%	20%	824%	-17%
		Sc3 Hybrid turf, reinforced (1000 hr)	62.20238095	71.44992526	66.81957187	68.7593423	54.83425414	57.3388203	54.82573727	25.23616734	90.23323615	46.18644068	53.27868852
		Sc5 Artificial turf with plastic infill (16000 hr)	100	43.79671151	91.13149847	91.77877429	16.85082873	17.83264746	29.35656836	100	84.83965015	5	100
	STST2.3		61%	-39%	36%	33%	-69%	-69%	-46%	296%	-6%	-89%	88%

(Magnusson & Mácsik, 2017)			GHG total	Energy use
			1 ton of CO2 Eq	1000 MJ Eq
		Sc1 Synthetic turf with recycled tyre infill	20.31763155	1144.357545
		Sc2 Synthetic turf with Thermoplastic elastomers infill	264.7416996	7410.014383
	STST3.1		1203%	548%
		Sc1 Synthetic turf with recycled tyre infill	20.31763155	1144.357545
		Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill	99.96464102	1984.687762
	STST3.2		392%	73%
		Sc4 Synthetic turf with recycled EPDM infill	23.53170322	1292.610572
		Sc2 Synthetic turf with Thermoplastic elastomers infill	264.7416996	7410.014383
	STST3.3		1025%	473%
		Sc4 Synthetic turf with recycled EPDM infill	23.53170322	1292.610572
		Sc3 Synthetic turf with Ethylene propylene diene monomer (EPDM) infill	99.96464102	1984.687762
	STST3.4		325%	54%

(Säberg, 2021)			GWP total	Water use total
			CO2 Eq	m3
		Sc2.1 Synthetic turf + Cork infill w landfill	33331	2314
		Sc3.1 Synthetic turf + Recycled tyre infill w landfill	22235	21
	STST4.1		-33%	-99%
		Sc2.2 Synthetic turf + Cork infill w incineration	31871	2314
		Sc3.2 Synthetic turf + Recycled tyre infill w incineration	20775	21
	STST4.2		-35%	-99%

Appendix 7

Synthetic turf in public spaces - systematic assessment of heat and environmental impacts

WESTERN SYDNEY
UNIVERSITY

SYNTHETIC TURF IN PUBLIC SPACES

SYSTEMATIC ASSESSMENT OF SURFACE TEMPERATURES AND ASSOCIATED ENVIRONMENTAL IMPACTS

AUGUST 2022

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ACKNOWLEDGEMENT OF COUNTRY

With respect for Aboriginal cultural protocol, we pay our respects to the Darug, Tharawal (also historically referred to as Dharawal), Gandangara and Wiradjuri people who are the traditional custodians of the land where the metropolitan campuses of Western Sydney University are located. Through our work we hope to make an active contribution to a more respectful and just relationship to land and its traditional custodians today and tomorrow.

Parramatta, 10 August 2022

SYNOPSIS

Urban growth and densification can lead to increasing pressure on public recreational facilities like parks and sport fields. Traditionally, many of these public recreational facilities, especially those that support ball games, would be surfaced with natural turf. The confluence of inappropriate design, construction, and maintenance practices with the added pressure of increased use hours can lead to damage of turf surfaces and reductions in time such facilities are available for the public to use. In response to this situation, public and private organisations opt to install synthetic turf surfaces with the goal to extend use hours and provide appropriate facilities to support a more active lifestyle of local communities and sport clubs.

Synthetic turf is also widely used in playgrounds of parks, schools, early learning centres and increasingly around residential homes. These applications aim to benefit from the durability of the material, its visual appearance as 'green grassy' surface without the need for irrigation, and general low maintenance. However, synthetic turf, as small-scale application in a front garden or neighbourhood playground, or as large-scale application on a professional soccer field comes with a range of environmental impacts.

This systematic assessment reports environmental impacts of synthetic turf related to heat in a broad sense. More specifically, it ascertains the relationship between high surface temperatures of unshaded synthetic turf and why and how they translate into increasing air temperatures at a range of spatial scales. Unshaded synthetic turf is known to reach very high surface temperatures in summer and the industry manufacturing this product is working on reducing this particular impact on users. For this reason, we also assess the different strategies available to date that aim at lowering surface temperature of synthetic turf and highlight the importance of shade when mitigating these temperatures.

The global analysis presented here clearly indicates the limited use of unshaded synthetic turf in hot summer climates. Australia is the hottest, permanently inhabited continent, and the prevalent summer climate of Greater Sydney is generally hot with high solar irradiance intensity. However, no systematic and independent research is available that documents the heat performance of unshaded synthetic turf in any other settings than playgrounds in schools and public parks. Given the current trend of installation of much larger areas of synthetic turf in the region, and the unresolved heat-related impacts that can arise from these installations, a list of three priorities for research work is distilled from the literature analysis:

1. Documentation of the heating effect of solar irradiance under a range of environmental conditions (diurnal and seasonal) and the resultant warming of ambient air temperatures.
2. *In-situ* analyses of radiant heat and its impact on human thermal comfort, including children and adults.
3. Quantification of the effectiveness of different heat mitigation techniques for several situations where synthetic turf is used.

Results of such work will be paramount when developing a comprehensive decision-making framework for applications of synthetic turf surfaces in the Greater Sydney Region and urban landscapes with similar climate. Using the strategy suggested here for collection of the necessary measurements, will allow contrasting the benefits and impacts of both natural and synthetic turf in a transparent and objective science-based system. Only once this information is available to those that resource and manage public and private open spaces can evidence-based decisions be made that balance interests of all involved, including human needs and respectful handling of the natural environment.

CONTENTS

1. OVERALL ISSUES THROUGHOUT THE LIFESPAN

1.1 NATURAL TURF

1.1.1 DESIGN AND INSTALLATION

The type of facility, sport and competition level determines the design approach for the installation of natural turf surfaces (Kamal, 2019). A high-level, dedicated sports facility must comply with regulations and thus requires an engineered sub-subsurface (sand, subgrade, etc.) and drainage system, while more 'local' fields in public parks are typically constructed on the existing soils with surface slope drainage (Burton, 2011). In playgrounds, natural turf is not a common feature in the main play area due to wear, safety, and impact regulations. In these settings, natural turf is used for landscaping.

Natural turf types are typically grouped into warm and cool season species (Burton, 2011; Hatfield, 2017) and applied depending on the local climatic conditions. For example, the warm season 'Kikuyu' and 'Couch' types perform well in drought and can sustain wear damage, except for winter when the vigor of the plants is reduced (Burton, 2011). However, climate change negatively impacts the growth of many natural turf species in urban environments (Hatfield, 2017), including the commonly used cultivars for sport fields and playgrounds. Reason for this impact is that turf grasses will be affected by rising air temperatures and changes in the seasonality and intensity of rainfall events, which in combination have a major influence on soil moisture availability and growth conditions. Moreover, turf grass species predominately exist in urban environments where the impacts of climate change are amplified (Intergovernmental Panel on Climate Change, 2022). Drought and heat tolerant species that can also resist extensive use might be needed in the future.

1.2.1 MAINTENANCE

Natural turf surfaces require regular and continuous maintenance involving irrigation and mowing to sustain a playable surface (Burton, 2011; Kamal, 2019). Also, applications of fertilizer, weed, pest and disease management, and aeration are needed (Burton, 2011). Natural turf surfaces require more water during the summer months to maintain plant growth and provide fit-for-purpose surfaces. Irrigation can have negative effects on the environment where water is scarce, and restrictions may be in effect during periods of exceptionally low rainfall. This situation applies to many Australian regions that experience droughts frequently. Management of natural turf in Perth, where warm season turf species are used, requires application of approximately 5.5 to 6.8 ML of water per ha (Burton, 2011). During a dry and warm summer, this volume of water may need to be applied daily.

1.2 SYNTHETIC TURF

Synthetic turf was developed as an alternative to natural turf that requires no mowing and provides a durable surface. It can be used by a range of sport disciplines, and it is a common feature in outdoor playgrounds worldwide. In Australia, synthetic turf surfaces are used in a range of sports, including hockey, football and cricket fields.

1.2.1 DESIGN AND INSTALLATION

Synthetic turf consists of six components: turf fibres, backing layer, infill material, shock pad, sub-base and drainage system (Burton, 2011; Kamal, 2019; Sheppard, 2019). The fibres mimic the blades of natural turf and are typically made from polypropylene (Sheppard, 2019). The length of the blades (also known as *yarn*) depends on the type of sport, ranging from the shortest for cricket and hockey to the longest for football/soccer fields (Burton, 2011; Sheppard, 2019) (Table 1). The turf blades are attached to the backing layer with a bonding agent (commonly polyurethane) so that the individual tufts of blades remain in place. However, the backing material is also critical to keep the field itself in place, preventing any floating, shifting or shrinkage (Sheppard, 2019). This layer allows water to infiltrate and thus reduces surface runoff. Each sport has guidelines on the amount of water that needs to pass through this layer which will determine the type of backing layer (Sheppard, 2019). Table 1: Range of synthetic turf blades according to different sport disciplines. Information provided in Sheppard (2019).

Sport discipline	Length of grass blade (mm)
Cricket Wicket	9-12
Bowls	10-15
Tennis	10-25
Hockey	10-45
Football (5-a-side)	20-60
Football (11-a-side)	50-60
Australian Rules Football	50-65
Rugby League/Union	minimum 60

Infill materials are used to weigh down the synthetic surface, provide impact attenuation and support the plastic blades. Various materials are used as infill for artificial turf surfaces: crumbed rubber (i.e., SBR, TPE or EPDM), sand and organic infills (Burton, 2011; Cheng et al., 2014; Sheppard, 2019). The rubbers may be perceived as sustainable since they are made from recycled tyres that would otherwise contribute to landfill and potential other environmental pollution. Availability of this recycled product is high, making it cheap to purchase, and its weather-resistance helps to extend the lifespan of the overall field (Cheng et al., 2014; Sheppard, 2019). However, some rubbers pose heat-related and toxin-leaching issues for the environment and people (see Sections 3.1.1 and 8). A typical installation on a soccer field requires at least 100 tonnes of the material – equal to 22,000 tyres. Foot traffic and carelessness can be an issue that causes trafficking the rubber crumb into the surrounding environment (Fig. 1).

Sand is another common infill material used on synthetic turf fields, as a stand-alone material or in combination with rubbers and/or organic fibres (Burton, 2011; Cheng et al., 2014). Also safer for humans and the environment are the organic infills. Most widely used are cork and coconut fibres, which represent a cooler alternative to rubbers, particularly when wet (Cheng et al., 2014). In fact, moisture is essential for the integrity of these organic infills, otherwise, the material may break down and degrade over time. Therefore, synthetic turf fields with organic infills require regular watering and maintenance, occasional replacement and top-up to sustain their properties (Sheppard, 2019). New products using coated sand that retains water for extended time and thus cools synthetic turf surface are also being introduced to the market (e.g., HydroChill from APT Asia Pacific and Southwest Greens).

The shock pad separates the synthetic turf from the sub-base to increase force absorption upon impact. The material type and thickness as well as the maintenance of management interventions of the shock pad layer varies with the usage and intensity of sport discipline (Sheppard, 2019). For instance, synthetic turf field that will receive excessive use (multi-purpose public field) or its aimed for contact sports (i.e., Rugby Union, Australian Football) should have a shock pad to reduce deterioration of the system and provide players safety (Sheppard, 2019). A shock pad reduces the cost for the infill material and also reduces the length of the blades that need to be used (Eunomia Research and Consulting, 2017). Hence, depending on the sport discipline, the use of a shock pad layer will influence overall design and cost of the synthetic turf field. Beneath the pad is a sub-base, typically made from gravel to support the synthetic turf system above (Kamal, 2019). The drainage system is located within the sub-base material to direct the rainwater into the local stormwater system and thus prevent flooding of a sport field. Various drainage systems exist, and their application depends on sport, site, and climatic conditions (Sheppard, 2019).

FIGURE 1: An example for tracking of rubber crumb infill from synthetic turf sport fields. The image was taken on 22 February 2022 at a recently opened soccer field in Sydney. The access gate to the field, equipped with a brush-gris system to collect crumbs was approximately 12 meters away from the section shown in this image..

1.2.2 MAINTENANCE

Like natural turf, synthetic turf fields require regular maintenance to remain safe and playable (Burton, 2011; Kamal, 2019). Preserving the integrity of a synthetic turf field also prolongs its lifespan and thus reduces costs for any repairs and end-of-life replacement. Although mowing is not required, these artificial surfaces need regular cleaning, grooming, topping up the infill material, and repairing any damage (Burton, 2011; Kamal, 2019). When sand or organic infills are selected, occasional weeding and removing of algae is required (Burton, 2011). The frequency of maintenance tasks depends on how often the sports field is used. As opposed to installation, maintenance costs can be expected to be lower or comparable to natural turf (Kamal, 2019).

1.3 HYBRID TURF

A hybrid turf is a combination of synthetic and natural turf as a one-design system. This is a relatively new application for Australian conditions and no independent and systematic research has assessed its environmental performance, carbon footprint, life cycle or capacity for end-of-life recycling. It can be expected that intensive grounds work is needed to keep the natural and artificial surfaces at the same height, impact attenuation and other important aspects to maintain safe use of such surfaces.

2. PERCEIVED BENEFITS OF SYNTHETIC TURF

Outdoor surfaces covered with synthetic turf have become prominent across public spaces (i.e., sports facilities, playgrounds) and private properties because of the wide range of benefits. Although the installation can be expensive, traditional maintenance costs are considered low since synthetic turf does not require regular irrigation, mowing or fertilising (Cheng et al., 2014; Kamal, 2019). This is a common misconception because other preservation forms are necessary to maintain the integrity of the synthetic surface so it remains user safe and prolongs its lifespan (Jastifer et al., 2019; Kamal, 2019; Sheppard, 2019). It is important to note that hybrid turf requires maintenance comparable to natural turf since grass is a part of the design; however, they can become stiff (Nunome et al., 2020).

Synthetic turf sustains prolonged and repeated use, making it an ideal surface for sports fields and playgrounds (Cheng et al., 2014; Kamal, 2019). Sheppard (2019) stated that the artificial surface could be used three times more frequently than natural turf because it does not need a 'recovery time'.

3. HEAT-RELATED ISSUES

3.1 NATURAL TURF

Natural green turf is a cool surface used in urban spaces like sports facilities, playgrounds, outdoor gyms and private gardens. The grass absorbs a significant proportion of the incoming shortwave radiation. At the same time, the remaining amount is reflected from the foliage surface, and only a small portion is transmitted through the leaves onto the underlying soil surface. Natural turf reflects approximately ten times more solar energy than synthetic turf (Devitt et al., 2007; Golden, 2021), due to the reflection of a significant proportion of incoming shortwave ($K\uparrow$) with less longwave radiation ($L\uparrow$) (Figure 2A). As most absorbed energy is used for photosynthesis, a small amount is lost as sensible (Q_H) and ground heat flux (Q_G). Given the water content under natural turf is high, the largest component of the energy balance in natural turf is latent heat flux (i.e., transpiration cooling, Q_E). Even with the continuous rise of solar radiation, natural turf maintains low surface temperatures (Aoki, 2009) due to the cooling by transpiration, high water content, and low thermal mass. In contrast, synthetic turf reflects less and absorbs more incoming solar radiation than natural turf (Figure 2B). A proportionate amount of incoming longwave radiation is emitted back into the environment. A portion of the absorbed energy is lost into the ground, and it can be as large as combined soil and sensible heat fluxes of natural turf. The largest component of the energy balance of synthetic turf is sensible heat flux, which can be similar to the latent heat flux of natural turf. Without natural moisture within the synthetic turf structure, latent heat flux does not exist (unless irrigated).

While passive or active irrigation keeps grass surfaces cool, dry turf can reach high surface temperatures comparable to synthetic materials. Figure 3 shows an example of a large lawn in a public park in Jordan Springs (Sydney, NSW). The images were taken at 16:40 on 1 March 2021, when the maximum ambient air temperature was 36°C. On that day, the sunlit green turf reached surface temperatures of 34°C, 8°C cooler than dry turf and 19°C lower than synthetic turf and black concrete in a nearby front yard (Fig. 3). These measurements highlight the essential role of moisture in maintaining low surface temperatures, something that natural dry and artificial turf lack.

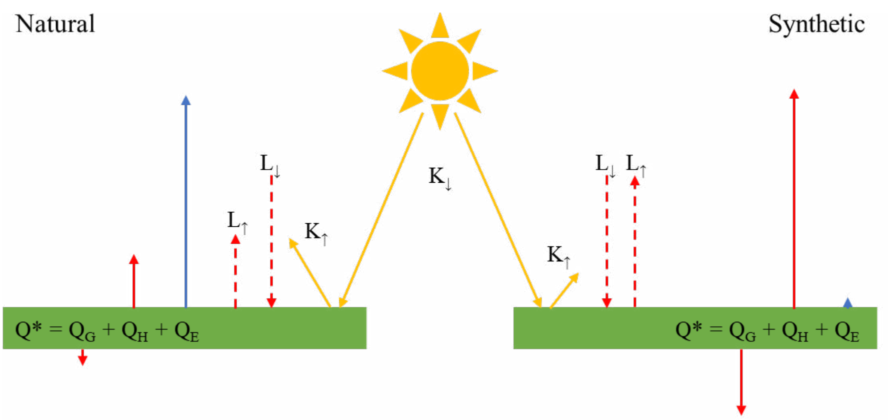

FIGURE 2: The daytime energy balance of well-watered natural (A) and dry synthetic turf (B). See text for explanation of symbols. The diagram was created using information from Carvalho et al. (2021), Devitt et al. (2007), and Jim (2017)

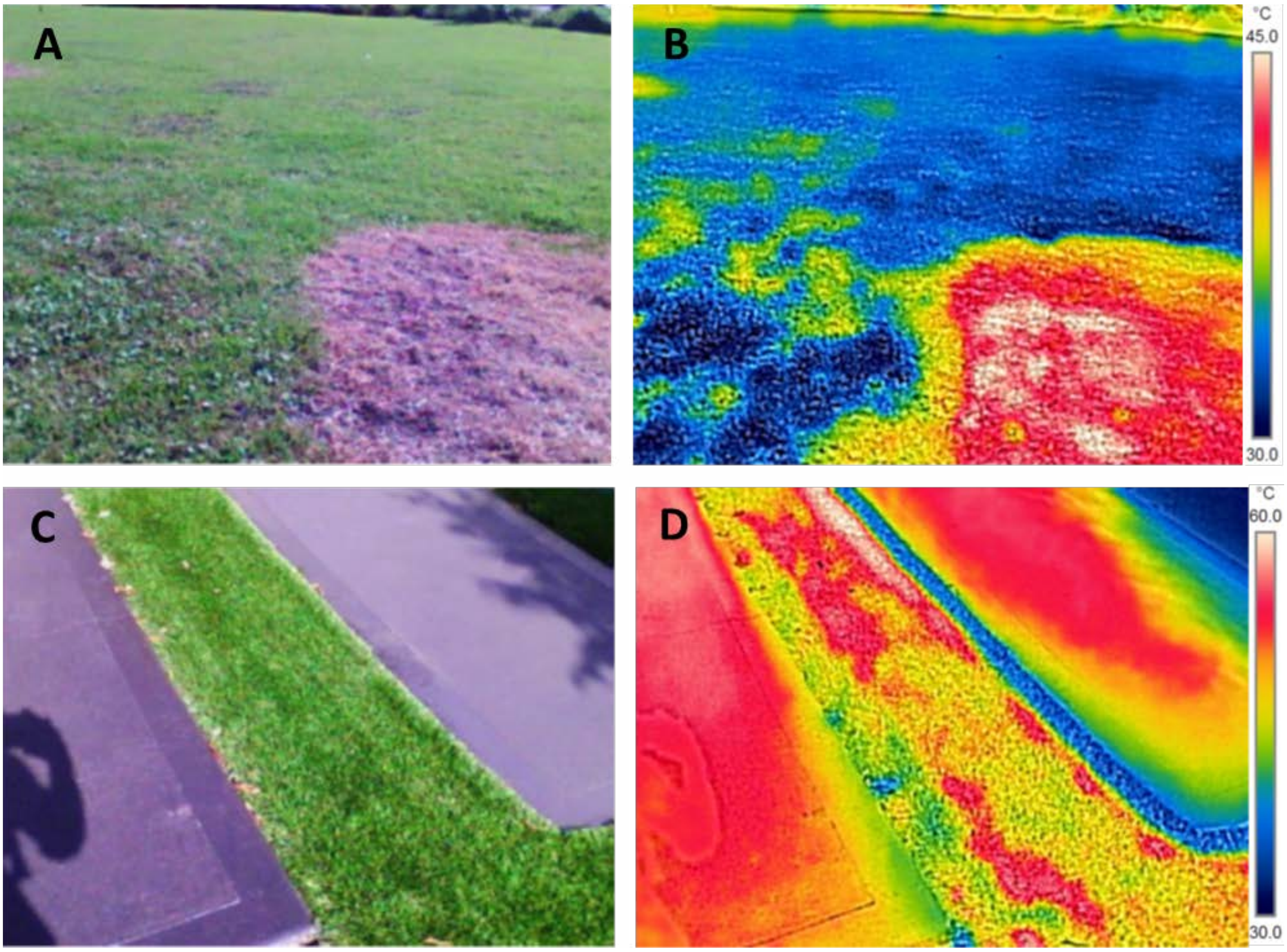

FIGURE 3: Normal (left) and infrared images (right) of green and dry grass surface temperatures at a public park (A, B) and a nearby house with synthetic turf and black painted concrete (C, D) in a western Sydney suburb. The images were taken at 16:40 (A, B) and 17:00 (C, D) on 1 March 2021. In full sun, the natural turf reached on average 34°C and the surface temperature of dry turf was 42°C. The moisture within the green natural turf was responsible for the 8°C-cooler temperature. The synthetic turf reached 53°C in full sun, which was the same temperature as the black concrete. The colour scales on the right-hand side indicate the range of surface temperatures measured.

3.2 SYNTHETIC TURF

3.2.1 CURRENT STATE AND NEW PRODUCTS

It does not matter whether artificial turf is used on the sports field, outdoor gym, schoolyard, playground or private garden; the risk of potentially dangerous surface and air temperatures is the same for all applications. Currently, no systematic assessments based on scientific studies are available to provide guidance on synthetic turf suitability, particularly for the Australian climate. The available science discusses mainly the heat-related problems of conventional, third-generation types of synthetic turf. The scientific literature showed that the temperature of artificial lawns depends on the environmental conditions, type of material and the overall system design. The section below describes the heat-related issues reported by the scientific literature on synthetic, hybrid and natural turf types globally and in Australia.

The synthetic turf industry is aware of the thermal issues associated with unshaded synthetic turf. A range of products was developed to address the heat-related problems of artificial lawns, with many invented for extreme Australian heat and high UV radiation (for details, see Section 5). For instance, the new technology keeps surfaces cool by allowing high reflectivity and thus low heat absorption (COOLplus™ from APT Asia Pacific, HeatBlock™ from Synlawn – APT Asia Pacific, and TigerCool from TigerTurf), with some innovations improving water retention that increases passive radiative surface cooling (HydroChill™ from APT Asia Pacific and Southwest Greens, and Cool & Fresh from Titan Turf). These products are aimed for small-scale applications, such as residential landscaping, playgrounds and schools; however, limited cool material types can be used for large-scale projects like sports facilities. Although the companies conducted measurements to verify the cooling properties of their new products, independent scientific research is missing, especially at large-scale facilities. It can be assumed that if cool technology for synthetic lawns work, cooling benefits for the microclimate and energy savings for the surrounding buildings may be expected.

3.2.2 ENVIRONMENTAL FACTORS

Ambient conditions such as solar radiation and air temperature are among the main factors influencing the temperatures of synthetic turf systems around the globe as well as in Australia (Petrass et al., 2014; Sheppard, 2019). The surface temperature is strongly correlated with the amount of solar radiation and often continues to rise after the peak of radiation due to the stored heat (Aoki 2009). By contrast, Petrass et al. (2014) found that artificial turf surfaces cooled down immediately after cloud cover blocked the incoming solar radiation. Studies from other climatic regions also reported considerably hotter surfaces of synthetic turf systems on clear-sky sunny days, with the temperatures decreasing during cloudy and overcast conditions (Devitt et al., 2007; Jim, 2017; Liu and Jim, 2021; Shi and Jim, 2022). Similar findings were reported using modelling data from the US (Thoms et al., 2014) and the UK (3rd generation turf; Gustin et al., 2018). These studies highlight solar radiation and ambient thermal conditions' enormous role in determining synthetic turf's surface temperatures.

Since weather conditions are the driving forces in the thermal response of synthetic types of turf, the surface temperatures will differ depending on the climate (Fig. 4). We collected data from 20 publications (published between 1976 and 2021) with different environments, experimental setups and types of synthetic turf (i.e., infill type and depth). In all studies, the maximum surface temperature of artificial turf was recorded on sunny days and ranged from 53°C to 93°C across the studies (Fig. 4). They were between 14°C and 64°C hotter than a natural turf measured in the same studies. Most of the published data on the various types of synthetic turf designs were from arid, tropical and subtropical climates, with little information from the Mediterranean and temperate conditions. The four Mediterranean studies were from Western Australia (Loveday et al., 2019) and Victoria (Englart, 2020; Petrass et al., 2015; Twomey and Petrass, 2013). Although these experiments were conducted in different regions of the Australian continent, all reported surface temperatures >70°C, most likely due to generally high solar radiation for this part of the globe. A study from arid Arizona investigated the thermal properties of a cool synthetic turf ('HydroChill'), which despite morning irrigation warmed to 78°C as the water evaporated by the afternoon (Guyer et al., 2021). In the temperate climate of the Netherlands, the synthetic turf still reached low 60°C, but the water was more efficient in cooling the surfaces as the summers are generally mild (van Huijgevoort and Cirkel, 2021). The variability among the studies highlights careful consideration of synthetic turf design for a specific climate zone because not all systems are suitable for all conditions.

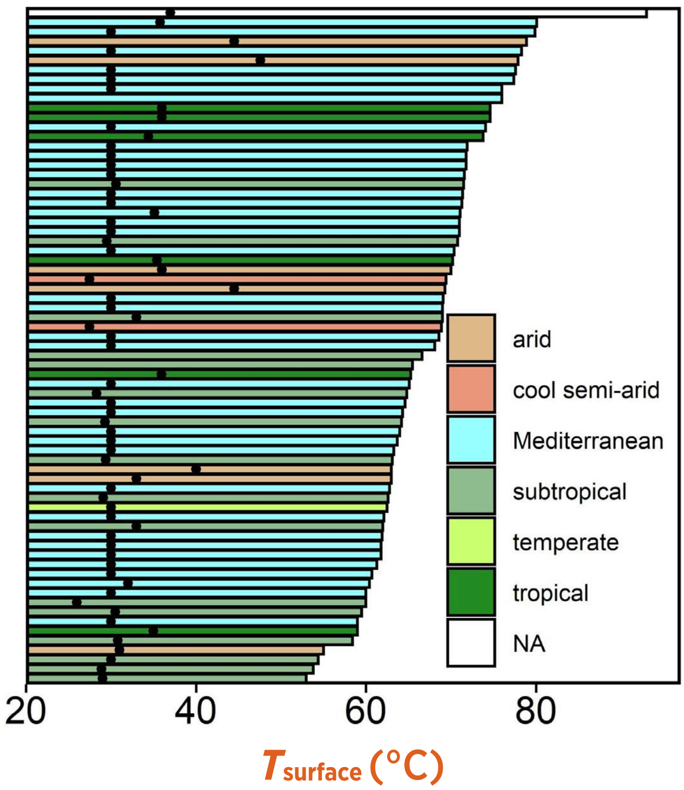

FIGURE 4: Surface temperatures (horizontal bars, $T_{surface}$) extracted from the literature in different climatic conditions. The data were collected in the laboratory, and in situ on the sports fields. The black dots refer to the air temperatures measured in these studies, either ambient or above the synthetic turf surface. Arid (Arizona, New Mexico, Nevada): N = 3; cool semi-arid (Utah): N = 1; Mediterranean: N = 4 (Ballarat, Melbourne, Perth); subtropical (New York, Massachusetts, Otsu (Japan), Pennsylvania): N = 5; temperate (Utrecht): N = 1; tropical (Hong Kong, Hawaii): N = 5. Studies included: Aoki, 2009; Brakeman, 2004; Claudio, 2008; Devitt et al., 2007; Englart, 2020; Guyer et al., 2021; Jim, 2016, 2017; Kanaan et al., 2020; Kandelin et al., 1976; Lim and Walker, 2009; Liu and Jim, 2021; Loveday et al., 2019; McNitt and Petrunak, 2007; Petrass et al., 2015; Sciacca, 2008; Shi and Jim, 2022; Twomey and Petrass, 2013; van Huijgevoort and Cirkel, 2021; Williams and Pulley, 2002.

3.2.3 MATERIAL TYPE AND DESIGN

The thermal properties of the material (i.e., fibres, infill) that is exposed to solar radiation and the overall design (i.e. infill depth) also determine the temperatures of synthetic turf (Petrass et al., 2014; Thoms et al., 2014; Twomey and Petrass, 2013; Villacañas et al., 2017). The manufactured types of turf are typically made from plastic and rubber infills with low surface albedo and small thermal mass (Jim, 2016; Loveday, 2020). When surfaces of unshaded synthetic turf systems are exposed to a large amount of solar energy, they absorb most of the incoming shortwave radiation while little is reflected (K↓ and K↑ in Fig. 3; Devitt et al., 2007; Golden, 2021). With more energy absorbed than reflected, artificial surfaces reach extreme temperatures on hot and sunny days (Golden, 2021; Jim, 2016; Loveday, 2020).

The rubber infill is often considered responsible for high temperatures in synthetic fields. However, unfilled turf can be thermally comparable to the filled surfaces (McNitt and Petrunak, date unavailable; Serensits, 2011), indicating a significant role of plastic fibres in the warming process. The fibre morphology also contributes to high temperatures, with fibrillated being hotter than monofilaments because of the generally lower durability (Villacañas et al., 2017). We also found that the length of the blades made a thermal difference in our in situ study. A maximum surface temperature of green synthetic turf types with different sizes of blades (i.e., 40mm, 30mm and 13mm) was measured during a hot summer day in western Sydney. When the ambient air temperature was 34°C, the synthetic turf with the longest blades reached 84.5°C. It was 4°C warmer than turf with 30mm blades and 10°C hotter than the sample with the shortest blades (Pfautsch et al., 2022, under review). A similar result was reported by Siebentritt (2020) who also indicated higher surface temperatures for synthetic turf with longer blades in experiments done in Adelaide, Melbourne and Sydney. By contrast, Twomey and Petrass (2013) found that only one product showed thermal difference associated with the length of blade, while the other one did not.

From the fibres, the heat is transferred into the infill, and it can be retained on a sunny day, depending on the type of material. In Victoria (Australia), Petrass et al. (2014) reported that types of artificial turf with the thermoplastic elastomer (TPE) infill were 2.5°C and 7.9°C cooler than products with organic fibres or styrene-butadiene rubbers (SBR).

The difference was assigned to the various heat absorption properties, greater for SBR than TPE. Similar findings were reported in the soccer fields across two cities in Spain, where TPE infill had lower temperatures than other conventionally used products (Villacañas et al., 2017). Moreover, Villacañas et al. (2017) found that the temperatures of TPE can reduce further with the number of hours used, while the SBR sports fields reach an even higher temperature with more frequent use.

The depth of the infill material also determines how hot the synthetic turf can be. McNitt et al. (2008) found a negative relationship between the temperature and thickness of the infill. In that study, the samples with low infill content were hotter compared to synthetic turf with more rubber material.

Apart from the heat stored by fibers and infill, a portion of absorbed energy is transferred into the ground (Q_G, Fig. 2; Devitt et al., 2007; Carvalho et al., 2021). However, the efficiency in conducting the energy depends on the design approach. Petrass et al. (2014) found that the space created by the tuft gauge and the presence of shock pads affected the temperatures. In that study, the absence of a shock pad allowed more heat loss into the ground than when that layer was present. The likely reason is the better thermal conductivity of the soil compared to the shock pad layer (Golden, 2021).

A proportionate amount of incoming longwave radiation is emitted back into the environment (L↑) leading to sensible heat loss (Q_H), which is greater than through Q_G (Fig. 2; Devitt et al., 2007; Carvalho et al., 2021). Without the naturally occurring moisture within synthetic turf and no active irrigation, transpiration cooling and latent heat loss do not exist (Q_E, Fig. 2; Carvalho et al., 2021; Golden, 2021).

3.2.4 **HUMAN THERMAL COMFORT**

Because of the large Q_H and absence of Q_E, synthetic turf can create thermally uncomfortable and hazardous conditions for the users (Abraham, 2019; Shi and Jim, 2022). A recent study from subtropical Hong Kong showed that players and spectators experienced significantly hotter summer temperatures on artificial than on natural turf during sunny days (Shi and Jim, 2022). As the thermal comfort worsened on the sunlit synthetic surfaces, the users performing medium or no activity were exposed to potentially extreme heat stress (Shi and Jim, 2022). The surface type was irrelevant with intense physical activity as the heat exposure was high and comparable on both types of turf (Shi and Jim, 2022). A previous study by the same research team found that already vulnerable children were exposed to extreme heat for longer than adults, regardless of whether they played soccer or walked on the artificial surface (Liu and Jim, 2021). In both studies from Hong Kong, the surface temperatures and human thermal comfort were similar for the turf types on cloudy and overcast days when the incoming solar radiation was reduced (Liu and Jim, 2021; Shi and Jim, 2022). Moreover, the relatively low thermal mass of artificial turf allows for efficient heat loss through convection at sundown, cooling the surfaces close to natural turf (Jim, 2016; Loveday, 2020), with some studies reporting only slightly warmer surfaces (Shi and Jim, 2022).

Similarly to the tropical climate of Hong Kong, public areas covered with synthetic turf in Sydney (NSW) created comparably uncomfortable and potentially hazardous conditions for surface skin burns (Pfautsch and Wujeska-Klause, 2021). Figure 5A,B depicts the surface temperature of artificial turf at the playground in Bennalong Park. The measurements were taken on the hottest day in 2020 when the maximum ambient air temperature exceeded 40°C. On that day, the surface of unshaded synthetic turf reached 85°C (Fig. 5A,B), while the air temperature 1 m above the surface warmed to 48°C. As the portion of the absorbed energy was released as sensible heat and warmed the surrounding air, it felt like 63°C, which was 15°C hotter than the ambient conditions. This 'feels like' temperature was measured using a black globe thermometer that combines the heating and cooling effects of air temperature, relative humidity, incoming solar irradiance, sensible heat flux from the surface and wind speed. This temperature metric is widely used as a proxy to capture the thermal sensation of a person that is exposed to both solar irradiance and sensible heat emissions from surrounding surfaces.

It was cooler on 10 February 2022 in Gardiner Park, yet high surface temperatures were still captured at a synthetic soccer field (Fig. 5C,D). This artificial material reached 74°C before noon when the daily maximum ambient T_{air} was 33.5°C (BOM station 66037). Even though we did not measure the human thermal comfort that day, it is highly possible that the air felt much hotter than the ambient temperature measured by the official weather station.

These findings highlight the enormous impact of synthetic turf on worsening human thermal comfort with potential heat stress experienced on sports fields and playgrounds, especially when being physically activity. A practical measure of thermal suitability is being developed. For instance, Shi and Jim (2022) proposed a nine-point thermal suitability index that helps decide if synthetic turf is a surface materials suitable for a range of climates.

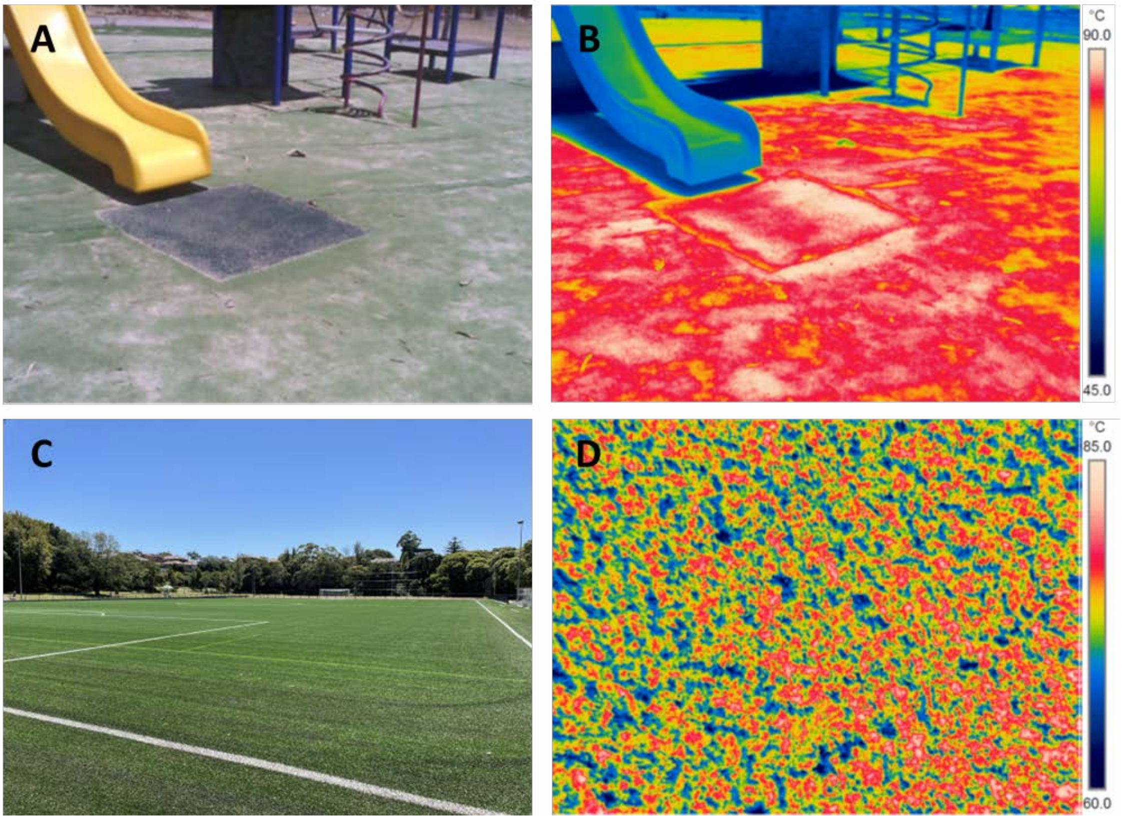

FIGURE 5: Normal and infrared images of synthetic turf surface temperatures at a public playground in western Sydney (panels A and B) and at the soccer field in eastern Sydney (panels C and D). The images were taken at 13:30 on 4 January 2020 (panels A and B) and at 11:00 on 10 February 2022 (panels C and D). In full sun, the synthetic turf reached on average 85°C at the playground and 74°C at the sports field. The colour scale on the right-hand side indicates the range of surface temperatures measured.

The thermal impact of synthetic turf surfaces on humans worsens as the material ages or deteriorates faster than expected due to high frequency, duration and intensity of use and/or insufficient maintenance. Villacañas et al. (2017) reported that as fibres are compacted over time, more rubber infill is exposed to solar radiation, resulting in higher surface temperatures. For instance, 5-year-old artificial grass with an SBR infill was 2°C hotter than the newly installed sports field with the same rubber material (Villacañas et al., 2017). A similar finding was reported for the playground in western Sydney, where old synthetic turf had 6°C higher surface temperatures than new material in the same location (Pfautsch and Wujeska-Klause, 2021).

3.2.5 PERFORMANCE UNDER NON-EXTREME SUMMER HEAT

Although the hazardous conditions of synthetic turf surfaces are often discussed during extreme summer days, high surface temperatures and low human thermal comfort can also be experienced on summer days with moderate air temperatures. Table 2 shows measurements taken at an unshaded playground covered with synthetic turf in western Sydney (same site as depicted in Fig. 5A, B). The data was collected on two sunny summer days with clear sky. The daily maximum air temperatures were around 30°C, but the surfaces warmed to 57°C and 75°C (Table 2). While ambient air temperature was quite similar during both days, the black globe temperature was extreme due to emission of high quantities of sensible heat. The data shows that even during relatively cooler ambient air temperatures below 30°C, the thermal experience of a human on synthetic turf can be similar to spending time in a place that feels like it is more than 45°C. The higher thermal sensation was likely due to the higher surface temperature that day, that in turn was likely due to more intensive solar irradiance. These results indicate that low-albedo materials such as synthetic turf fields can reach extreme surface temperatures and worsen human thermal comfort also on days when ambient air temperatures are below 30°C.

	T_{max} (°C)	T_{air} (°C)	$T_{surface}$ (°C)	T_{globe} (°C)	6-day sum net radiation (kWm²)
6 December 2020	31.2	30.4 ± 0.8	57.4 ± 1.1	44.4 ± 0.4	253.1
16 January 2021	28.2	29.2 ± 0.8	75.1 ± 1.0	45.5 ± 0.5	336.3

TABLE 2: Thermal conditions of synthetic turf playground in Bennalong Park on 6 December 2020 and 16 January 2021. Daily maximum air temperature (T_{max}) was measured by the nearest official BOM weather station (station 066212). A mean (±SD) surface ($T_{surface}$), air (T_{air}) and feels-like (T_{globe}) temperatures of the synthetic turf were recorded with a FLIR camera and Kestrel in the sun, 1 m above the ground. A 6-day sum of net solar radiation was measured at the Hawkesbury Institute for the environment in Richmond (NSW).

Days with ambient air temperatures at and below 30°C are not limited to the summertime. Such thermal conditions are common during spring and autumn when users of synthetic turf surfaces are likely to expect extreme surface temperatures in public spaces. On such days, children would spend time in playgrounds and physical activities would be carried out in sports facilities. These conditions would indicate that users of synthetic turf surfaces and facilities could be exposed to thermally uncomfortable conditions also outside of summer.

Using a 14-year air temperature data set collected at the Hawkesbury Institute for the Environment (Richmond, NSW), we calculated the number of days equal or above 27°C for each year between 2007 and 2020 (Fig. 6). During that time, maximum air temperature reached more than 47°C. The number of days where mean maximum ambient air temperature was at or above 27°C varied between 105 (2011) and 145 days (2019). We did not analyse how many of these days had clear skies but based on our sound understanding of the local climate we expect that most of these days would have been at least partly free of cloud cover. This analysis indicates that on a synthetic turf surface in Richmond, hazardous heat conditions could be experienced during 29-40% of days in a single year. Notable is the large number of days in any year where ambient air temperatures can rise at or above 27°C outside of summer. In some years, the sum of days with such conditions were recorded in spring and autumn exceeds their occurrence in summer. It is necessary to point out that the number of days with such "moderate thermal conditions" is likely to increase due to global warming (Intergovernmental Panel on Climate Change, 2022). These boundary conditions will further limit the number of hours users can safely spend time on synthetic turf surfaces throughout the year and can be expected for places across the Sydney Basin.

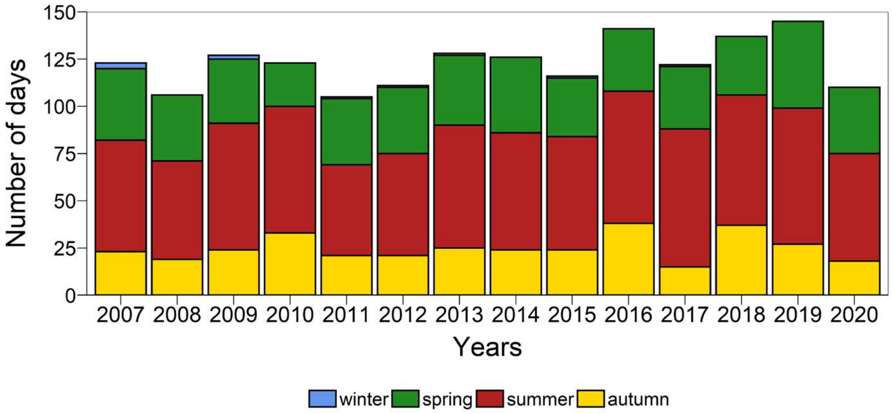

FIGURE 6: Number of days per year where daily maximum air temperature was above 27°C. Research at Western Sydney University has shown that at air temperatures below 30°C, surface temperatures of synthetic turf and associated black globe temperatures can be above 70°C and 40°C, respectively. Data were recorded at the Western Sydney University Forest Research Experiment site in Richmond between 1 January 2007 to 31 December 2020. Data were separated into the four seasons to demonstrate that potentially very hot surface temperatures can occur outside the summer season.

3.3 HYBRID TURF

Only two studies have tested hybrid turf' thermal properties to date (Dickson et al., 2021; Lulli et al., 2011). In Knoxville (Tennessee, US), synthetic turf containing 'Northbridge' bermudagrass was compared with natural turf (Dickson et al., 2021). The authors found no difference in surface temperatures between the treatments at the hottest time of day. Although specific data was not shown, a similar result for hybrid turf with perennial ryegrass 'Citation III' in Italy was reported. The authors claimed that the surface temperature of hybrid turf was comparable with natural grass during the summertime (Lulli et al., 2011). Even though data is limited and more studies are required to fully test the thermal properties of synthetic turf systems, available findings highlight the hybrid turf as a potential cooler alternative to conventional synthetic materials. Still, hybrid turf may be challenging for Australian conditions where drought and heatwave events frequently affect the growth of natural grass and considerably heat the artificial turf to hazardous temperatures. Given the extreme temperatures measured on plastic and rubber surfaces, it is unknown if natural turf can sustain the heat load within the hybrid system during heatwaves. More research is needed to determine the thermal suitability and survival of turfgrasses in hybrid design systems.

4. THE CONTRIBUTION TO THE UHI EFFECT

The Urban Heat Island (UHI) effect occurs when surfaces and air in the cities are hotter than the surrounding non-urban environments (Intergovernmental Panel on Climate Change, 2022). Two types of UHI can be distinguished depending on the urban layer influenced by the built environment: surface (UHIs) and air (UHIa) (Oke et al. 2017). The UHIs refer to urban surface temperatures with different thermal properties, whereas the UHIa relates to the air temperatures between the ground and the roof level (Oke et al. 2017). The thermal variability of UHIs and UHIa differs during daytime and night-time. During the day, solar radiation considerably influences the UHIs within the urban space, while UHIa remains relatively constant between the city and rural areas (Intergovernmental Panel on Climate Change, 2022). At night, the difference between UHIs and UHIa diminishes, with both surfaces and the air warmer inside than outside of the metropolitan area (Gago et al., 2013; Oke et al., 2017; Sharifi et al., 2021).

The main factors contributing to city warming are tight urban geometry, anthropogenic heat and heat-retaining urban materials (Intergovernmental Panel on Climate Change, 2022). While many materials in urban space retain heat leading to warmer conditions, water bodies and vegetation help cool the urban microclimate (Bowler et al., 2010; Intergovernmental Panel on Climate Change, 2022; Yuan et al., 2021). Although the cooling benefits of blue and green spaces and their contribution to UHI mitigation are well known (Aram et al., 2019; Bowler et al., 2010), they are often scarce in the cities, which is an ongoing issue, particularly as the urban population increases. Arshad et al. (2022) showed the thermal impact on surface temperatures due to vegetation loss and gains across the city in Pakistan. In that study, parts of the metropolitan area warmed considerably as the built environment replaced the vegetation. By contrast, one experimental site had more cool surfaces as the green infrastructure was increased (Arshad et al., 2022). With 38 km2 of green and blue infrastructure lost over 20 years, warming was also observed across Fuzhou (China) (Cai et al., 2019). Moreover, the loss of vegetation and urban densification in Kennedy (Bogota, Colombia) led to 5°C - 14°C warming across the city (Molina-Gómez et al., 2022). These studies show that the UHI effect will intensify as the urbanisation further replaces the green and open spaces that provide cooling with a heat-retaining built environment that leads to warming.

4.1 NATURAL TURF

Given the small sensible and significant latent heat fluxes (see Fig. 2), well-watered turf maintains low surface temperatures, and thus, it does not warm the local microclimate. Using vegetation, including natural grass, is a common strategy to mitigate the negative impact of UHI (Cheela et al., 2021; Krayenhoff et al., 2021; Santamouris et al., 2017; Yenneti et al., 2020). Across studies, natural grass was found to cool the urban space by 1°C - 10°C at the microscale and 3.3°C - 8.4°C at the mesoscale (Krayenhoff et al., 2021). Moreover, a modelling study from the arid city of Cairo found that a street covered in 70% grass effectively reduced the ambient temperature and improved the building energy savings (Aboelata, 2020).

In Australia, Siebentritt (2020) reported that irrigated natural turf can provide surface cooling of up to 5°C and maintain low air temperatures over synthetic turf up to 1 m away, Its synthetic alternative warms by up to 11°C, increasing air temperatures at 1.2 m by up to 3°C. These cooling benefits of natural turf extended to nearby spaces, where natural turf minimised the thermal impact of solar irradiance and heat storage by urban surfaces.

Non-irrigated turf caused, on average, 1°C of cooling in that study, ranging from 1.7°C warming in South Australia to 4.4°C cooling in Victoria. However, it is important to remember that the cooling benefit of unirrigated lawn largely depends on precipitation, where the thermal influence can switch to warming as the turf dries (Siebentritt, 2020).

4.2 **SYNTHETIC TURF**

Synthetic turf surfaces are among the urban surfaces that are good at absorbing and storing heat, and they increasingly replace natural turf in metropolitan areas. Given the high sensible and negligible latent heat flux (see Fig. 2), areas covered with synthetic turf can become a hot spot during the daytime (Abraham, 2019; Golden, 2021; Jim, 2016; Loveday, 2020). Although the spatial footprint of this warming effect is confined to the area covered by synthetic turf and its immediate vicinity, the material has been found to contribute to the Surface and Canopy UHI locally (Golden, 2021). The function driving this effect is the lower transmission of energy in the near-surface atmosphere compared to the amount of energy emitted into the near-surface atmosphere from synthetic turf surfaces (Golden, 2021).

Scientific literature on the contribution of synthetic turf systems to UHI is limited with only a few examples at a micro-scale. For instance, local surface UHI was identified by Addas et al. (2020) within the University campus in an arid climate using land surface temperatures. In that study, a previously cool sports facility became a hot spot when the natural grass was replaced with synthetic turf. A similar situation was found in California, where three sports fields with artificial turf created a local surface heat island compared to a cool natural turf stadium (Mantas and Xian, 2021). In an arid city in Chile, a hot spot was also found within an urban park where the surface of a sports stadium with synthetic turf was ~30°C warmer than the surrounding vegetation (Smith et al., 2021).

These local heat islands are not limited to sports fields; they can also be present within the school grounds and playgrounds containing synthetic turf. In western Sydney, areas covered with artificial grass were the hottest at school during summertime, especially during morning recess and the lunch break when children were likely to be outside (Pfautsch et al., 2020). The synthetic turf warmed the surfaces and the air, negatively affecting human thermal comfort. The heat was not restricted to these particular spaces, reaching surrounding classrooms and other parts of the school.

One study tested the overall impact of synthetic turf on air temperatures in urban spaces. Yaghoobin et al. (2010) modelled the thermal implications of replacing natural with the manufactured turf at the microscale level. This study focused on a microscale suburban development without trees and an area of approximately 8.8 ha with a built environment. The authors found that replacing the entire natural turf with a synthetic alternative would warm the urban air temperature by 4°C (Yaghoobin et al., 2010). In another example from the Australian city of Adelaide, the thermal impact of a sports field covered with synthetic turf was modelled using the 'Extreme Heat Assessment Tool' developed by the Cooperative Research Centre for Water Sensitive Cities (Siebentritt, 2020). A natural turf was replaced with a synthetic grass in 2017. The soccer stadium covered 6.5% of the broader study site, which was 13.6 ha in size (Siebentritt, 2020). The study found that the surface of synthetic turf was 16°C hotter than when the area contained natural turf. Moreover, the author also indicated the broader thermal impact of the artificial surface for the entire study site would increase the average surface temperature by 1.1°C (Siebentritt, 2020).

It is unknown whether hybrid turf systems would mitigate urban warming as no data on this system were available. However, the thermal effect would likely be small or similar to natural grass since studies reported no difference in surface temperatures between the natural and hybrid types of turf (Dickson et al., 2021; Lulli et al., 2011).

5. COOLING STRATEGIES FOR SYNTHETIC TURF SURFACES

The available literature provides a few examples of how surface temperature of synthetic turf can be reduced. Among the cooling strategies are shade (natural and artificial; Pfautsch et al., 2020), organic (cork, coconut and sugar cane fibres; Greenplay Organics; APT Asia Pacific) or inorganic infill (Yang et al., 2021) and active irrigation (Kanaan et al., 2020; McNitt et al., 2008). Moreover, new products that can retain moisture for longer (i.e., HydroChill® - APT Asia Pacific and Southwest Greens) or reflect more and absorb less of the incoming solar radiation (i.e., COOLplus® technology - APT Asia Pacific) are being introduced. Given the limited number of studies on thermal impact of hybrid turf, this material type is not discussed here.

5.1 SHADE

Trees or artificial structures can provide shade, which is an efficient strategy to cool surfaces and thus reduce air temperatures and improve human thermal comfort. A shade canopy reflects and blocks the incoming solar radiation from reaching the ground beneath. The surfaces do not absorb the solar energy and do not store heat that will otherwise contribute to daytime urban warming. Figure 7 shows an outdoor space covered with synthetic turf in one of Sydney's schools (Pfautsch et al., 2020). The image was taken at noon on 19 December 2019, when the ambient air temperature was 43°C. On a day of extreme heat, the surface temperature of synthetic turf reached 61°C. The shade created by the building cooled the manufactured turf to 35°C, lowering the surface temperature by 26°C.

Although shade is the most efficient strategy to reduce surface temperatures of any urban space, installing these structures in large areas like sports fields is not always feasible. Thus, sporting facilities featuring synthetic turf fields should ideally be located indoors. However, compromises can be reached when surrounding synthetic sport fields with shad infrastructure, like statia and large sails or roofs that will block solar radiation for most or all of the day (Shi and Jim, 2022). Shade is the most efficient strategy to cool surfaces on a small scale such as playgrounds.

Pfautsch and Wujeska-Klause (2021) reported sunlit and shaded surface temperatures of playground materials across Cumberland Local Government Area (Sydney, NSW). In that study, the shade was the most efficient in reducing surface temperatures of the hottest material which was the softfall rubber (by 40°C). Even though synthetic turf was present in several locations, it was unshaded which is a common phenomenon. Shade structures should be a requirement for outdoor play spaces, especially when artificial materials like synthetic turf and softfall rubbers are used. Natural turf can potentially be used surrounding the hotter synthetic turf areas, yet natural turn in high-activity areas will be difficuly to maintain.

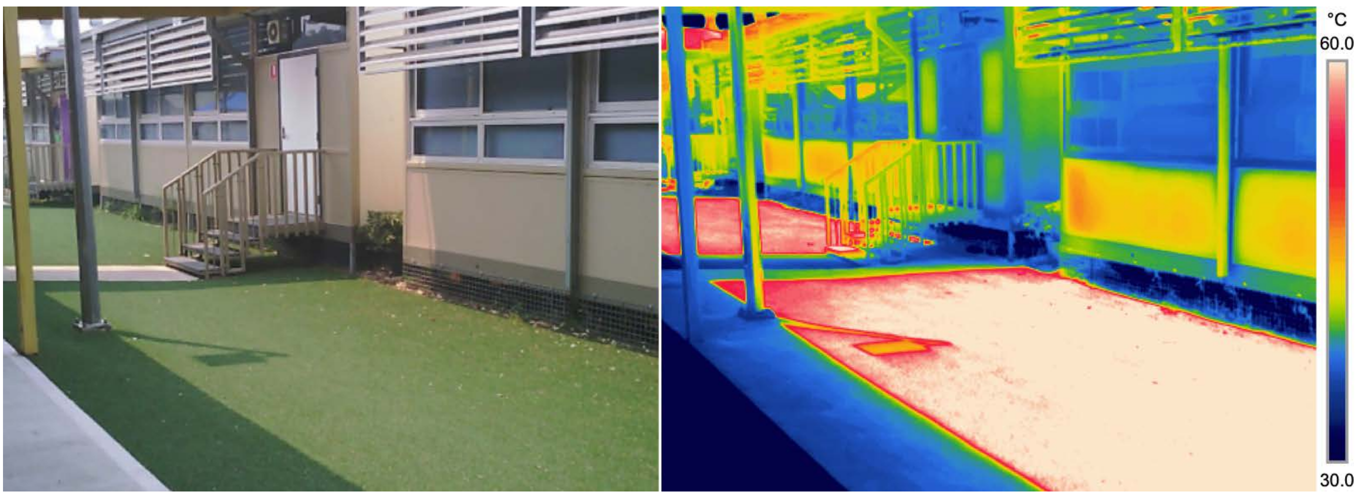

FIGURE 7: Normal and infrared images of synthetic turf in the sun and shade at a primary school in western Sydney (NSW). The images were taken at 12:03 on 19 December 2019. The sunlit synthetic turf reached on average 61°C and when shaded the surface temperature was 35°C. The colour scale on the right-hand side indicates the range of surface temperatures (°C) measured

5.2 **ORGANIC INFILL MATERIALS**

Organic materials are often considered a cool alternative to the manufactured rubber infills used with synthetic turf. Such infills are typically made from natural cork and coconut fibres. An informal experiment tested organic infill against natural and artificial turf with only rubber and rubber with sand (Greenplay organics, 2012). The cork and coconut infill retained water for the longest period of time, which kept the surface temperature low and comparable with the natural turf (Greenplay organics, 2012). A new product derived from 60% sugar cane was introduced to the Australian market (APT Asia Pacific). This plant-based turf sustains the high durability of the conventional system while being more environmentally friendly. The manufacturer combines it with a COOLplus™ technology which maintains lower surface temperatures (see section *Increased surface reflectance* for details; APT Asia Pacific).

Petrass et al. (2014) indicated that organic infill might retain heat, and thus caution needs to be taken when selecting the product. Although the surface temperature of the organic product was 5.4°C lower than an SBR rubber in that study, other types of rubbers were cooler than organic material. A possible explanation for different results is water content, which Petrass et al. (2014) did not apply, including a lack of specifying organic material type used. In another study, the same research team tested a cool climate polyethylene fibre with sand infill and found it 9°C cooler than a third-generation synthetic turf with sand:rubber mix (Petrass et al., 2015). However, the study sites were spatially separated and thus exposed to different weather conditions, with high humidity responsible for the low temperatures.

5.3 **LIGHT-COLOURED FIBRES AND INFILL MATERIALS**

Although synthetic turf is typically associated with a green colour to resemble the look of natural grass, various tones are now available for plastic fibres. Such products are available from companies in China (RelyIR), the UK (Artificial Grass Direct) and Australia (Artificial Grass Online; Recreational surfaces Australia). However, a limited number of studies measured the surface temperatures of multicoloured fibres. Serensits (2011) found that white fibres were 6°C cooler after one hour of exposure to high radiation than the traditionally used green plastic. Moreover, the reflective and cooling properties of the white fibres were negligible when combined with a black rubber infill (Serensits, 2011).

A range of colours for SBR, EPDM, TPO and TPV infills are available on the market. This includes light colours that can be used as an alternative to dark and black rubber materials. Two recent studies investigating surface temperatures of playground materials found that light-coloured rubbers were significantly cooler than the dark alternatives, regardless of the material type (Pfautsch and Wujeska-Klause, 2021; Pfautsch et al., 2022, in review). A similar result was found by Devitt et al. (2007), who found a 9°C difference between a black and white rubber surface (not as infill). However, the cooling effect was minimised to only 5°C when the light-coloured rubber was used as an infill in that study. These findings highlight the importance of light colours for plastic fibres and rubber infills in surface cooling.

5.4 **INCREASED SURFACE REFLECTANCE**

Other cooling strategies include the increase of solar reflectance from the surface of synthetic turf, which minimises their heat absorption and reduces the temperatures. For instance, a TigerCool from the US helps decrease the surface temperatures by 15% (or 10°C; TigerTurf: https://tigerturf.com/). Products COOLplus™ (APT Asia Pacific) and HeatBlock™ (SynLawn, a brand of APT Asia Pacific) apply the same principles and are available in Australia. With high reflectivity and less heat absorbed, the surface temperatures were 10% - 20% cooler than conventional synthetic turf surfaces (APT Asia Pacific; https://synlawn.com.au/info/coolplus-technology/). Although this technology is typically offered for residential/commercial uses and playgrounds, APT Asia Pacific uses COOLplus™ in AFL, hockey, rugby and soccer sports fields. To date, no independent scientific research has been conducted to verify the cooling potential of the above products and their applicability in various climatic conditions. In addition, it would be necessary to also assess how the materials influence the thermal comfort of different aged players (represented by measuring thermal comfort at different heights above the surface to represent differences in centre of bodymass and associated heat adsorption). This needs to take into account differences in surface temperature and in the amount of directly reflected solar radiation.

Currently, one study examined the increased reflectivity of synthetic turf. Yang et al. (2021) tested inorganic-polymeric infill material with chromium oxide and titanium dioxide embedded within high-density polyethylene (HDPE). The artificial turf reflected around 50% more near-infrared radiation and radiated approximately 80% of mid-infrared wavelengths (Yang et al., 2021). By minimising absorption of solar radiation, synthetic turf was thermally comparable to natural grass in that study. The authors stated that the infill material helped to improve heat loss through longwave radiation.

5.5 ACTIVE IRRIGATION AND PRECIPITATION

Irrigation is often suggested as a measure of decreasing and maintaining the low surface temperatures of synthetic turf systems. The infill material absorbs the water, and the environmental factors promote evapotranspiration cooling to reduce the temperature, similarly to the natural turf. How long synthetic turf maintains low temperatures depends on the length of water application and retention capacity of infill material. A few studies reported that this strategy efficiently cooled surfaces; however, synthetic types of turf warmed to previous temperatures after a short time post irrigation (Brakeman, 2004; Kanaan et al., 2020; McNitt et al., 2008; Serensits et al., 2011; Williams and Pulley, 2002). It is also important to consider the increased humidity that enhances the perception of heat by the user on the synthetic turf (Serensits, 2011). Jim (2016) reported a similar limited and short-lived impact of rainfall on surface temperatures once the sky cleared and solar radiation warmed the sports field. Based on modelled data by Kanaan et al. (2020), synthetic turf requires approximately 480 m^3 of water to reduce the surface temperature by 30°C. Although the surfaces cool significantly after irrigation, this strategy is less viable than irrigating a natural turf that maintains low surface temperatures for an extended time. Active irrigation with a short-lived cooling effect is unsustainable in countries with dry and hot climates where water is scarce, including parts of Australia. By contrast, this cooling method might be efficient in milder climates during the summer months (van Huijgevoort and Cirkel, 2021).

Given the short-lived effects of manual irrigation for the conventional synthetic turf systems, the industry developed a range of products that retain water for an extended period. These new products include HydroChill™ (APT Asia Pacific and Southwest Greens) and Cool & Fresh (Titan Turf). To work, they require water (i.e., irrigation, rainfall or dew) and solar radiation to cool surfaces through evaporation. The moisture is gradually released over time, with the cooling most effective when the sun is positioned directly above the surfaces (APT Asia Pacific and Southwest Greens).

HydroChill™ is a new technology using a pre-coated sand infill that retains moisture, and it can be added to a new or existing synthetic turf (APT Asia Pacific and Southwest Greens; T°Cool, https://www.tcoolpt.com/). The manufacturer compared the surface temperature of irrigated HydroChill™ with dry and wet artificial types of turf without coated sand (no details about the coating and its thermal performance are available). They found that their product was 16°C - 28°C cooler than the conventional synthetic systems (at surface level), particularly at the hottest time of the day (APT-Hydrochill-Brochure_Email.pdf). Apart from irrigating the lawn for cooling, this product requires occasional surface maintenance, including applying UV-resistant coating every two years to maintain the passive cooling properties (APT and Southwest Greens). Titan Turf offers a similar infill product with a Cool & Fresh application. Independent scientific studies that investigate the effectiveness of these products are missing.

6. RISK MANAGEMENT

Although cooling strategies for synthetic turf systems exist (see section 5), these surfaces may still reach hazardous temperatures on hot and sunny days. This particularly applies to arid climates or regions with restricted water supply where moisture within these materials evaporates faster, warming the surfaces to extreme temperatures. Thus, regardless of the cooling strategy used, areas covered with synthetic turf should be equipped with signage that warns about the hot surface and its effect on human thermal comfort.

In dry and hot climates, access should be restricted to morning and evening hours to avoid heat exposure and potential heat-related health risks (Jenicek and Rodrigues, 2019; Sheppard, 2015; Shi and Jim, 2022). The Heat Policy of Football Australia reflects this recommendation, in stating that matches should be delayed or postponed when the Wet Bulb Globe Temperature (WBGT) is above 28°C. The WBGT will be strongly influenced by sensible heat flux from the surface and it is recommended that sport clubs using synthetic turf fields purchase the necessary equipment to determine WBGT. Cost for such equipment is around AU$1,500 and grant or incentive programs from government and/or industry could assist clubs in buying these tools.

A practical heat index is needed to recommend or prevent the use of synthetic turf for outdoor facilities depending on the local site conditions and sport type. For instance, Shi and Jim (2022) developed a nine-point thermal suitability index for three weather types in Hong Kong. This measure allows councils to decide whether synthetic turf is suitable for a specific location, but with some limitations, such as a broad application to various climates, not just tropical cities. Currently, Australian cities do not have a system to communicate potential risks to the users of playgrounds or sports facilities, exposing them to skin burns and heat stress. Thus, a similar measure should be developed for Australian conditions, especially Sydney (NSW), which often experiences hot and dry summers. Such parameters would help develop evidence-based warning signage depending on the location, facility use and weather conditions.

7. RESEARCH PRIORITIES RELATED TO HEAT

To date, the thermal impacts of synthetic turf surfaces at the micro-site scale, the neighborhood scale and the city scale are largely unknown for Greater Sydney and beyond. Not a single systematic analyses has been conducted and published. To our best knowledge, we are the only research group that is currently working on this issue. We have published a report (Pfautsch and Wujeska-Klause, 2021) that described, amongst other data related to common playground surfaces, the only available systematic in-situ test. This test was small in scale and used only four synthetic turf types that would be used in private gardens and potentially playgrounds. No data of temperature regimes on, above, and around larger synthetic sport fields across Greater Sydney are available. We see this as a fundamental barrier for government and private organisations to make informed decisions when the question is to decide between an installation of a natural and a synthetic turf surface.

Consequentially, **the first research priority** is to document the impact of solar irradiance on surface temperatures, and the resultant warming of ambient near-surface air above and around synthetic turf surfaces. Surface temperature measurements should be focused on areas covered by the synthetic turf and adjacent reference areas covered by natural turf and other surface types. This study would be 2-dimensional. A 3-dimensional approach should be taken when documenting air temperatures over the synthetic turf field and adjacent reference areas. Measurements should be taken at 10 cm, 30 cm, 80 cm and 150 cm above ground to capture existing gradients in air temperature. Moreover, the distance where air temperatures are assessed around the site covered by synthetic turf should increase as the area covered by synthetic turf increases. For example, while it is sufficient to collect air temperature measurements 20-30 around a small playground that contains a 10 x 10 m square of synthetic turf, air temperatures around a typical soccer pitch between 7,000 m2 and 10,800 m2 should at least be collected 300-400 m around the field. All surface and air temperature measurments should be collected systematically along defined transects and fixed distances along these transects.

The second research priority is to measure the impacts of radiant heat from unshaded synthetic turf surfaces on human thermal comfort, including that of young children. Results of the first and second research priority would be combined in a comprehensive guideline about the safe use of synthetic turf surfaces in a range of applications – from private gardens to school yards, to recreational and professional sport fields.

The necessary investigations for both priorities should take place under different environmental conditions (diurnal and seasonal). As we have shown in this review, surface temperatures on synthetic turf that can cause serious skin burns are not limited to hot or very hot summer days. Naturally, physical, and recreational activities under such conditions should be limited. Yet, potentially harmful surface temperatures have been measured in the Greater Sydney region when maximum daytime air temperatures are at or greater than 27°C. We provided evidence that such conditions are present every year during spring and autumn (see Fig. 6).

Continuous measurements of the following parameters would be essential for the systematic research necessary to address the above research priorities:

- → Ambient air temperature
- → Solar irradiance
- → Surface temperature
- → Mean Radiant Temperature (or any other metric that captures outdoor human thermal comfort)

Parameters that need to be documented alongside these measurements are:

- → Product specifications
- → Age
- → Colour and reflectivity (albedo)
- → Infill type
- → Maintenance plan (e.g., irrigation, raking, brushing)

Essential instruments:

- → Air temperature data loggers
- → Weather station (with logger) with Pyranometer, wind speed, wind direction, precipitation detection capacity
- → Hand-held infrared camera
- → Infrared radiometer with logger
- → Instruments to determine mean radiant temperature (different set ups available)
- → Geospatial information (e.g., aerial images, GIS layers, LiDAR data)

Importantly, any such research needs to establish baselines prior to the installation of synthetic turf. This is especially important when larger areas of this material are installed, to separate any effects from the introduction of the material from those that may naturally take place in the area. The BACI design (Before-After-Control-Impact) is an ideal tool for such an application. Its capacity to disentangle real impacts from natural phenomena has been demonstrated in countless ecological research projects (Smith, 2002). Applying the BACI framework would make use of similar sized nearby natural turf areas as 'Control' sites. Coordination with site managers (i.e., local governments, sprot clubs, etc.) would be paramount to capture meaningful 'Before' data that will be used to establish the necessary baseline conditions against which 'Impact' during the 'After' phase will be assessed.

The third research priority should cover all aspects that relate to mitigation and avoidance of extreme surface heat of synthetic turf surfaces. As established with work for Priorities 1 and 2, and as shown by the international studies reviewed here, surface temperatures of this material can exceed 90°C, representing a clear danger for surface skin burns. Research related to the third priority should quantify the cooling magnitude, cooling duration and cooling distance of a range of interventions that can realistically be applied to several applications that differ in scale and complexity. For example, high quality shade can be introduced in a school playground but is not a realistic option for a professional outdoor soccer field. Available strategies need to be categorised and their effectiveness quantified.

Research suggested here for the three priority areas should be conducted under field conditions to capture the most relevant data. This type of work depends on environmental conditions and thus should be planned to cover at least two years with representative long-term seasonal conditions. As exemplified by the climatic conditions during the summers of 2020/21 and 2021/22 with their higher rainfall amounts and lower average ambient air temperatures, it will be important to incorporate a realistic degree of flexibility for field work. Given the fundamental importance of the knowledge generated by this work, which has the objective to protect humans and the environment from harm, consideration should be given to such arrangements between the funder and the research team.

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Appendix 8

Synthetic Turf in Public Spaces: Thermal Comfort, Heat Strain, and Heat-related Health Risks

Synthetic Turf in Public Spaces: Thermal Comfort, Heat Strain, and Heat-related Health Risks

Summary Report prepared for the NSW Chief Scientist & Engineer

Climate-Resilient Cities Lab. UNSW Sydney

July 2022

Objective and Scope

This report is commissioned by the Office of the NSW Chief Scientist & Engineer to investigate the impacts of synthetic turfs on thermal comfort, heat strain, and associated heat-related health risks for individuals. The report is focused on the *human scale*, identifying users exposed to synthetic turfs in different spaces across NSW, and highlighting their vulnerability and adaptive capacity in response to heat exposure. To holistically assess the impacts of heat on humans, this report discusses different aspects of heat exposure risks such as *skin burn*, *thermal discomfort*, and *heat strain and stress*, which can collectively lead to negative impacts on human well-being and health.

The summary report details a systematic review of the peer-reviewed publications as well as international literature produced by government agencies, academic institutions, and industry stakeholders. The report aims to synthesize the state-of-the-art knowledge, as well as research gaps, on the impacts of synthetic turfs on heat-related health risks. It further provides recommendations on how knowledge gaps can be addressed in research and application.

While chemical compositions of synthetic turfs and their impact on overall heat and environmental factors are discussed, their in-depth impact analyses are beyond the scope of this report. Appropriate references are instead provided for the readers.

Research Team

This report is prepared by **Dr. Negin Nazarian** (Scientia Senior Lecturer, UNSW Built Environment) and Mr. **Pooriya Mohseni** (Research Assistant, Climate-Resilient Cities research lab).

About the authors

The **Climate-Resilient Cities research lab** is a multidisciplinary group, led by Dr Negin Nazarian, dedicated to exploring the climate impacts in the built environment and realizing pathways to making our cities climate-resilient. Through research, the CRC lab aims to address the pressing challenges of urban climate (such as urban heat, ventilation, energy, and air quality) using a range of established and emerging methods such as climate modelling, environmental sensing, and IoT technologies.

Dr. Negin Nazarian is a Scientia Senior Lecturer at UNSW Built Environment, Associate Investigator at the ARC Centre of Excellence for Climate Extremes, and Fellow at the City Futures Research Centre. She is an urban climatologist evaluating the ways the built environment interacts with the climate, and in return, how urban dwellers are affected by this interaction. In her work, she has extensively analysed the impact of surface materials on urban energy balance and further investigated personal thermal exposure impacts on human comfort, well-being, and health. Mr. Pooriya Mohseni is a Research Assistant at CRC lab with a background in Engineering Sciences and extensive experience with systematic review practices.

Citation

Nazarian, N. and Mohseni, P. (2022) *Synthetic Turf in Public Spaces: Thermal Comfort, Heat Strain, and Heat-related Health Risks.* A Summary Report prepared for the NSW Chief Scientist & Engineer.

UNSW SYDNEY

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1 Synthetic turf: Introduction and usage in NSW

The installation of synthetic turf has become widespread globally, and in NSW, in a range of public, private, and commercial spaces such as sports fields and courts, playgrounds, school districts, recreational spaces, and residential lawns. Promoting active recreation, and subsequently human wellbeing, across all seasons and climate conditions has been the key driving factor behind the installation of synthetic turfs. Natural turf surfaces require regular and continuous maintenance (involving irrigation and mowing) and are susceptible to climate events and disease infestations. These challenges have prompted various organizations and private actors to use alternative surface fields – such as synthetic and hybrid surfaces – in place of natural grass surfaces across NSW.

Synthetic turfs, however, present environmental, social, and economic impacts that should be assessed together with their benefits. These impacts range from modification of thermal environment (and subsequent contribution to urban heat) to health impacts on individuals exposed to synthetic turf fields during a range of activities and exposures. Among these, the heat-related health hazard is among the least studied fields and is the focus of this report.

Material compositions of synthetic turfs fields and usage across NSW

The synthetic grass carpet was first introduced in the 1960s and was made with high-density nylon yarns. Since then, the materials and the construction of turfs have evolved dramatically (DPCD 2011), introducing new generations of synthetic grass that address various requirements for durability, sports performance, and environmental impacts.

The third generation of synthetic field turfs (Fig. 1) - most commonly installed in NSW and Australia - often include synthetic carpets (including yarns, infills, and backings) placed on top of shock pads and compacted sub-soil and drain rocks as the base. The most common infill in the third generation is crumb black rubber, sand, or a mixture of sand and recycled rubber granules. The base layer can also vary from pervious soil and land covers or a drainage system to impervious asphalt and levelling layers (Jastifer et al. 2019).

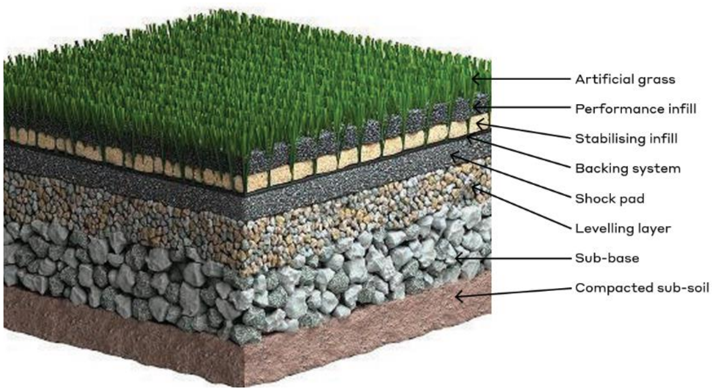


Figure 1. Construction method and materials in a typical third-generation synthetic turf commonly used in Australia.

In NSW, synthetic turf of different types is widely installed in sports fields, particularly for hockey, football, lawn bowls, athletics, tennis and cricket fields. The use of synthetic grass in playgrounds, and private lawns is also widespread, though data on detailed usage compared to natural grass is not available. The three most common types of infills (where used) in NSW include silica, styrene-butadiene rubber (SBR), and Polyurethane Rubber all of which are constantly lost to the environment during active usage. These materials have significantly different characteristics and thermal properties compared to the natural land cover and therefore modify the microclimate. Furthermore, depending on the base layer used, the penetration and evaporation of water into the sand and atmosphere is significantly affected. Collectively, these factors create a different thermal environment compared to natural grass cover with subsequent health hazards for users exposed (detailed in Section 2).

2 Potential heat-health risks of synthetic turf: Heat exposure and skin burn

Material compositions of synthetic turf are significantly different from natural land covers (Section 1), leading to critical environmental footprints with potential impacts on human health. Overall, three key health risks can be noted in synthetic turf fields: 1) ***Release of toxic or carcinogenic compounds** to the environment*, 2) ***skin burn** due to contact with elevated surface temperatures*, and 3) *increased **heat strain** due to modification of microclimate*. Taking a more holistic view on health - defined as a state of complete physical, mental, and social well-being (World Health Organization 2021) and not merely the absence of disease - synthetic turf fields also pose potential risks of indirect health outcomes to human wellbeing and lifestyle. ***Thermal discomfort*,** for instance, has been shown to affect the cognitive and physical performance of individuals (Lan et al. 2011) and can lead to reduced outdoor activities and subsequently a sedentary lifestyle (Huang et al. 2016; Nazarian et al. 2021; Nazarian et al. 2021b) with significant negative impacts on human health and wellbeing.

Focusing on the heat-health hazards, it is evident that elevated surface temperature, and subsequent risk of skin burn injuries, thermal discomfort, and heat stress, are currently the primary concerns in synthetic turf fields. Compared to natural land covers, synthetic turf materials have a lower albedo (i.e., lower reflectivity), absorbing more solar (shortwave) radiation and emitting more thermal (longwave) radiation (Jim 2017; Thoms 2015; Yaghoobian et al. 2010). Additionally, materials used as infill for synthetic turfs (such as black rubber and SBR granules) have higher heat capacities and/or thermal conductivities, leading to heated surfaces with a higher potential to cause extensive burns (Vanos et al. 2016; Petrass et al. 2014b).

Solar radiation is one of the key driving factors of elevated surface temperatures of synthetic turf (Devitt et al. 2007; Petrass et al. 2014a; Jim 2016; Xinhua et al. 2007). Several observational measurements of synthetic turf were conducted in various climatic backgrounds, reporting consistently hotter surface temperatures during the day compared to natural turf (Jim 2016; Wardenaar et al. 2022; Mantas and Xian 2021; Shi and Jim 2022). Particularly on a clear-sky day and under direct sunlight, synthetic turf surfaces can reach temperatures that are above the threshold for a burn injury, particularly for children. Surface temperatures of up to 72.4°C were reported, 36°C higher than natural grass, in Hong Kong (Jim 2017) while during very hot summer days in Western Sydney (Pfautsch and Wujeska-Klause 2021), old and new synthetic turf covers reached average surface temperatures of 70-75°C, compared to 37°C for irrigated natural grass. During an extreme heat day (air temperature of 49.4°C recorded in the playground of Bennelong Park) maximum surface temperature of 93.7°C was observed on old synthetic turf in the playground. Similar findings were reported using modelling in Tennessee, USA (Thoms et al. 2014) and the UK (Gustin et al. 2018). Overall, it is clear that reported surface temperatures of synthetic turf in direct sunlight can approach or surpass values likely to result in burns (particularly in children and vulnerable populations), as burns can occur within 3 seconds of contact on solid surfaces with temperatures ≥60°C (Vanos et al. 2016).

In addition to skin burn risks, the potential thermal discomfort, heat stress, and heat strain should be considered when evaluating synthetic turf impacts. Unlike surface temperature measurements, however, limited analyses are conducted where the subjective evaluation of thermal environments (thermal comfort) or physiological responses to heat exposure (heat stress and strain) are evaluated holistically (i.e., in different synthetic field materials and considering long-term analyses in relevant background climates and climate projections, as noted in Section 4.1). Nonetheless, there is evidence that synthetic turf may induce thermal discomfort and heat stress on athletes and children on hot summer days. When assessing the thermal environment of sports fields on different surfaces in a humid subtropical climate, Xiao and Cao (2013) showed that not only air temperature is increased in synthetic turf fields (1.5°C at 1m and 1.1°C at 1.5m height), but also users experience a higher level of thermal discomfort that is attributed to microclimate changes. In one of the earliest studies on heat strain in synthetic turf fields, (Elsworth et al. 1971) placed thermocouples on the inner soles of cleated shoes while individuals walked on the synthetic surface. This study was mainly focused on assessing the amount of heat transferred directly from the surface to the individual's foot, and the additional heat gain to the body that needs to be dissipated by blood flow and physiological responses (Section 3.1.2). Buskirk et al. (1971) concluded that the heat transfer from the surface to the sole of an athlete's foot was significant enough to contribute to greater physiological stress that may result in serious heat-related health problems. In another study of football players exposed to different surfaces (Wardenaar et al. 2022), a significantly higher skin temperature value was found on the synthetic turf during exercise compared to natural grass and indoor domes, leading to a higher heat load on the human body. The same pattern was seen for the body core temperature, which is the main indicator for heat strain in individuals, as well as RPE (rate of perceived exertion) and self-reported heat stress. The outcomes of this study indicate that even in small changes in microclimate parameters (such as air temperature), both physiological and psychological responses of individuals exposed to synthetic turf can be noticeably altered.

These health hazards are due to the thermal properties of synthetic turf materials (and the subsequent impact on microclimates), as well as the user profiles and types of activities commonly seen in synthetic turf fields. Accordingly, this section details how thermal exposure can be holistically assessed by a) discussing the microclimate modifications by synthetic turfs (Section 2.1) and b) identifying the users (individuals and populations) with increased vulnerability levels caused by physiological and behavioural factors (Section 2.2).

2.1 Modification of microclimate and ensuing thermal exposure in synthetic turf fields

Quantifying thermal exposure, i.e., exposure of individuals to thermal environments (including but not limited to the surface and air temperatures), in synthetic turf fields requires a clear understanding of microclimate variations. This section focuses on detailing environmental factors that collectively influence thermal exposure and describes how these microclimate parameters are modified by synthetic turf fields.

When assessing the impact of synthetic turf, the majority of the focus has been placed on surface temperature measurements while air temperature above surfaces has been evaluated in limited studies. Although these parameters are important, they are not sufficient to holistically determine the impact of synthetic turfs on the thermal environment (and subsequent heat exposure). The four key components of thermal environments are *air temperature*, *radiative heat exchange* (characterized as *Mean Radiant Temperature)*, *airflow*, and *humidity* (Fig. 2. left), which collectively impact people, infrastructures, and resources (such as energy and water) in cities (Nazarian and Norford 2021). Table 1 describes the importance of these four components in determining heat transfer between the human body and the environment that subsequently affect human thermal comfort. Furthermore, it details how synthetic turf surfaces modify each microclimate parameter in indoor and outdoor spaces.

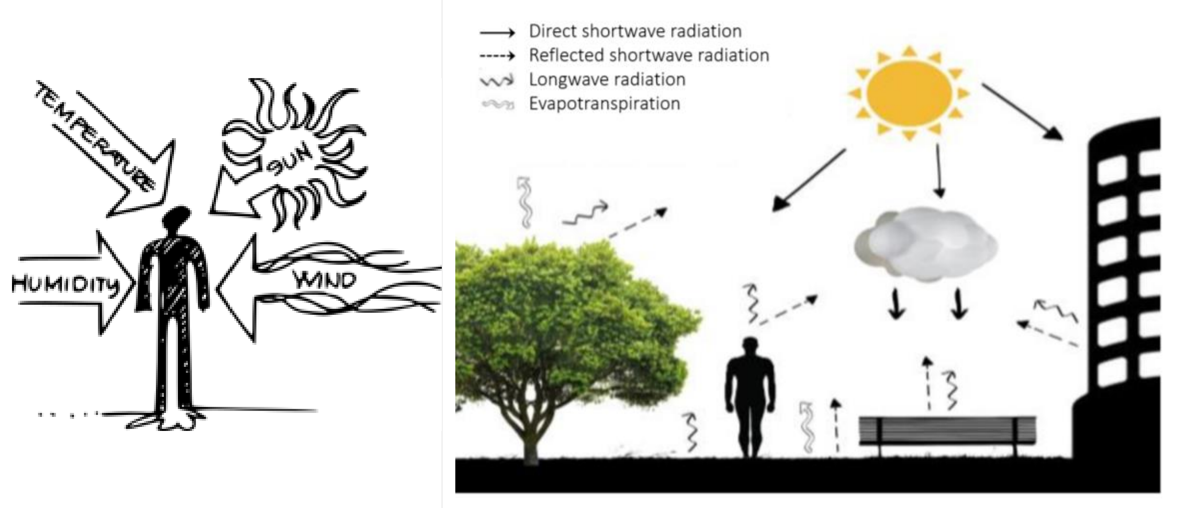


Figure 2. Left: Schematic of key microclimate parameters that affect human thermal comfort. Right: An overview of radiation components in urban environments that holistically determine mean radiant temperature (adopted from Naboni et al., (2020)).

How can future generations of synthetic turfs modify local microclimates?

Industry reports a range of new products are being developed (4th generation and later) in the UK and Australia (SPORTENG 2021; Artificial Grass Maintenance n.d.; AWP n.d.) some of which aim to address heat-related problems including extreme heat and high UV radiation. New technologies include keeping the surfaces cool by allowing high solar reflectivity and low heat absorption. While these methods can decrease the surface temperature, it is likely that they increase the radiative heat transfer to individuals exposed to synthetic turf fields and therefore increase the chances of heat strain (Middel et al. 2020). For instance, if the surface temperature is reduced by increasing albedo, higher shortwave radiation is likely to be reflected to users exposed to synthetic field surfaces (Fig. 2. right), increasing mean radiant temperature and subsequent heat discomfort. This was similarly seen in “cool” solar-reflective pavements in Los Angeles. Holistic measurements of microclimate changes indicated that although 4°C lower surface temperature is observed during midday compared to regular asphalt concrete, mean radiant temperature over reflective pavement was 4°C higher and air temperature was only reduced by 0.5 °C (Middel et al. 2020).

Additional methods and innovations include improving water retention or increasing irrigation that increases passive radiative surface cooling as well as evaporative cooling of temperature. However, the impact of humidity on human comfort and heat stress is highly dependent on climatic backgrounds (Potchter et al. 2018). In the same air temperature, increasing humidity levels can dramatically worsen thermal comfort conditions and is most detrimental to human heat strain in hot conditions (Table 1 and Fig. 4). On the other hand, International Hockey Federation

(FIH) have announced dry artificial turfs from 2024 onward in times where water is a scarce resource around the world (The News International 2019). Traditionally, hockey pitches are irrigated before the match, or at times during half-time breaks when the weather is hot. Sports players exposed to wet synthetic fields are acclimatized to these conditions and may be impacted by the microclimate changes (and reduced humidity and evaporative cooling capacity) of new dry turf in hot seasons. Accordingly, these new innovations should be evaluated more holistically in the context of human thermal comfort and heat strain to determine the suitability of the synthetic turf applied in various sports fields (detailed in Section 3).

Lastly, not only the changes in infill materials (such as corks instead of rubber) but also the height of the pile is likely to have an impact on the thermal environment, and subsequent impacts on human thermal exposure. During a measurement conducted in full sun during midday of an extreme heat event in Western Sydney, (Pfautsch and Wujeska-Klause 2021) found that synthetic turf with medium and long pile heights reached average surface temperatures of 91°C, compared to 83°C temperature observed by synthetic turf with a short pile height. These findings indicate the importance of comprehensive and holistic analyses of future generations of synthetic turf to better identify the microclimate modifications that result from changes in material decomposition.

Table 1. Environmental factors that influence the thermal comfort of individuals and the influencing factors in synthetic turf fields.

Microclimate	**Effect on thermal comfort**	**Influencing factors**
Air temperature	In the absence of solar radiation and in low wind speed conditions (often seen indoors), air temperature is the most critical factor determining the thermal comfort of individuals. Air temperature impacts convective heat transfer to, and heat loss from, the human body.	Synthetic turfs are shown to affect air temperature right above the turf (e.g. 15cm) as well as the pedestrian height of 1.2-1.5m (Jim 2017; Xiao and Cao 2013; Shi and Jim 2022). Modelling of synthetic turf impact in urban areas also found that replacing grass ground cover with artificial turf can add 2.3 kWh/m2.day of heat to the atmosphere, which could result in urban air temperature increases of up to 4°C (Yaghoobian et al. 2010). The impact on air temperature is reduced with increasing height, i.e., at the pedestrian height, the differences in air temperature between synthetic and natural turf are smaller than close to the ground (Jim 2016).
Radiation (determined through mean radiant temperature)	In warm seasons and clear-sky days, mean radiant temperature - a measure of the average temperature of the surfaces that surround a particular point - is the most critical determinant of thermal discomfort and the most significant agent of heat gain to humans (Johansson et al. 2014; Kántor and Unger 2011). During hot sunny days, solar radiation may cause extreme surface temperatures leading to thermal burns. Reflected solar (shortwave and longwave) radiation from surfaces directly affects human comfort and can be more critical than air temperature (Kwon and Lee 2019; Middel and Krayenhoff 2019)	An overview of radiation components in urban environments that holistically determine mean radiant temperature is shown in Fig 2 (right). The difference between synthetic turfs and natural land cover is mainly in absorbed shortwave radiation and emitted longwave radiation (Liu and Jim 2021). Synthetic turf often has a lower albedo than natural grass, therefore absorbing more solar (shortwave) radiation that leads to increased surface temperature (regardless of composition and age), particularly when unshaded. On the other hand, synthetic turfs emit more longwave radiation. For users that are exposed to synthetic turf, this translates to more upward longwave radiation but less upward shortwave radiation, highlighting important control by the radiant environment (Fig 2. right). In experimental campaigns in Hong Kong, the averaged mean radiant temperature (MRT) of synthetic turfs was shown to be 3.4°C and 0.8°C higher than natural turf in sunny and cloudy weather, respectively (Shi and Jim 2022). The open design of urban parks and playgrounds (where synthetic turfs are commonly used) with high radiant heat loads and no shading devices make them more likely to experience elevated MRT.
Relative humidity	High humidity levels limit the capacity of individuals to cool through sweat evaporation (Fig 4) and lead to increased thermal discomfort even in moderate air temperatures.	Even when natural turf is used, if not irrigated, it turns yellow and exposes dry patches of dry bare soil with higher surface temperature (Pfautsch and Wujeska-Klause 2021). For synthetic turfs, irrigation, as well as the underlying base layer, affects the moisture level and the relative humidity in the environment. In many sports fields, synthetic turf surfaces are not irrigated (or irrigated sporadically in hybrid turfs) which reduces the water vapour and modifies the humidity level. The base layer of the synthetic turf field (or drainage system potentially used under surfaces) may also have a different capacity to absorb water than natural surfaces, modifying the overall moisture balance of the synthetic turf fields. When synthetic turf was used indoors, the lack of radiation lessened the overall heat load, but higher humidity and lower airflow were observed (Wardenaar et al. 2022).
Wind speed	In high air temperatures (particularly with high solar radiation), stagnant air significantly reduces thermal comfort. Airflow enhances evaporative cooling of sweat and convective cooling of the skin and has the most effect in higher mean radiant temperature (Fig.4).	Synthetic turfs are unlikely to change the wind speed. However, they are often used in areas with less obstruction of wind (due to lack of trees or shade) which results in higher wind speed compared to urban surroundings.

2.2 Identifying the vulnerable populations in synthetic turf fields

In addition to modification of microclimate due to synthetic turf, the characteristics of individuals and populations exposed to synthetic turf fields are critical in assessing the heat-related risk levels.

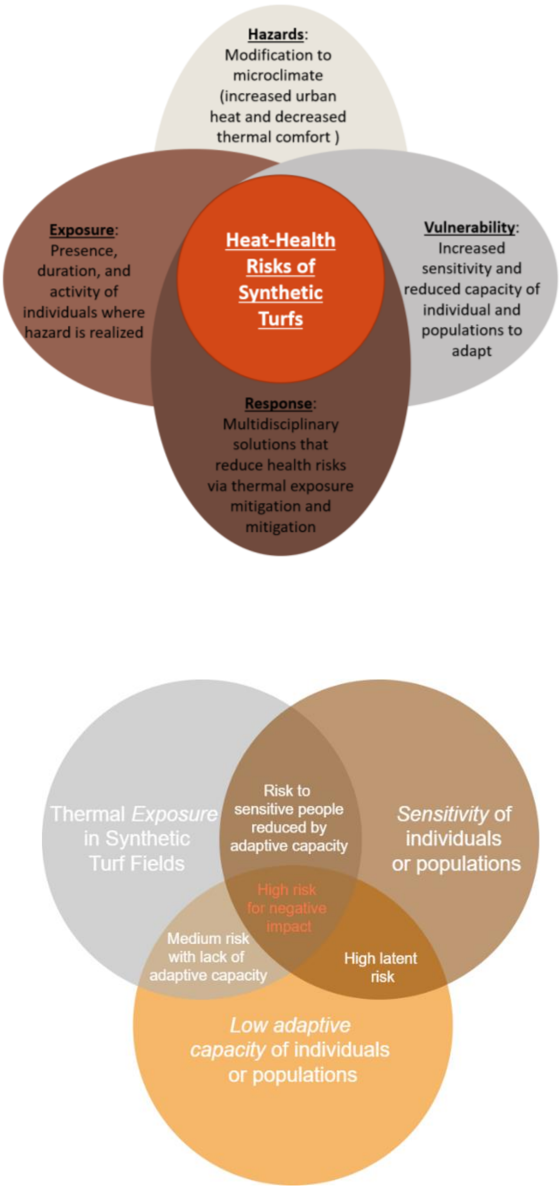


Figure 3. Integrated framework for determining heat-health risks of synthetic turfs.

Figure 3 (top) shows the integrated framework that describes the compounding effects of heat exposure with the vulnerability of users in synthetic turf fields. To understand this framework, it's paramount to note that the impact of synthetic turfs on modifying the thermal environment may be critical, but it is only the trigger and in itself may not lead to health risks. Exposure to heat hazards gets compounded with (physiological and psychological) sensitivity of each individual and/or their reduced capacity to adapt, which subsequently leads to increased risk levels (Nazarian et al. 2021b).

Heat vulnerability exists when sensitive individuals, populations, or infrastructures are exposed to adverse thermal environments in synthetic turf fields. One of the key individual sensitivities to overheating is shaped by physiological responses to heat. For instance, children and infants, athletes, outdoor workers, firefighters, those with pre-existing illnesses and/or on medication, and the elderly are among the population subgroups that are physiologically vulnerable to heat (Ebi et al. 2021). If these individuals are exposed to heat, and lack the capacity to respond and adapt, negative impacts ensue. The adaptive capacities of individuals to respond to heat range from adjusting clothing levels or reducing activity intensity to minimizing exposure by seeking shade. Figure 3 (bottom) further describes the ensuing levels of health risks when sensitivity and adaptive measures are combined with heat exposure.

The following section identifies individuals and populations that are more likely to be vulnerable to heat exposure from synthetic turf fields. This vulnerability level is caused either by physiological sensitivities (due to age or health conditions), behavioural patterns (such as activity levels), or lack of access and awareness of adaptive measures (breaks, water intake, active cooling).

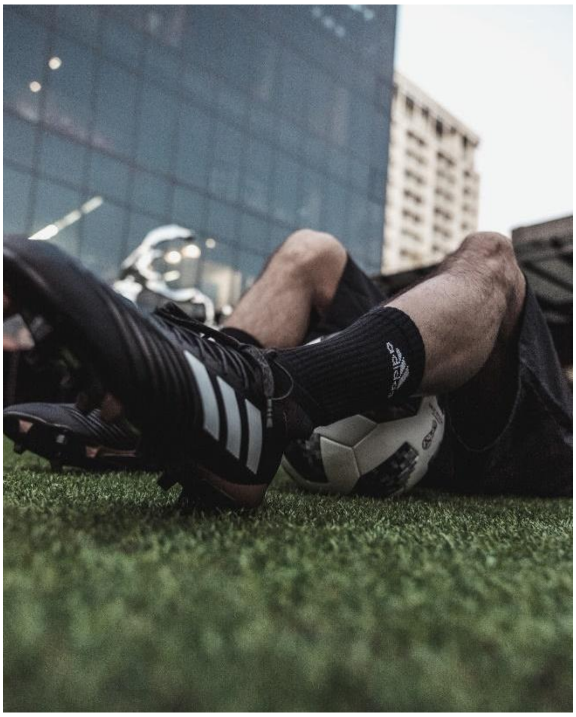
2.2.1 Children in playgrounds and school fields

Synthetic fields are seen in playgrounds and school playing fields which prompt attention to their users' vulnerability and exposure to heat exposure. In the absence of design measures to mitigate heat, playgrounds may become microscale heat islands with dangerously hot surfaces that enhance, rather than mitigate, the larger urban heat island effect (Vanos et al. 2016). In a multi-scale measuring campaign in Arizona USA, rubber soft fall and synthetic turf were generally the hottest surface materials to be found in playgrounds (Guyer et al. 2021).

More importantly, playgrounds and school fields host children that are more vulnerable to the effects of heat stress and high surface temperature than adults (Vanos et al. 2016). This is mainly due to their high ratios of metabolism-to-surface area (Children produce more metabolic heat per mass unit) and higher surface-area-to-body-mass which results in higher sensible heat received from the environment (Falk and Dotan 2008), as well as closer proximity to the hot surfaces during playtime (Liu and Jim 2021). Children's sweating rates are also lower than that of adults, leading to lower evaporative cooling capacity (Coccolo et al. 2017). Lastly, children have more sensitive skin, lower awareness of changing environments, and slower reflexes to remove their hands from what may be causing the burn.

The combination of these factors results in more stress on an already less-efficient thermoregulatory response relative to adults, particularly during physical activity in hot conditions (Falk and Dotan 2008), and leads to a quicker path to heat stress for children than for adults exposed to synthetic turf surfaces. In an analysis done in Hong Kong, it was found that compared to natural grass, children suffered a 24% longer "Extreme danger" thermal sensation when exposed to synthetic turf during sunny daytime (Liu and Jim 2021).

2.2.2 Athletes and sports players



Quantifying thermal exposure in areas commonly used for active use (i.e., parks and sports fields) is important for better understanding the health effects of synthetic fields (McGeehin and Mirabelli 2001). In these fields, users are more likely to spend an extended period of time and/or perform more vigorous activities, both affecting their physiological response and pathways to thermal discomfort and heat strain.

Metabolic heat production and the thermal environment provoke separate and largely independent physiological strains (Brotherhood 2008) as detailed in Section 3.1.2. The higher intensity in sports activities leads to higher metabolic heat production that drives heat stress. Accordingly, it is likely that athletes and sports players (particularly at a younger age) are more physiologically sensitive (and therefore more vulnerable) to elevated thermal exposure due to synthetic turf. In addition to the type of activity and age group, it is critical to assess the gender and climatic background of players. In a 10-year assessment of heat illnesses in soccer, female players were found to be 1.6 times more likely to sustain heat illness than males (Elias 2001). These findings draw attention to the individual sensitivities of sports players based on a series of physiological profiles.

Furthermore, synthetic turf may affect the perception of exercise and deter activities on sports fields. In the analyses of Swedish elite football players on artificial turf and natural grass, players reported a negative overall impression and greater physical effort (Andersson et al. 2008). Accordingly, to have a more holistic view of health impacts, it is important to assess the indirect impacts of synthetic turf on human health through reduced activity levels and exposure outdoors.

2.2.3 Sports Spectators, Non-Acclimatized Visitors, and Vulnerable Residential Populations

In addition to considering children, young adults, and athletes that are exposed to synthetic turf, the thermal comfort of parents and carers, as well as sports spectators, should be considered (Pfautsch and Wujeska-Klause 2021). Even when seated or standing, these groups are likely to be in areas that are unshaded and may experience higher temperatures due to longer exposure as well as modification of microclimate (through surfaces including but not limited to synthetic turfs).

Acclimatization is another known factor in modulating the impact of heat exposure on health risks (Sawka et al. 2015). For instance, athletes and spectators attending international events in different (and hotter) climates are more likely to experience heat strain and might be more vulnerable to synthetic turf surfaces.

Lastly, when installing synthetic turf in urban environments, vulnerable residential populations in the area should also be considered. For instance, if synthetic turf surfaces are used in neighbourhoods with a higher elderly population or lower socioeconomic status, it may result in more risk of heat strain as the physiological sensitivity of these populations to heat is significantly higher while their access to adaptive capacities (such as active cooling) is lower (Nazarian et al. 2021b). Accordingly, vulnerable residential populations in surrounding infrastructures are more likely to be affected by the cumulative impacts of microclimate changes and heat exposure.

3 How to Holistically Describe Thermal Comfort and Heat Strain for Synthetic Turfs Fields

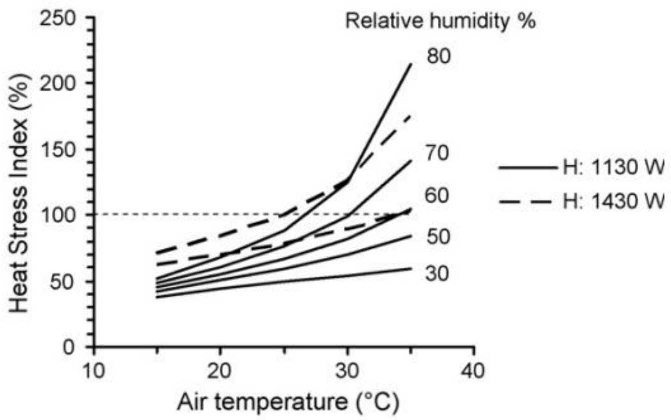
This section describes the principles of thermal comfort and heat exposure monitoring in synthetic turfs. Considering the impact of synthetic turf on microclimate, the first section details how environmental factors modulate the thermal comfort, and subsequent heat stress, in individuals. Second, we describe the physiological changes in response to heat exposure that can either stabilise thermoregulation in the human body or lead to heat strain. Lastly, we detail various thermal indices commonly used for describing thermal comfort and heat strain and describe their strength and limitation when analysing heat-health risks in different vulnerable populations.

3.1 Principles for monitoring and assessing thermal exposure in synthetic turf fields

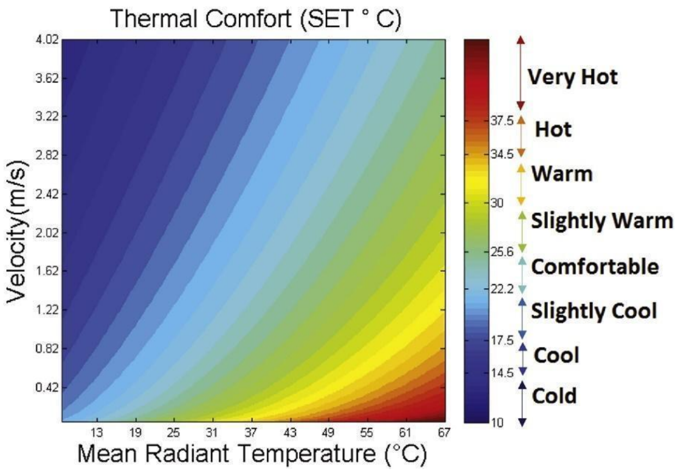
3.1.1 Environmental factors (temperature, humidity, wind speed, and MRT)

While it is important to consider all microclimate parameters affecting thermal environments, it is critical to note that their impacts on human thermal comfort and heat strain are not linear. Heat transfer between the body and the environment occurs by heat flow and humidity gradients through three independently acting physical processes: thermal radiation, convection, and evaporation. Radiative heat transfer is the transfer of heat between surfaces of different temperatures. Convective heat transfer is a function of three factors: 1) temperature of the skin, 2) temperature of the air, and 3) wind speed over the body. Evaporative heat transfer is then determined by a combination of these factors, as well as humidity levels. Generally, these heat transfer mechanisms facilitate overall heat loss from the body, but heat may also be gained from the environment or environmental conditions may prevent adequate heat loss (Section 3.2.2).

Figure 4 shows how these parameters impact human thermal comfort and heat stress non-linearly. For instance, the impact of increasing air temperature on heat stress is significantly more pronounced in higher humidity and the wind speed is more important for decreasing thermal discomfort when higher MRT values are observed. In other words, in humid outdoor environments, a slight increase in air temperature can result in significant impacts on heat stress. Similarly, when unshaded sunny areas experience a slight change in wind speed, thermal discomfort is diminished dramatically which this change is not seen in shaded areas. The impact of metabolic heat production (from physical activity) is also shown in this Figure. In the same environment, if individuals perform higher levels of physical activity, their thermal stress and discomfort zone will be significantly modified due to metabolic heat production explained in Section 3.1.2.



Impact of temperature and relative humidity on heat stress during different levels of activity at two different running speeds (indicated by the metabolic heat production, H). Figure taken from Brotherhood (2008).



Impact of wind speed and radiation on thermal comfort levels for the same temperature and humidity. Figure taken from Nazarian et al. (2017)

Figure 4. Impacts of various microclimate parameters on thermal comfort.

3.1.2 Physiological Responses (HR, Skin Temperature, and core temperature)

This section will detail physiological responses to heat exposure and how they lead to heat strain (i.e., increased core temperature, blood pressure, or heart rate). Furthermore, we describe the evidence in the literature regarding physiological responses to heat in synthetic turf fields.

Heat stress refers to the combination of environmental conditions, metabolic heat production, and clothing characteristics that alter human heat balance and ultimately contribute to the accumulation of heat energy inside the human body. ***Heat strain*** refers to the resultant physiological responses from heat stress, such as the rise in thermal strain, cardiovascular strain, and dehydration (Nazarian et al. 2021b). Accurate risk assessment of human heat strain exposed to synthetic turf surfaces requires a comprehensive and in-situ representation of all four parameters that define a thermal environment (Section 2.1). However, environmental determinants alone are insufficient to understand the implications of urban heat exposure; physiological responses must also be assessed to fully understand the impact of synthetic turf on individuals and populations.

Figure 5 outlines how environmental drivers of heat exposures interact with human behavioural and physiological responses and lead to individual sensitivity to heat exposure with ensuing impacts on heat strains and thermal comfort. In summary, three mechanisms should be considered as drivers of thermal discomfort, heat stress, and heat strain: exposure to heat, physiological responses, and behavioural activities and psychological responses. For instance, an athlete may be exposed to more heat in unshaded sports fields but is likely to be more heat-acclimatized and experience a lower rate of change in core temperature due to higher levels of aerobic fitness, all shown to reduce the chances of heat stress (Alhadad et al. 2019). An elderly resident, however, is likely to be more sensitive to lower levels of heat exposure even in low to moderate activity levels.

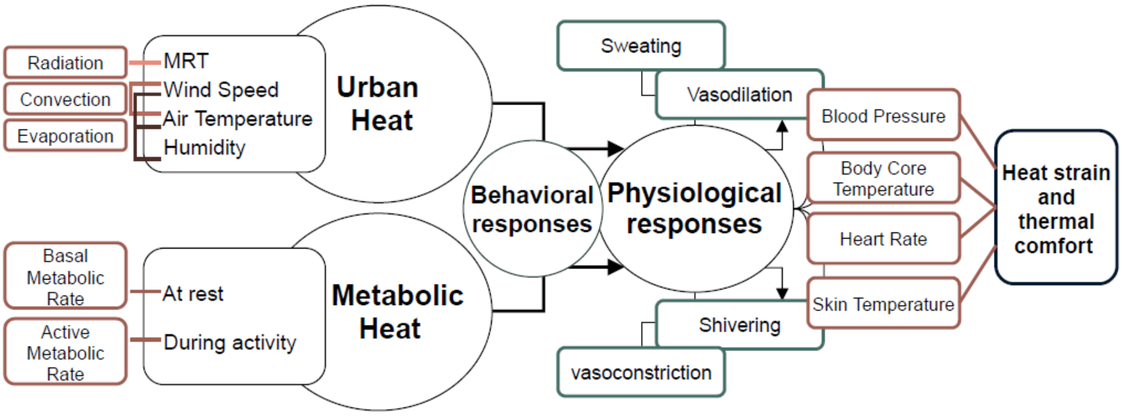


Figure 5. Physical, physiological, and behavioural mechanisms in response to heat (Nazarian et al. 2021b).

The physiological response in synthetic turf fields depends on the combination of the thermal environment as well as users' profile and activity level (Section 2.2). The higher intensity in sports activities leads to higher metabolic heat production that drives body core temperature, which prompts thermoregulation processes such as sweating and vasodilation (Fig. 5). The thermal environment, on the other hand, drives skin temperature and the ability of the body to cool via sweating. The balance between the two mechanisms drives human thermal comfort and strain.

On a hot (sunny or cloudy) day, it appears that the heat stress in high-intensity exercises (such as running and playing soccer) is mostly driven by metabolic rate and not the surface materials such as synthetic turf (Liu and Jim 2021; Shi and Jim 2022). For low to moderate intensity workouts, however, surface temperature significantly affects human thermal stress. In an analysis in Hong Kong, natural turf was found to provide a better thermal environment than synthetic turf for activities with a relatively low to medium metabolic rate (Shi and Jim 2022). Similarly, when thermal stress of children was considered using adjusted thermal comfort indices, children walking on sunny days on the synthetic turf sports fields (in the sports centre of the University of Hong Kong) were estimated to experience 29% of the time in "Extreme danger" thermal conditions, which was 24% longer than natural grass, while the differences for playing soccer was only 3% (Liu and Jim 2021). The daytime exposure to "extreme danger" and "danger" thermal conditions was also significantly larger for children compared to adults, indicating the importance of using suitable metrics that account for physiological sensitivities of vulnerable populations (Section 3.2).

3.2 Quantifying thermal exposure in synthetic turf fields through appropriate thermal indices

This section details various thermal indices commonly used for describing thermal comfort and heat strain and describe their strength and limitation when analysing heat-health risks in different vulnerable populations.

The thermal environment has various physical and environmental representations in outdoor urban climate and is often quantified in either temperature metrics (such as air temperature, surface temperature, or mean radiant temperature) or comprehensive indices (such as thermal comfort and heat stress indices) that aim to quantify the impact of heat on the human body (Nazarian and Norford 2021).

Freitas and Grigorieva (2015) compiled a comprehensive catalogue of human thermal comfort indices (Freitas and Grigorieva 2017) and identified 165 indices to “integrate the heat-related aspects of the environment and human body in a way that gives simple meaning to the thermal significance of the overall condition”. They classified these into eight categories: (A) simulation device for integrated measurements; (B) single sensor (single-parameter) measurements; (C) algebraic or statistical model; (D) proxy thermal strain index; (E) proxy thermal stress index; (F) energy balance stress index; (G) energy balance strain index; and (H) special-purpose index. Each index has a purpose and is most commonly defined to quantify thermal comfort, physical health, or environmental risk of heat exposure on individuals. Potchter et al. (2018) also analysed the use of indices in de Freitas and Gregorvia’s catalogue and, based on published, peer-reviewed articles, concluded that out of the 165 indices, five are widely used for outdoor thermal perception and heat exposure studies: Wet-Bulb Globe Temperature (WBGT), Physiological Equivalent Temperature (PET), Heat Index (HI), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET*). For physiological analyses of heat stress, the Heat Stress Index (HSI), Index of Thermal Stress (ITS), and COMfort FormulA (COMFA) are also used (Coccolo et al. 2016). These indices are compared in Table 2 based on their ability to analyse the microclimate parameters and human characteristics.

Table 2. List of procedures presented in this report, as a function of their ability to analyse the climate, microclimate and human characteristics. Legend: Gr (Global radiation), Ta (air Temperature), RH (Relative Humidity), Ws (Wind speed), SVF (Sky View Factor), Dr (Direct radiation), Dfr (Diffuse radiation), MRT (Mean Radiant Temperature), St (Surface temperature), Gt (Ground temperature), Ba (Building's albedo), Ga (Ground albedo), Ma (Metabolic rate) and Cl (Clothing). Adapted from Coccolo et al. (2016).

	Climate				Microclimate								Human	
Model	**Gr**	**Ta**	**RH**	**Ws**	**SVF**	**Dr**	**Dfr**	**MRT**	**St**	**Gt**	**Ba**	**Ga**	**Ma**	**Cl**
HI		✓	✓											
WBGT	✓	✓	✓	✓									✓	
PET	✓	✓	✓	✓				✓					✓	✓
UTCI		✓	✓	✓				✓						✓
ITS	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
COMFA	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
COMFA-Kid	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓

Various analyses are done to compare the suitability of thermal comfort indices and it is clear that no one index is suitable for all ranges of human behaviour, thermal environments, and climatic backgrounds (Potchter et al. 2018; Grundstein and Vanos 2021). For instance, the heat index (based solely on temperature and humidity) is used in the Extreme Heat Policy issued by Sports Medicine Australia (Jay et al. 2021) and the estimated heat stress range is adjusted based on Sport Risk Classifications according to the combined effects of exercise intensity and clothing/equipment worn. This guideline is comprehensive in its classification of behavioural activities (including activity level, duration, and clothing) and relies on available datasets (such as weather data by the Bureau of Meteorology) but does not include all four environmental factors (such as MRT and wind speed) or the consideration of different physiological sensitivities. Football NSW Hot Weather Policy, on the other hand, considers temperature thresholds for game cancellation differently defined for adults and children and encourages the use of a weather gauge, WBGT, or Heat Stress Meter to monitor player conditions (Football NSW 2016).

Another commonly-used metric for heat stress is WBGT, which has been used widely for heat stress analyses in the sports fields (including those with synthetic fields). However, eight years (2010–2017) of meteorological data, ambulance transport and medical records analysed from Gothenburg's half-marathon showed that PET and UTCI show stronger correlations with ambulance-required assistances and collapses compared to the WBGT index (Thorsson et al. 2021). Compared with the PET, the WBGT underestimated heat stress in this study, especially at a high radiant heat load. In another study, HI and WBGT were found to underestimate the heat stress level when exercising while COMFA is more targeted for heat stress assessment in sports (Liu and Jim 2021). Figure 6 indicates the difference between these common bioclimate indices and a human heat balance modelling approach that considers various metabolic rates based on the intensity of human activity level (and the subsequent impact on metabolic heat production). It is evident that the non-modifiable physiological assumptions within these indices (e.g., PET assuming a constant 80 W of activity) critically diminish the accuracy of the output if used for dynamic sports or occupational purposes (Grundstein and Vanos 2021). Therefore, for rigorous activities, more appropriate thermal comfort indices should be used or heat stress thresholds should be adjusted accordingly (Jay et al. 2021).

When analysing heat stress for children and youth athletes, the COMFA-Kid formula (Cheng and Brown 2020; Cheng et al. 2020) is particularly designed to consider their physiological responses in the energy balance model. When exposed to synthetic-surface football fields in Texas USA, standard thermal indices (such as HI and WBGT) indicated that conditions on the field were relatively safe for youth to engage in activities related to football practice or games, whereas the COMFA-Kid (which is adjusted to account for children's physiology) indicated that conditions were dangerously hot and could lead to exertional heat illness (Cheng and Brown 2020; Cheng et al. 2020). Overall, it is critical that thermal comfort and heat strain indices are selected with the users exposed to synthetic turf fields in mind.

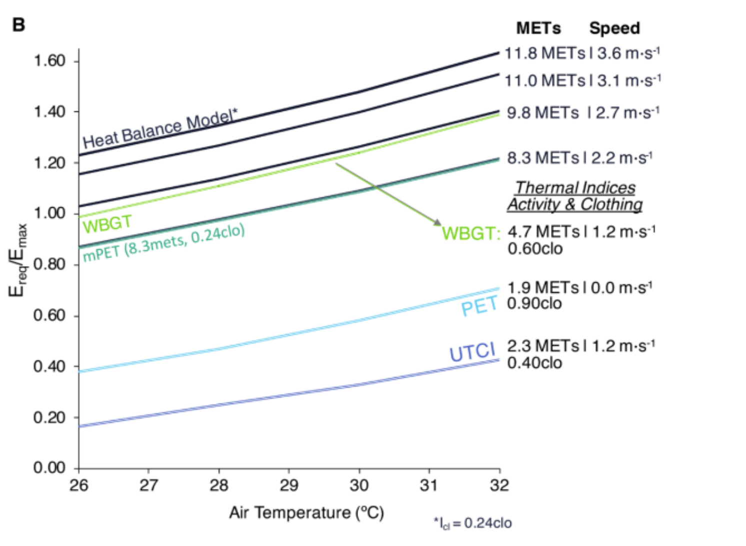


Figure 6. Comparisons of common bioclimate indices with a human heat balance modelling approach (Grundstein and Vanos 2021).

4 Knowledge Gaps and Future Directions

Considering the current state of knowledge regarding the heat-health hazards of synthetic turf fields, this section highlights a number of important gaps and discusses future directions in research and application to address them. First, we note the need for datasets (obtained through measurement campaigns or modelling exercises) that comprehensively assess the thermal environment in synthetic turf fields (Section 4.1) and the importance of extending these analyses to monitoring physiological responses and thermal perceptions (Section 4.2). Furthermore, approaches for quantifying, communicating, and potentially mitigating the heat-health risks are noted in Sections 4.3-4.4.

It is worth noting that these knowledge gaps are noted *not* in the order of importance (as they are equally relevant to quantifying, communicating, and addressing heat-health hazards) but rather in the preferred order of execution. In other words, the recommendation for future analyses is to focus on comprehensively and holistically quantifying the heat-health risk of synthetic turf, and subsequently deploy proposed strategies for communicating and mitigating potential risks for individuals and populations.

4.1 More comprehensive data collection and modelling of thermal environments in synthetic turf fields

Section 2.1 details how key microclimate parameters are modified by synthetic turf fields based on the review of the peer-reviewed literature as well as available reports. It is evident that thermal environments of synthetic turf fields are assessed in a limited range of conditions particularly highlighting the knowledge gap in the following areas:

I. **Comprehensive characterization of thermal conditions**: Overall, one of the key gaps in synthetic turf heat-health assessment is the lack of comprehensive measurements in representative thermal conditions. For instance, to date, no study has conducted *long-term measurements* of synthetic field surfaces to analyse the seasonal variability of microclimate parameters and how they contribute to thermal comfort and heat stress throughout the year. An example of such analyses is shown in Fig. 7, indicating the diurnal and seasonal variability in thermal stress ranges that are not represented in average values (Matzarakis et al. 2018). Furthermore, existing studies are commonly focused on one *climate background* with the majority of studies done in humid subtropical climates which is significantly different from to warm and temperate climates seen in NSW. These gaps in the literature motivate future work in conducting long-term and multi-year measurements in a range of climate conditions that provide more fit-for-purpose analyses of heat-health risks in synthetic turf fields.

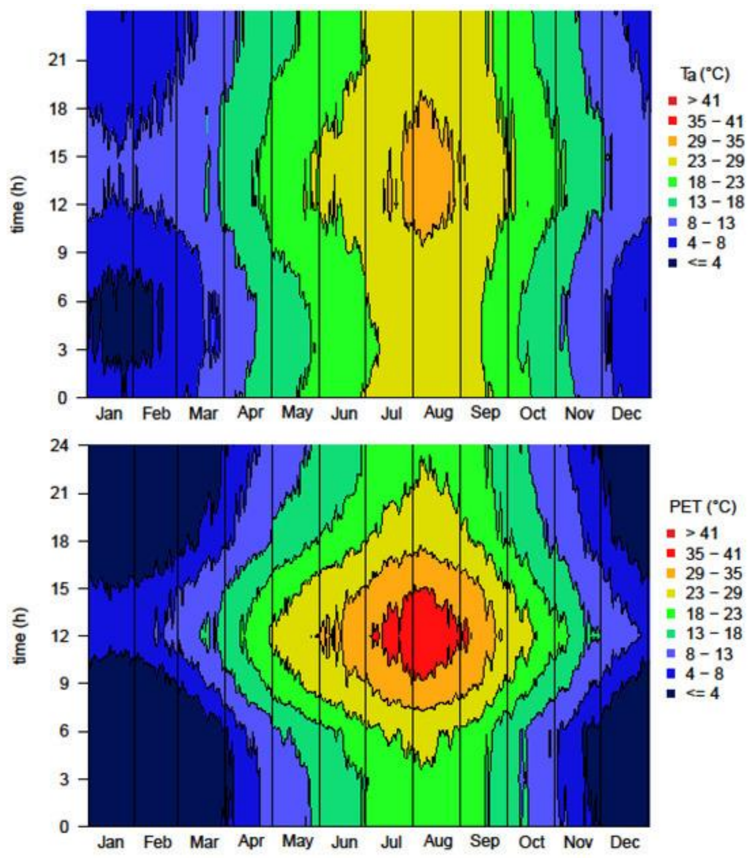


Figure 7. The temporal diagram for Ta (top) and PET (bottom) for Tokyo averaged during the period August 1966 to June 2018 (3 h resolution). The variation throughout the day can be seen in the y-direction, while the variation over the year is given in the x-direction. Colours indicate the thermal stress classification for Central European human beings with low metabolic heat production and moderate clothing level. Figures taken from Matzarakis et al. (2018).

II. **Consideration of climate projections for risk assessment:** The climate of NSW is changing due to global climate change and local urbanization that exacerbate heat challenges. We are already observing increases in average temperatures as well as greater frequencies, duration, and strength of very hot days (Perkins et al. 2012). Therefore, in addition to data collection and analyses in current climate conditions, it is critical that the impact of synthetic turf surfaces is analysed with respect to climate projections (Broadbent et al. 2020).

III. **Comprehensive analyses of synthetic turf compositions:** There are various types and generations of synthetic turfs with different material decomposition (Section 1) and subsequent impacts on the thermal environment (Section 2.1). When analysing the microclimate variations and heat-health impacts of synthetic turf surfaces, it is critical that a comprehensive range of synthetic turf with different material properties and pile heights (Pfautsch and Wujeska-Klause 2021) are considered. This approach would extend to the analysis of materials used in other public spaces.

4.2 Quantifying thermal exposure using appropriate parameters and sensing methods

In addition to the duration, setup, and conditions of data collection and modelling approaches, it is critical that thermal exposure in synthetic turf fields is quantified using appropriate parameters and thermal indices. These include microclimate parameters as well as physiological responses and behavioural activities that holistically quantify heat-health risks.

4.2.1 Comprehensive measurement campaigns that include all microclimate parameters

In addition to air temperature monitoring, it is critical that the following considerations are made for comprehensive measurement campaigns that assess microclimate changes due to synthetic turf surfaces:

I. **Mean Radiant Temperature:** More accurate and directional measurements of mean radiant temperature at different heights above the synthetic turf surface are needed. The most accurate measurement tool for MRT is a six-directional net radiometer setup developed in Arizona USA (Middel and Krayenhoff 2019) and currently available in Australia for comprehensive thermal environment assessment of pedestrians (Liu et al. 2021). Although most comprehensive, this sensing method may be costly and more appropriate for short-term measurements. In these cases, a black or grey globe thermometer can be used for estimating the mean radiant temperature in synthetic turf fields (Thorsson et al. 2007).

II. **Surface temperature:** Monitoring surface temperature at high resolution (since lower resolution underestimates surface temperature and subsequent impacts on heat stress) is important for monitoring potential risks of synthetic turf fields. Monitoring the surface temperature of synthetic turf fields in a more holistic way is critical to minimise the impacts on skin burn, thermal comfort, and heat strain. However, this is at times obtained through satellite imagery which may not agree with in-situ measurements at higher resolutions (Vanos et al. 2016). In situ surface temperature measurements (cm scale) in direct sunlight are shown to approach or surpass values likely to result in burns to children. When larger scale monitoring is assessed (i.e., surface temperature resolved by airborne remote sensing), the observations of ground surface temperature were up to 7◦C less than the Ts at higher resolutions, up to 10.1◦C lower for playground equipment Ts, respectively. This indicates that not only surface temperature monitoring is important, but also it should be done at resolutions that are most appropriate for assessing burn.

III. **Relative humidity:** There are currently no studies evaluating the impact of irrigation (or lack thereof) of synthetic surfaces on relative humidity and the subsequent impact on human thermal comfort. Relative humidity can be assessed using a range of low-cost sensors and can deploy IoT monitoring for long-term observation of thermal exposure (Pantelic et al. 2022).

4.2.2 Personalized monitoring of heat exposure

To fully address the multi-faceted challenges of urban heat, it is paramount that humans are placed at the centre of the agenda. This motives more personalized monitoring of heat exposure in synthetic turf fields and surroundings, defined as evaluations of heat exposure either in the immediate environment of individuals (extrinsic) or with the inclusion of physiological and/or behavioural and subjective responses in individuals (intrinsic) together with the environmental parameters (Nazarian and Lee 2021). This perspective is currently lacking in synthetic turf literature and should be addressed to fully quantify the potential heat-health hazards of synthetic turf.

I. **Comprehensive characterization of physiological responses:** To date, there are very limited studies that go beyond measurements of the thermal environment (often focused on surface temperature and at times air temperature) and instead focus on the ways individuals (with varying levels of vulnerability as noted in Section 2.2) are affected by the thermal environment. A more comprehensive assessment of heat risks in synthetic turf fields requires more data collection, modelling, and analyses of physiological responses (including heart rate, skin temperature, and core temperature) focused on a representative group of users (such as children, athletes, elderly, and non-acclimatized participants). Physiological monitoring can be done using scientific-grade sensors for core temperature, skin temperature, and heart rate monitoring in controlled settings or more accessible solutions such as wearable technologies (Nazarian et al. 2021; Nazarian and Lee 2021).

II. **Inclusion of thermal comfort perceptions:** Heat exposure threatens the health and wellbeing of the Australian population, with flow-on effects on social resilience and economic productivity (Lawrance et al. 2021; Au et al. 2019). Increasing indoor and outdoor urban temperatures negatively impact several aspects of human well-being stretching far beyond heat-health analyses conducted so far. In particular, urban heat impacts a) people's levels of activity and sedentary behaviour, b) sleep quality and c) time spent outdoors (Nazarian and Lee 2021; Maloney and Forbes 2011; Xiong et al. 2020). In turn, these changes in behaviour can contribute to increasing rates of mental health challenges (Liu et al. 2021) as well as obesity. Accordingly, it is critical that synthetic turf fields are also assessed based on not only physiological responses, but human perception, sensation, and satisfaction, particularly with regard to thermal comfort. This can be achieved through more personalized and human-centric feedback collection of users exposed to synthetic turf surfaces through supervised survey questions (Huang et al. 2016) as well as non-intrusive phone and smartwatch applications deployed in the field (Jayathissa et al. 2019).

4.3 A Three-step approach for comprehensively assessing and communicating the risks of heat exposure:

Developing appropriate heat-health advisories and guidelines is critical for mitigating and addressing the heat-health risks in various settings. However, it is important to note that guidelines that are solely based on climatic conditions have limited efficacy. To address this, existing heat policies in Australia have focused on various aspects of activity levels and the vulnerability status of individuals and populations exposed to heat (Jay et al. 2021; Football NSW 2016). Future work should further focus on the development and implementation of personalized heat mitigation guidelines that are a) based on comprehensive characterization of thermal environments, and b) tailored according to an individual's health, environment, and capacity to adapt. This can be achieved by coupling climatic data with biophysical inputs and known influencing factors of heat illnesses (e.g., sex, age, body size, aerobic fitness, and activity type).

To achieve this overarching goal, heat-health advisories can rely on a three-step approach proposed by Grundstein & Vanos (2021) that focuses on the most appropriate method for quantification and communication of heat exposure impacts:

1. **Identify thermal indices based on user profile and activity:** Heat balance models or thermal indices must be applied appropriately with users (such as children and active individuals in mind and allow for altering key physiological factors like metabolic output, clothing ensembles and activity speed (e.g., cyclists vs runners) as noted in Section 3.2.
2. **Develop holistic suitability evaluation of thermal conditions:** More laboratory and field-based studies in an athletic setting are needed to determine the validity and reliability of thermal comfort and heat strain indices in identifying dangerous conditions relevant to health outcomes. With a limited understanding of synthetic turf's total environmental and health encumbrance, developing a holistic suitability evaluation scheme is pertinent.
3. **Communicate implication of thermal exposure impacts:** In addition to selecting appropriate thermal comfort and heat stress indices based on users and desired outcomes, clear communication of their impact should be developed so that they are easily

conveyed to, and understood by, the general public, parents, teachers, athletes, and sport and exercise medicine clinicians such as athletic trainers (e.g., Heat Stress Scale).

4.4 Analyses of additional design factors and adaptation strategies for improving thermal safety in synthetic turf fields

In addition to more data collection and development of appropriate heat-health advisories, it is important to consider the impact of urban design on mitigating heat challenges in areas where synthetic turf surfaces are used. Pfautsch & Wujeska-Klause (2021) details numerous design factors that modulate the impact of surface materials while Vanos et al. (2016) notes that the provision of shade (of any type) is found effective in reducing surface temperature and improving thermal safety in playgrounds. The critical impact of surface cover and tree canopy on thermal environments in Western Sydney is also detailed (Pfautsch and Tjoelker 2020). These urban design and planning considerations can further assist in quantifying and addressing heat challenges in synthetic turf fields.

Lastly, minimizing the heat-health risks particularly in the built environment relies on not only mitigating elevated temperatures and heat exposure, but also informing and enabling individuals and populations with evidence-based cooling strategies that are sustainable and accessible in a wide range of scenarios and communities. The most comprehensive guideline of such cooling strategies at the individual level is developed by Jay et al (2021) identifying the most effective and scalable strategies to keep individuals, workers, and vulnerable populations cool, comfortable, and productive. The infographic summary of these strategies is included here, which details the benefits (e.g., effectiveness) and limitations of each identified cooling strategy as well as optimal interventions for settings for different population groups.

In short, the most effective pathway forward is not only to identify, quantify, and communicate potential heat-health risks in synthetic turf fields, but also deploy a combination of multi-disciplinary solutions that mitigate heat exposure hazards and further enable vulnerable populations with effective adaptation strategies.

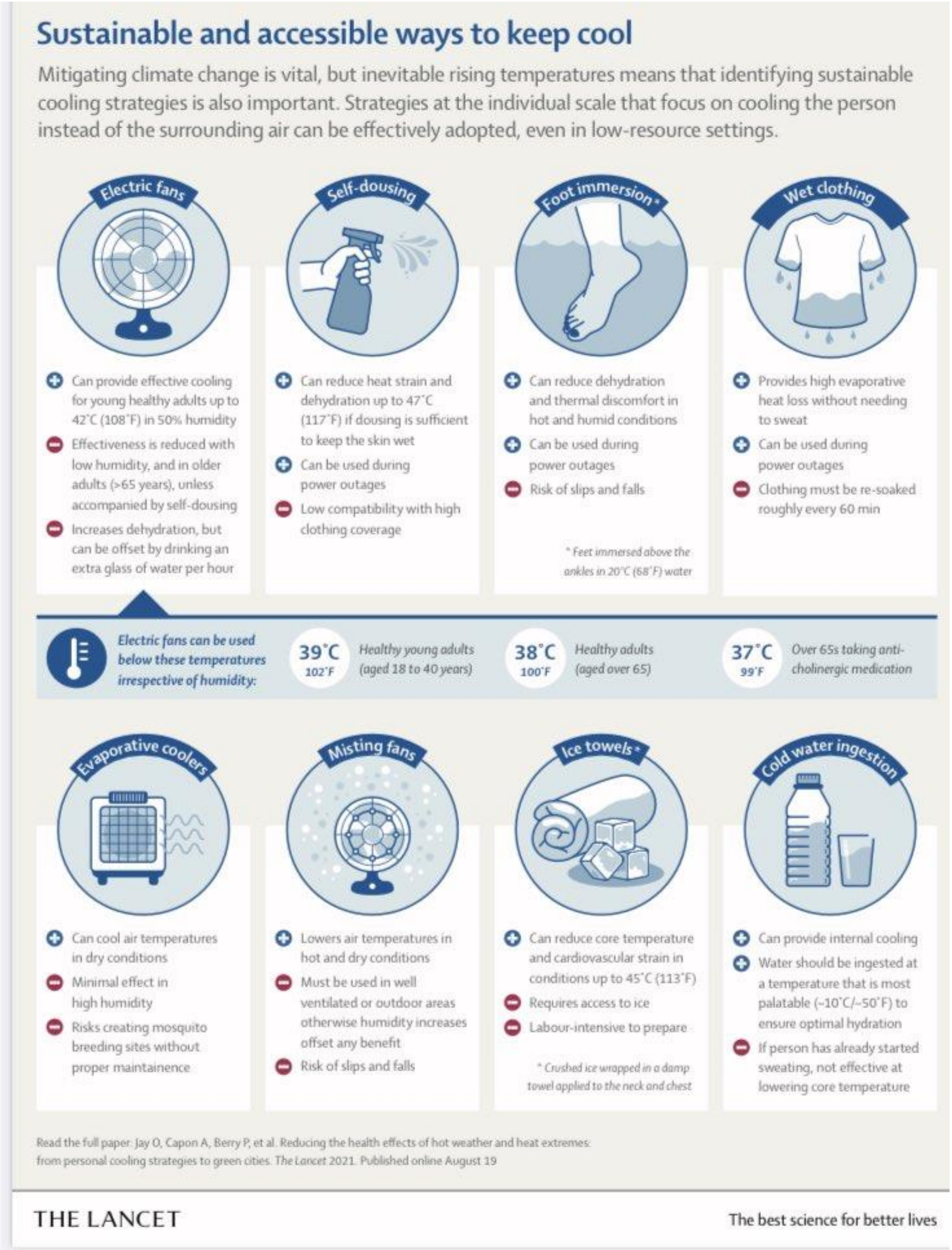
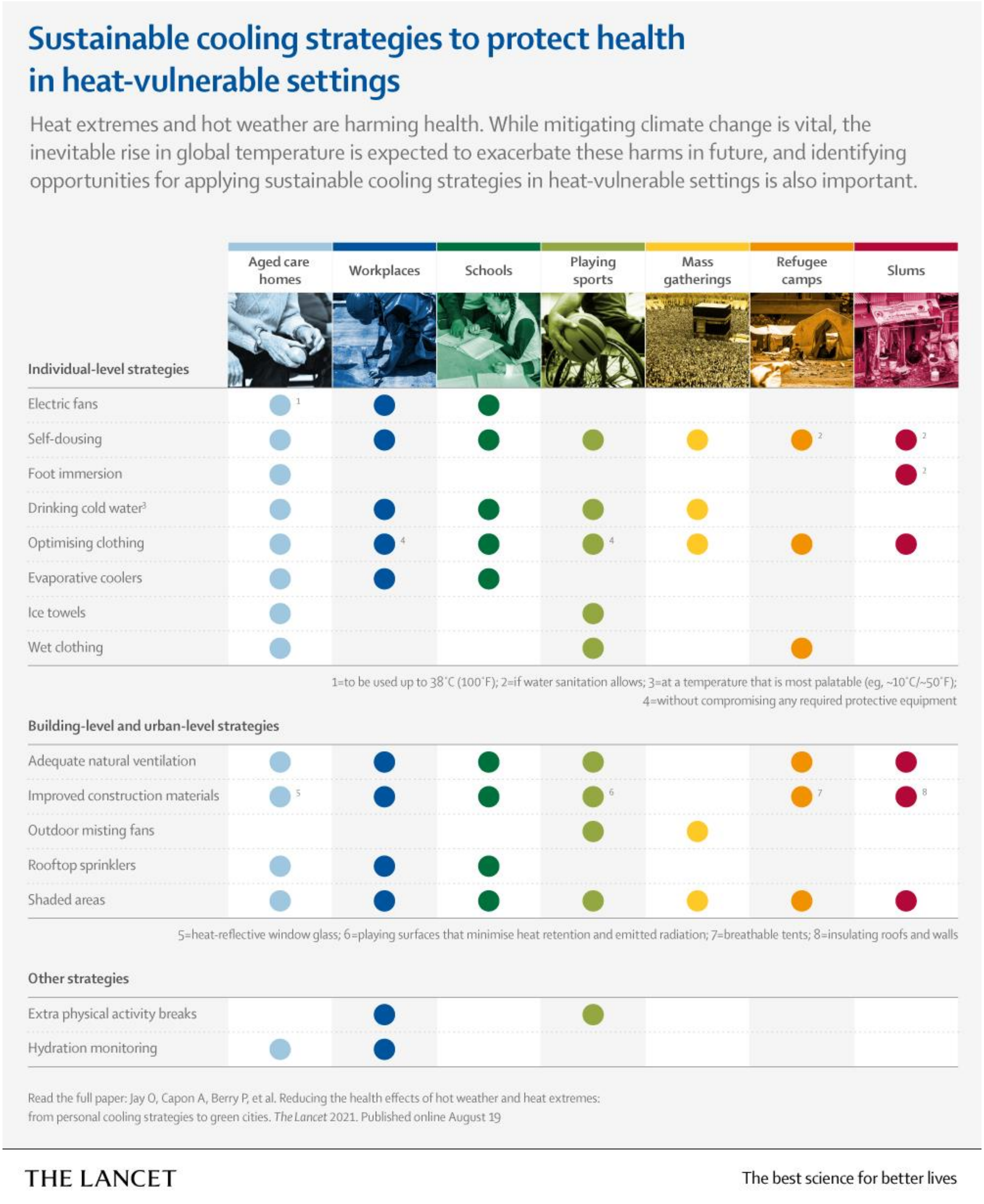


Figure 8a. Human-centric, accessible, and sustainable cooling strategies proposed by Jay et al. (2021).



Sustainable cooling strategies to protect health in heat-vulnerable settings

Heat extremes and hot weather are harming health. While mitigating climate change is vital, the inevitable rise in global temperature is expected to exacerbate these harms in future, and identifying opportunities for applying sustainable cooling strategies in heat-vulnerable settings is also important.

Individual-level strategies	Aged care homes	Workplaces	Schools	Playing sports	Mass gatherings	Refugee camps	Slums
Electric fans	● [1]	●	●				
Self-dousing	●	●	●	●	●	● [2]	● [2]
Foot immersion	●						● [2]
Drinking cold water[3]	●	●	●	●	●		
Optimising clothing	●	● [4]	●	● [4]	●	●	●
Evaporative coolers	●	●	●				
Ice towels	●			●			
Wet clothing	●			●		●	

1=to be used up to 38°C (100°F); 2=if water sanitation allows; 3=at a temperature that is most palatable (eg, ~10°C/~50°F); 4=without compromising any required protective equipment

Building-level and urban-level strategies	Aged care homes	Workplaces	Schools	Playing sports	Mass gatherings	Refugee camps	Slums
Adequate natural ventilation	●	●	●	●		●	●
Improved construction materials	● [5]	●	●	● [6]		● [7]	● [8]
Outdoor misting fans				●	●		
Rooftop sprinklers	●	●	●				
Shaded areas	●	●	●	●	●	●	●

5=heat-reflective window glass; 6=playing surfaces that minimise heat retention and emitted radiation; 7=breathable tents; 8=insulating roofs and walls

Other strategies	Aged care homes	Workplaces	Schools	Playing sports	Mass gatherings	Refugee camps	Slums
Extra physical activity breaks		●		●			
Hydration monitoring	●	●					

Read the full paper: Jay O, Capon A, Berry P, et al. Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet* 2021. Published online August 19

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The best science for better lives

Figure 8b Application of cooling strategies for different settings and user groups. Infographics taken from Jay et al. (2021).

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Appendix 9

Limitations and future directions for research on environmental measurements on synthetic grass sports surfaces

Limitations and future directions for research on environmental measurements on synthetic grass sports surfaces

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Introduction

There have been concerns that individuals could experience heat stress while exercising or playing sport on synthetic grass sports surfaces [1–3]. It is well documented that the surface temperature on synthetic grass surfaces can become considerably hotter than natural grass fields, particularly in hot environmental conditions [2–10]. The hot surfaces can also affect the surrounding microclimate [2,3], potentially creating thermally challenging conditions for athletes and spectators on synthetic grass surfaces [3,6,8]. However, there is an assumption that hot synthetic grass surfaces will cause increased human heat stress, despite no clear evidence demonstrating this. Therefore, this report aims to outline the limitations of the research on environmental measurements on synthetic grass sports surfaces and propose future research directions that would support decision-making regarding investment and use of synthetic grass sports surfaces for exercise and sport.

Biophysical Properties of Human Heat Stress

Heat stress occurs when there is an imbalance between internal heat production (i.e. from metabolic processes) and heat loss in the environment, resulting in high core body temperatures [11]. The human body is thermally inefficient at converting energy into movement, with only ~20-25% of chemical energy generated from metabolic processes used for movement and the rest released as heat. This heat production is further exacerbated during exercise because metabolic heat production is proportional to the rate of oxygen consumption [12]. Therefore, thermoregulatory mechanisms are initiated to maintain a stable core body temperature within a homeostatic limit of ~37°C [12]. Specifically, an individual will experience increased cutaneous vasodilation, peripheral blood flow and sweat production, which transport heat from the core towards the skin surface, where heat can dissipate into the environment via evaporation, convection, conduction and radiation [11].

The environmental conditions influence the capacity for heat exchange since heat moves through a thermal gradient (i.e. from high to low temperatures) [11]. Four environmental parameters govern the capacity for effective heat exchange via the thermoregulatory mechanisms mentioned earlier: ambient temperature, absolute humidity, mean radiant temperature and wind velocity [11–13]. Hence, these are the important measures to capture and to predict how heat may be exchanged from the microclimate around different synthetic sports surfaces, and compared to natural grass fields. In hot environmental conditions, the ambient and mean radiant temperature is often higher than an individual's body temperature, diminishing the capacity for heat exchange [12]. Similarly, in humid conditions, evaporative heat loss decreases because water particles saturate the air, reducing the water vapour gradient and minimising the capacity for sweat evaporation [12]. Accordingly, exercising in hot and/or humid environments may increase the likelihood of experiencing heat stress.

Environmental Measures on Synthetic Sports Surfaces

A systematic literature search was performed using seven academic databases, including Academic Search Premier, Medline, SPORTdiscuss with Full Text, Sage Journals, Web of Science (Core Collection), Scopus, and Proquest. Studies discussed in this section measured at least one environmental parameter (i.e. surface temperature, radiant temperature, humidity, solar radiation or wind velocity) and compared it to another sports surface (i.e. a natural grass surface or another type of synthetic grass surface). Twenty studies satisfied the inclusion criteria and are summarised in Table 1 below, including details of the study, sample size, surface types and the measurements collected. Some studies were performed on full-sized synthetic fields at specific 'sites' [2–10,14–19], while others were performed on small 'plots' of the synthetic surface that were laid outdoors next to each other at the same location [20–24].

Limitations

Across the included studies, 70% measured surface temperatures, 55% measured air temperatures, 50% measured solar radiation, 40% measured relative humidity and 40% measured wind velocity (see Table 1). Given the importance of the four environmental parameters necessary for human heat exchange (i.e. ambient temperature, humidity, mean radiant temperature and wind velocity), it is concerning that many researchers have instead focused on surface temperatures. Indeed, synthetic grass surface temperatures have been studied extensively since the 1970's, demonstrating that these surfaces become hotter than natural grass fields in all environmental conditions [3,8,9]. These high surface temperatures can be explained by synthetic grass surfaces having a low specific heat capacity, meaning that it requires less energy (i.e. from the sun) to heat the surface than natural grass [6]. Unfortunately, the high surface temperatures have led researchers, athletes and the community to assume that this can cause meaningful heat stress for humans exercising on the surface [1–3,25]. Researchers have suggested that heat could transfer from the surface to the body via foot conduction [25]. However, conduction is considered negligible in outdoor environments unless there is direct contact with a conductive surface for prolonged durations (i.e. standing stationary without shoes or laying on a synthetic grass surface) [11]. In sports such as association football (soccer) and field hockey, where synthetic grass surfaces are commonly used, athletes are constantly moving on the fields. As such, there is minimal foot contact time with the surface at a given time and the footwear worn further reduces the effects of that contact; therefore, it is unlikely that this alone can cause meaningful human heat stress.

An interesting finding was that the ambient temperature was higher over synthetic grass surfaces than over natural grass fields [2,6–10,15,17], which has potential implications for human heat exchange and the subsequent risk of heat stress. The higher ambient temperatures are likely due to synthetic grass surfaces transmitting higher levels of long wave radiation back into the environment when compared to natural grass fields [7]. However, ambient temperatures have not been measured in a consistent way across these studies. Measurements have been collected from between 0.15 metres to 1.6 metres above the surfaces, with higher ambient temperatures reported closer to synthetic grass surfaces [2,6,7]. For example, the ambient temperatures 0.15 metres above synthetic grass surfaces were 5.4-8.4°C higher than natural grass fields, whereas the ambient temperature over synthetic grass surfaces at 1.5 metres was 1-3°C higher than over natural grass fields [6,7]. The issue with these findings is that it is challenging to draw inferences between studies that have measured ambient temperatures at different heights due to the large temperature fluctuations. Further, this issue raises interesting questions; (i) what height accurately describes the surrounding environment? and (ii) what change in ambient temperature can elicit physiological changes? Some studies have suggested that the measurement should be taken at a height that represents the mid-point of the person of interest, suggesting different measurement heights might be considered for adult vs. youth populations [17].

Although studies have also measured other environmental parameters (e.g. relative humidity, solar radiation and wind velocity), only one study monitored all four environmental parameters that govern human heat exchange (i.e. ambient temperature, humidity, mean radiant temperature and wind velocity) [18]. This study reported higher air (>0.5°C) and mean radiant temperatures (0.8–3.8°C) over a synthetic grass surface compared to a natural grass field [18], providing evidence that synthetic grass surfaces can affect parameters essential for human heat exchange. However, further research is required in different locations and climates to better understand the influence synthetic grass surfaces have on these environmental parameters. It is important to note that when the four environmental parameters essential for heat exchange are measured and considered together, researchers can predict the heat transfer rate in an environment and make calculations on the heat stress risk [13,26]. This further highlights the need for more research in this area. To date, only one study has investigated the body temperature and thermoregulatory responses to exercising on a synthetic sports surface compared to a natural grass surface, which was performed in only moderate-warm conditions, and no significant differences between the surfaces were observed [27]. Indeed, this study needs to be replicated in hotter conditions.

An important limitation of the available research on environmental measurements on synthetic grass sports surfaces is the sample size of the studies (i.e. the number of surfaces studied). When measurements were taken on full-size synthetic field ‘sites’, the majority of studies only investigated a single synthetic field site, with 3 studies investigating two synthetic field sites (see Table 1). Only one study included more than two sites [19]. It is generally accepted that for environmental observational research, a minimum of three sites are required to conduct any statistical analysis and make inferences beyond the sites studied. Yet, some studies that investigated one or two sites performed such analyses anyway. Other studies obtained their measurements on small ‘plots’ (i.e. ~1-2 m^2) that were laid outdoors next to each other at the same location. However, this research is limited to only measures of surface temperature, as the small plots are not big enough to create a realistic microclimate above the surface, and different plots laid in close proximity could impact the microclimate above adjacent plots. Therefore, the more important environmental parameters that influence heat gain such as ambient temperature, mean radiant temperature, humidity and wind velocity cannot be investigated appropriately above these plots. It is also important to consider that the available research covers many different types of synthetic surfaces, with a lack of research on more current types, and more research on dated types which are no longer used for sport (see Table 1). Hence, the available literature cannot even be pooled into a meta-analysis to increase the sample size and create more robust data and outcomes.

Another limitation of the current body of research involves the sampling intervals used to collect the environmental measures, and how these data were reported. Environmental measurements have been collected from anywhere between 15-minute to one-hour intervals, and these data were reported as either a median [14], mean [2,3,8,9,15,19], or a minimum and maximum value [2,4–8,10,23]. Unfortunately, if a study has only collected surface temperatures at 1-hour intervals and only reports a maximum temperature, it is unclear how long the temperature was present, and the subsequent impact it may have had. It can be assumed that the longer a synthetic grass surface remains significantly hotter, the greater its capacity to affect the surrounding environment and impact a person. Therefore, it is difficult to contextualise the results from studies of synthetic grass surfaces without comprehensive time-course data reported in full.

Future Research Directions

While studies have investigated the influence of synthetic grass surfaces on various environmental parameters, it has not been done comprehensively; therefore, it is still unclear whether these surfaces can affect the environment enough to increase the risk of heat stress. Further, environmental measurements can only be used to make predictions, and therefore data is needed on humans exercising on synthetic surfaces to ultimately determine the effects. Accordingly, after recognising the limitations of the research that currently exists (i.e. those studies summarised in Table 1), we propose the following future research directions;

- Include the key measurements of ambient temperature, mean radiant temperature, absolute humidity and wind velocity on synthetic grass surfaces in a range of environmental conditions and geographical locations. These environmental parameters can then be used to predict the rate of heat exchange to determine if synthetic grass surfaces can theoretically affect heat gain under scenarios.
- Determine if different synthetic grass surface variations have similar effects on the surrounding environment. Recently, there have been advancements to synthetic grass surface technology, including different infill materials and the introduction of Coolplus Technology® fibres, which contain specialised pigments that reflect more light into the environment, thus, reducing surface temperatures up to 5.9°C compared to a synthetic grass surface without Coolplus fibres [9]. This raises an interesting question; does the increased solar reflectance elevate the radiant heat load around the surface, and does this increase heat gain by radiation?
- Investigate whether synthetic grass surfaces affect markers of heat stress and thermoregulation in humans. Currently, there are no published studies measuring markers of heat stress and thermoregulation (i.e. core body

temperature, skin temperature, heart rate and sweat rate) in humans exercising on synthetic grass surfaces under hot environmental conditions. Such studies would be the best evidence to ultimately determine if synthetic grass surfaces elicit physiological changes and increase the likelihood of heat stress and the risk of hyperthermia (performance outcomes may also be of interest to athletes). Notably, these studies should be performed in a range of environmental conditions to identify different environmental conditions that might be dangerous and the *worst-case scenario* for exercising individuals or athletes competing in sport. Importantly, hot ambient temperatures (i.e. >30°C) are not the only conditions that might be dangerous, as clear sky conditions can increase heat gain by radiation, and low wind and high humidity can reduce heat loss by evaporation and convection.

- These findings should then be applied to current heat policies used for sports to identify whether modifications are required for synthetic grass surfaces. There are no specific heat guidelines for when sport is played on synthetic grass surfaces to date. Consequently, if there is a risk of increased heat stress on synthetic surfaces, adjustments in heat policy are needed to translate the research into practice.

Practical Applications

The ability to measure the ambient temperature, absolute humidity, solar radiation (mean radiant temperature) and wind velocity is important when considering the risk of heat stress [11,13]. Facility managers understand and measure the ambient temperature without considering all four environmental parameters that determine the rate of heat transfer [13]. The ambient temperature, humidity and wind velocity are usually acquired from publicly available weather stations (i.e. bureau of meteorology), however, local weather stations can underestimate the environmental conditions present at a venue [16] and cannot capture any differences in microclimate above different sports surfaces. This is concerning given that synthetic grass surfaces can affect the surrounding environment, and as such, on-site weather stations are recommended to capture the site-specific microclimate information. Thermal radiation is another parameter often neglected or estimated using theoretical equations (i.e. wet-bulb-globe temperature) [13]. However, thermal radiation needs to be measured with a 150 mm black globe to provide valid data [11,13]. Facility managers or councils may use cost-effective wet-bulb-globe thermometers, but it should be noted that if these devices do not have a 150 mm black globe, the reading should be interpreted with caution. Collectively, the ability to monitor these environmental parameters will allow facility managers to determine when there is an increased risk of heat stress and to implement any changes (i.e. increased water breaks) according to heat policy.

Table 1

Summary of Studies Investigating Environmental Measurements on Synthetic Grass Sports Surfaces

Author	Sample size and surface types	Measurements
Bozdogan Sert et al. [4]	1 x Synthetic grass field: Not specified 1 x Natural grass field: Not specified	Surface temperature
Carvalho et al. [5]	1 x Synthetic grass field: Not specified 1 x Natural grass: Augustine grass	Surface temperature, spectral irradiance, albedo, net radiation soil, and heat refluxes
Grundstein & Cooper [14]	1 x Third-gen synthetic grass field 1 x Natural grass and hard-court tennis (Plexipave)	WBGT, dew point, SR, WS
Hardin & Vanos [15]	1 x Third-gen synthetic grass field 1 x Natural grass field: Dry and wet Bermudagrass	Ta, WS, SR
Jim [6]	1 x Third-gen synthetic grass field 1 x Natural grass: Cynodon Dactylon (Bermudagrass)	Surface temperature, Ta, RH, SR, WS
Jim [7]	1 x Third-gen synthetic grass field 1 x Natural grass: Cynodon Dactylon (Bermudagrass)	Surface temperature, Ta, RH, SR, WS
Kandelin et al. [2]	1 x Synthetic grass field: Tartan turf 1 x Natural grass field: Bermudagrass	Surface temperature, Td, SR, WS and RH
Petrass et al. [9]	*Location 1(regional)* 1 x Third-gen synthetic grass field 1 x Natural grass field: Rye grass irrigated 30 min 3-4 days per week. *Location 2 (metropolitan)* 1 x Synthetic grass field (cool climate) 1 x Natural grass field: 50% Poa and Rye and 50% kikuyu irrigated weekly	Surface temperature Ta, RH, Tw and WS
Liu & Jim [8]	1 x Third-gen synthetic grass field 1 x Natural grass field: Bermudagrass	Surface temperature, Ta, RH, Tw, Tg, shortwave radiation downward, shortwave radiation upward, long wave radiation upward, longwave radiation downward and longwave radiation upward.

Table 1
Continued

Author	Sample size and surface types	Measurements
Loveday et al. [24]	1 x Synthetic grass plot: Tuff turf multi, 12 mm pile. 1 x Natural grass plot: Penniesetum clandestinum (kikuyu). Plot sizes 1200 mm x 1200 mm.	Apparent temperature
Loveday et al. [23]	1 x Synthetic grass plot: Tuff turf multi, 12 mm pile. 1 x Natural grass plot: Penniesetum clandestinum (kikuyu). Plot sizes 1200 mm x 1200 mm	Albedo
McNitt et al. [21]	10 x Synthetic grass plots: Astroplay (infill depth 40), Astroturf (0mm), Experimental (35mm), Fieldturf (43), Geoturf (33 mm), Nexturf (22 mm), Omnigrass 41 (39 mm), Omnigrass 51 (49mm), Sofsport (33mm), Sprinturf (22mm)	Surface temperature and Ta, water irrigation
Petrass et al. [22]	34 x Synthetic grass plots (details N/A)	Surface temperature, Ta and RH
Pryor et al. [16]	1 x Synthetic grass field: Nylon knit artificial green turf (AstroTurf), 1 x Third-gen synthetic grass field 1 x Natural grass field: Not specified	WBGT
Ramsey [17]	1 x Synthetic grass field: Astroturf 1 x Natural grass field: Bermudagrass	Td, Tw, Tg, WBGT and WS
Shi & Jim [18]	1 x Third-gen synthetic grass field 1 x Natural grass field: Bermudagrass	Surface temperature, Ta, RH, WS, SR, thermal radiation, reflected, ground thermal radiation, mean radiant temperature

Table 1
Continued

Author	Sample size and surface types	Measurements
Thoms et al. [20]	10 x Synthetic grass plots: Monofilament, pile height 5.1cm, polyethylene and nylon Monofilament, pile height 3.2 cm nylon Monofilament, pile height 5.1 cm polyethylene and nylon Monofilament, pile height 5.7 cm polyethylene Monofilament. pile height 5.1 cm exp polyethylene and nylon Slit film, pile height 5.7 cm polyethylene Monofilament, pile height 5.7 cm exp polyethylene Monofilament, pile height 5.7 polyethylene Monofilament pile height 5.7 cm polyethylene Monofilament/slit film. Pile height 5.1 cm exp polyethylene and nylon Slit film, pile height 5.1 cm exp polyethylene and nylon	Surface temperature
Twomey et al. [3]	1 x Third-gen synthetic grass field 1 x Artificial street soccer field 1 x Natural grass field: Rye grass	Surface temperature
Villacañas et al. [19]	14 x Third-gen synthetic grass fields with synthetic grass plot variations with different infills (SBR & TPE), grass blades (mono filament & fibrillated), age (< 5 years & > 5 years) and usage (< 35 hrs/week & > 35 hrs/week)	Surface temperature
Xia & Cao [10]	N/A	Surface temperature, Ta and RH

Note. Ta (ambient temperature), N/A (not available), Td (dry bulb temperature), Tg (globe temperature), Tw (wet bulb temperature), SR (solar radiation), WS (wind speed) and WBGT (wet-bulb-globe temperature).

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Appendix 10

Use of Synthetic Turf in Bushfire Prone Areas

Use of Synthetic Turf in Bushfire Prone Areas

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1. Introduction

Over recent years, synthetic turf has attracted much interest as a replacement for natural grass on athletic fields and lawns. Much of the uptake has been realised in residential and commercial landscaping settings, particularly in backyards and playgrounds, with the perception that synthetic turf will have lower maintenance requirements, and possibly lower usage of water, than natural turf [1,2]. Nevertheless, regular maintenance and servicing of the turf are still required.

This report has been commissioned to provide on the flammability of materials used in synthetic turf, bushfire and other fire-related hazards and alternate materials.

Synthetic turf is easily flammable and poses a fire risk, based on an experimental study performed according to EN 13501 – 1:2010 Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests [3]. In bushfire-prone areas, the nature of vegetation surrounding houses and buildings strongly influences the degree of bushfire damage/loss to which a building is exposed. The presence of flammable vegetation and combustible materials in close proximity to a house or building is a key factor that increases house/building ignition risk, whereas risk is reduced by vegetation and materials which are not conducive to being ignited by airborne embers or when exposed to high radiant heat levels. Synthetic turf that is commonly made from polymeric materials may be subjected to an approaching bushfire via three forms of attack: *radiant attack*, *ember attack* and *direct flame contact*. Because of the low melting point of these materials, they can be easily ignited by all forms of attack [3].

Amongst the many layers of synthetic turf, the infill material poses the highest fire risk since it is typically derived from scrap tyres. Tyre rubber crumb contains a range of organic contaminants and heavy metals that can be emitted into the air and/or leached into the percolating rainwater [1]. As the material burns, the toxicity and its associated negative environmental impact have been found to be more severe at elevated temperatures during a bushfire. In bushfire conditions, the concentration of volatile and semi-volatile organic compounds emitted in the air above artificial turf fields and the concentration of heavy metals and organic contaminants in the field drainages would be very concerning.

Because of the negative impact on the environment, the European Chemical Agency (ECHA) Committee for Risk Assessment has recommended that the use of rubber granules for infill materials in synthetic turf be prohibited in the European Union and East Economic Area [4]. This was part of a decision on using intentionally-added microplastics' in products in concentrations of more than 0.01 % weight by weight, including granular material from end of life tyres. Councils and regions have banned the use of rubber infill for synthetic turf within the USA, including Westport Connecticut and San Francisco California.

Improvement in the design and manufacture of synthetic turf has been made to address these concerns, via the development of green and thermally stable, flame retardant material. For example, the hybrid use of natural and synthetic turf or the implementation of alternative natural infills such as corks and materials such as ethylene propylene diene monomer (EPDM), thermoplastic elastomer (TPE) [5]. However, the cost of this hybrid material remains expensive, and such infill material generally requires additional backing (e.g. nonwoven textile and either latex or polyurethane) beneath to absorb the shock [6]. This material would also pose a fire risk. The addition of organic-based alternative material is also more vulnerable to weed growth than the polymer-based counterpart [7].

In light of the abovementioned knowledge gap and requirements for the research and industrial communities, this report aims to:

1) Identify potential fire risks to the impact of bushfire on synthetic turf;
2) Evaluate the current designs/configurations of synthetic turf;
3) Review current flame retardant solutions in synthetic turf applications; and
4) Propose potential flame retardant solutions to mitigate the flammability and other solutions of environmental impacts on synthetic turf.

2. Background

Synthetic turf, initially termed as Chemgrass, was developed and first installed in 1964 at Moses Brown School in Providence, Rhode Island, USA. This was followed by a larger installation at Houston Astrodome, from which it derived its colloquial label "Astroturf". Over the past 50 years, synthetic turf has undergone three main generations of product development [7,8]:

- The *first generation* was made of short, 10-12 mm, high-density nylon yarn. Unless it is thoroughly wetted, it can cause severe friction burns on exposed skin in situations where a person fell and slid on the dry synthetic grass.
- The *second generation* synthetic turf products were principally made of polypropylene and were designed with a longer blade length, 20-35 mm, and comprised a lower density of blades. To provide the required support and stability, rounded sand was utilised as an infill.
- The *third generation* of synthetic turf has been in use since the late 1990s, and the generation of synthetic turf products is commonly used today. It is made of softer polyethylene fibre, with a longer blade design than previous versions, of around 40-65 mm. Rubber or plastic granules are often utilised as infill to give the rigidity and support required for the turf. Many of these synthetic turf products feature synthetic "thatch" between the taller synthetic grass blades, giving a less uniform appearance better imitating the variability of colour found in natural lawn systems.

Synthetic turf is manufactured using methods that are similar to those used in carpet making. It has a backing material that holds the plastic blades of the synthetic grass, and an infill that maintains the turf structure. The backing material is typically a combination of polypropylene, polyethylene or nylon, and will be coated in latex or other adhesive to hold the materials together. The plastic blades are usually polyethylene (in *third generation* products) and the infill material varies, depending on whether the turf is for commercial or private use; silica sand combined with rubber, cork or envirofill is utilised. The rubber infill is often applied in commercial and/or sporting field use, and is made of old tyres, crushed down to create the supportive particles.

As described by the different compositions, the synthetic turf comprises a mixture of combustible polymers; when exposed to an ignition source, they can be predisposed to melting and ignition. The flammability of polymers varies greatly between the different types of polymers and the additives used. Typically, the polymers used in synthetic turf have relatively low melting points, e.g. $\sim 100℃$ to $170℃$ [7,9,10]. Further heating degrades the polymers; hydrocarbon vapours are subsequently generated with ignitions occurring from its flashpoint of around $330℃$, which is comparable to that of dead, dry grass. Glowing embers commonly blown in front of an advancing bushfire have a temperature of around $700-800℃$, and the flame of a burning leaf has an even higher temperature, e.g. above $1000℃$. The polymers used in synthetic turf can thus be ignited in a bushfire scenario.

All polyethylene and polypropylene turf products that were subjected to a heat radiation flux gradient test have been found to melt and subsequently ignite and burn at the critical heat flux (CHF) below $3\ kW/m^2$. This is significantly lower than the radiation intensity applied in any bushfire rating standard ($25-40kW/m^2$), and they are classified to be easily flammable (flammability class E_{fl}) [3,7]. For infill material, the cone calorimetry testing (explained in section 3) demonstrated that all infill materials ignited and burnt. Furthermore, the peak heat release rate of samples using rubber infill (Styrene-Butadiene Rubber (SBR) in Figure 1) provides a peak heat release rate above $200\ kW/m^2$, which is doubled compared to the threshold recorded by cork, EPDM and TPE. Depending on the composition of materials, different synthetic turf products have different propensity for ignition by embers and radiant heat and the potential for sustained fire spreading across the laid synthetic turf product. These materials may cause health risks due to the potential release of toxic gases like dioxin, furans and other noxious emissions product during the combustion process [9]. The release of those toxic gases can pose significant threat to the safety and health of not only the first responders such as fire fighters but also to the resident and communities in bushfire prone areas.

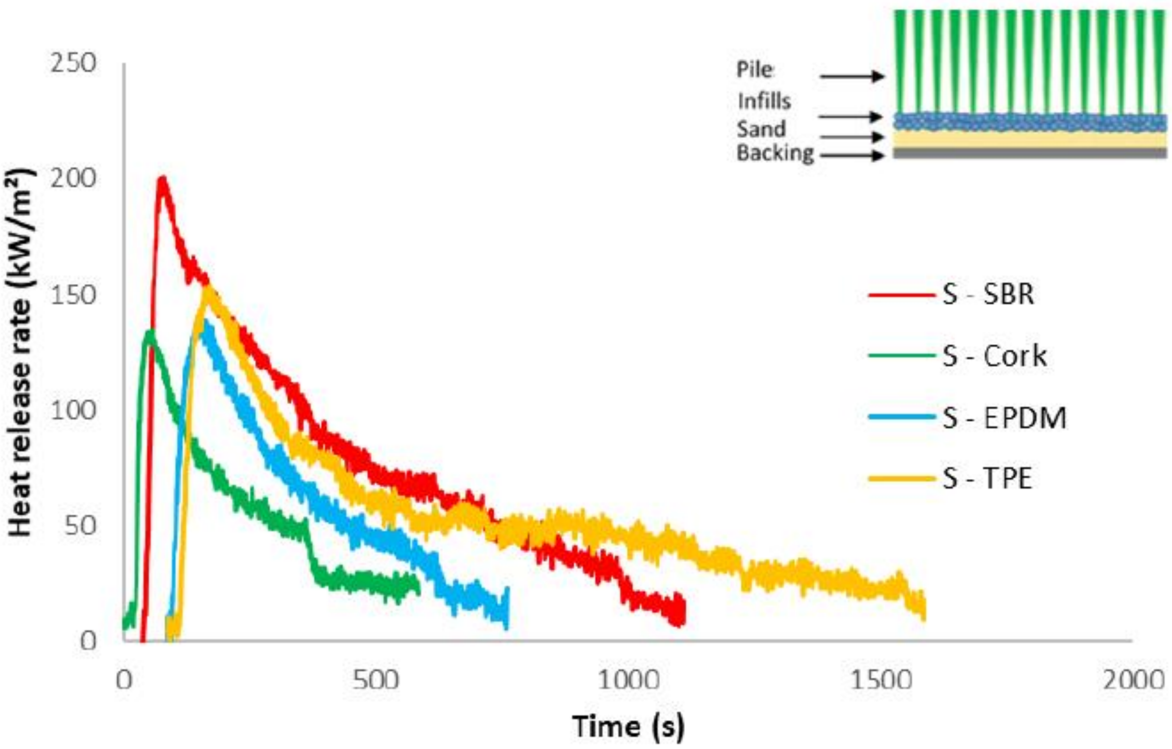

Figure 1. Heat release rates of different infill materials [8].

Bushfires cause damage to people and property in many ways: *through direct flame attack, ember attack, radiant heat, smoke and the strong, erratic winds induced by the fire propagation* [11]. Most people expect the direct flame attack to be the most significant risk to homes in a bushfire. However, this is generally not the case, except perhaps for houses built in bushland or peri-urban boundaries. In fact, most house loss due to bushfire (up to 90 per cent) occurs due to ember attack; the burning twigs, bark fragments, moss, or leaves become temporarily airborne and are carried by winds in a cluster kilometres away from the main fire front. They find weaknesses in houses, such as gaps, cracks and combustible construction materials and can quickly lead to an unstoppable house fire unless there is human intervention or engineered control solutions.

There are residential building standards for bushfire protection, which aim to improve the ability of buildings to withstand a bushfire attack. For example, the bushfire attack level (BAL) is commonly used to determine the type of construction required to acquire a building permit in a bushfire-prone region. The following figure outlines the BAL rating required for building subject to various forms of bushfire attack and the associated radiant heat exposure specified in AS3959.

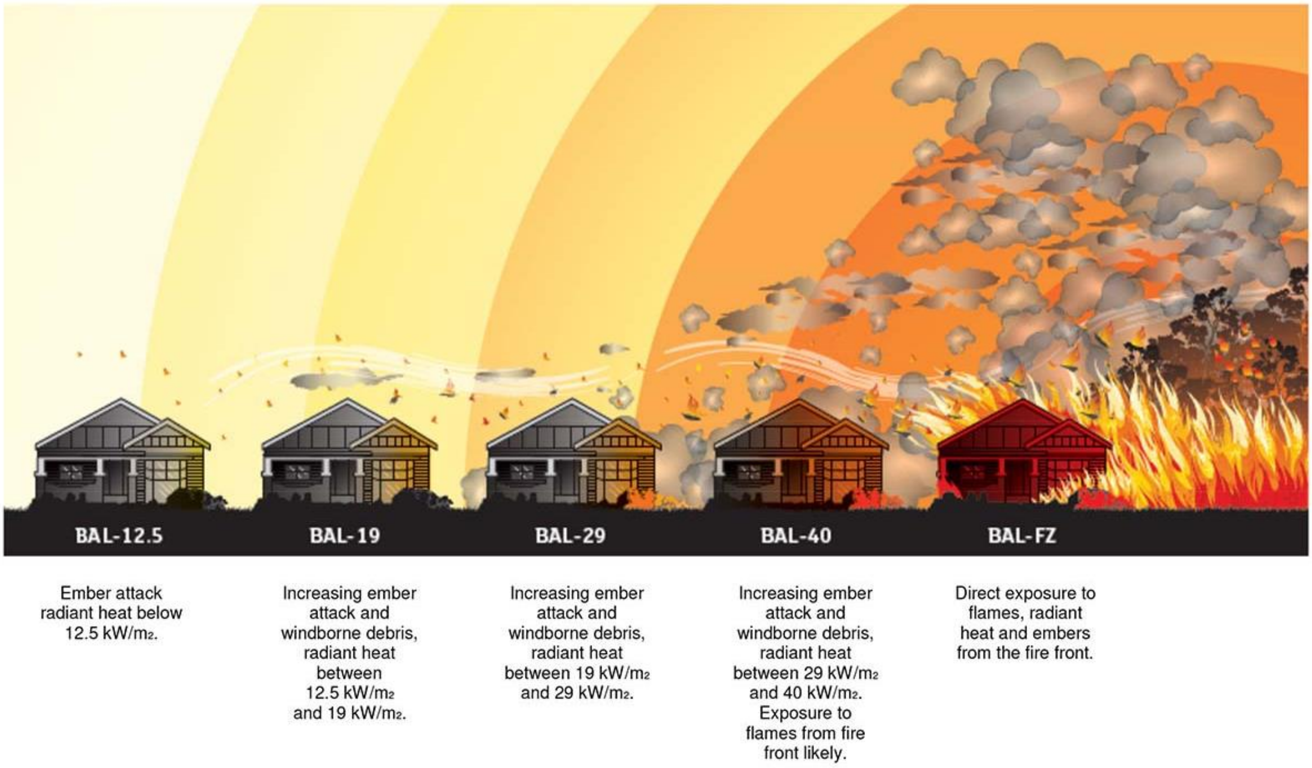

Figure 2. Bushfire Attack Level ratings refer to the fire intensity the house is likely to be subjected to in a bushfire, expressed in terms of radiant heat [12].

BAL defines the expected radiant heat exposure using heat flux in kW/m^2.The ARC Training Centre for Fire Retardant Materials and Safety Technologies has conducted experimental work to assess the equipment temperature that matches with the BAL ratings, i.e., a heat flux meter and a thermocouple positioned at the vicinity (with the same separation distance) of a heating element. The heating element was activated with a constant heating rate from room temperature up to ~1200℃, and the temperature of the monitoring point and the matching heat flux reading were measured and recorded. The result indicates that temperature at a direct exposure and ember attack zone could be ~1000℃ and 600℃-800℃, respectively. The in-house temperature measurement is supported by a CSRIO published work, as shown in the following Figure 3 [13].

At such elevated temperature conditions, the polymer-based materials used in various functional layers of the synthetic turf, e.g., Polypropylene, Polyethylene, Styrene-Butadiene Rubber are likely to undergo a series of physical and chemical processes, such as phase change, thermal degradation, the release of toxic gas and flammable volatile, ignition, and combustion etc.

In addition, wind can influence a bushfire in several ways. Wind governs the direction of fire propagation and can push flames onto new fuel sources (vegetation), increasing the fire size, speed and intensity. Wind also transports embers which can create new fire fronts. Both experimental and numerical studies on bushfires have demonstrated the complex correlation between bushfire burning and spreading behaviour and factors such as weather, vegetation and topography [14–16].

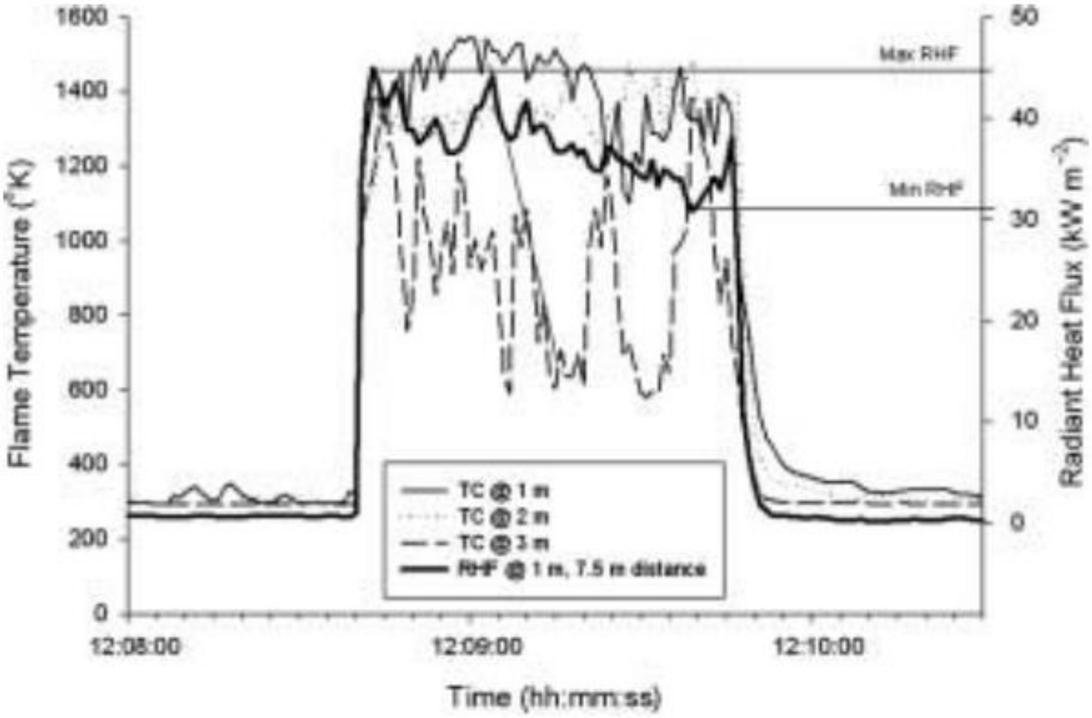

Figure 3. A graph showing the temperatures recorded by three thermo- couples and the radiant heat flux recorded by a radiometer during an experiment using the propane-fuelled bushfire flame front simulator [13].

3. Methods to test flammability, burning behaviour and weathering resistance of synthetic turf

As illustrated in the expanded view of Figure 4, the main layers of synthetic turf, particularly for sports applications, include: (a) backing, (b) sand, (c) infill and (d) pile. It is made of a complex material composed of synthetic fibres (usually made of polyethylene (PE) or polypropylene (PP)) inserted into a backing, usually in PP through a tufting process. A back coating is spread and then cured to bind the fibres to the backing. For sports applications, sand and a damping infill material are added respectively to stabilise the structure, act as a shock absorption system, and avoid player injuries. Note that other types of synthetic turf differ predominantly in the pile configuration of either having shorter or longer grass blades depending on specific applications. Nonetheless, the materials that are used to fabricate the synthetic turf system remain the same.

It should be noted that the main focus of discussion in this section is on the composite structure of synthetic turf in sporting fields that sits above the shock pad. This is because other functional layers of a synthetic system, such as blinding stone, base stone and levelled ground (or the pitch foundation), may not be as relevant to fire compared to the upper layer composite.

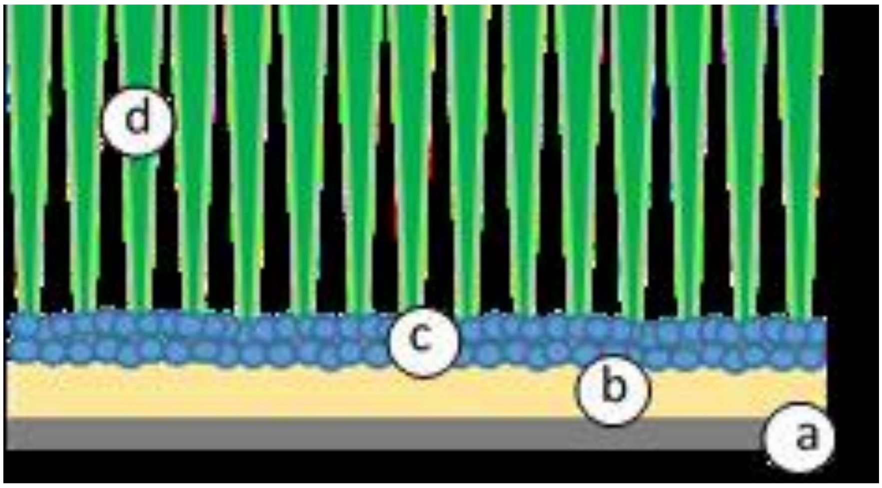

Figure 4. Different layers of synthetic turf for sports applications [8].

The principal components of installed synthetic turf products relevant to this report are:

- Synthetic grass blades, which can be fabricated from:
    - Polyethylene group polymers
    - Polypropylene group polymers
    - Nylon group polymers
- Infill material, which can be made of:
    - Polypropylene and/or Polyethylene group polymers
    - Rubber crumb (principally vulcanised tyre rubber)
    - Silica sand (non-combustible)
- Backing material
    - Typically polypropylene and/or latex rubber
- Adhesive (typically all-weather solvent-based adhesive contains a blend of polymers, solvents and additives)

Except for silica sand infill components used in some products, all other synthetic turf components being polymer-based components, are combustible.

Testing methods

There are typically two streams of testing methods for assessing the flammability, burning behaviour, and weathering resistance of synthetic turf – research-orientated and industrial-oriented test approaches. The following sections explain the methods used in each setting.

3.1.1.For research and development

Fire testing: mass loss cone calorimetry

The burning behaviour of the synthetic turf has been commonly evaluated through the cone calorimetry test. Cone calorimetry is one of the most effective medium-sized polymer fire behaviour tests. The principle of cone calorimetry is based on the measurement of the decreasing oxygen concentration in the combustion gases of a sample subjected to a given heat flux (generally from 10 to 100 kW/m^2). Figure 5 illustrates the experimental setup of a cone calorimeter. Cone calorimeter is a device used for predicting real-time fire behaviour and is able to determine parameters such as ignition time, heat release rate, mass loss, and other properties relevant to fire characteristics.

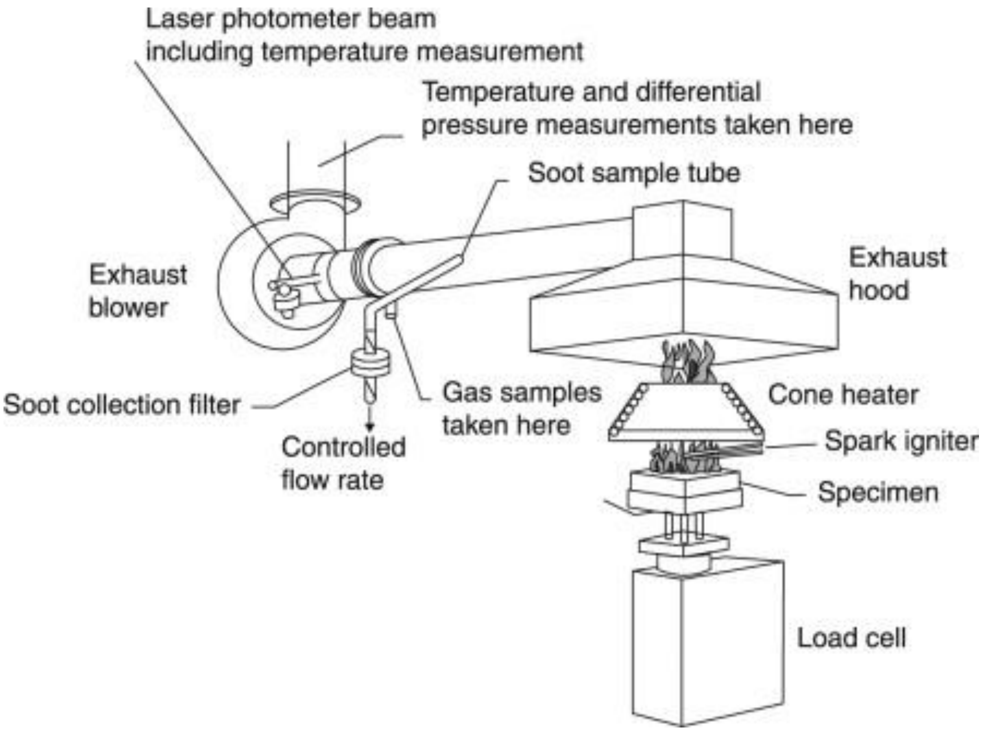

Figure 5. Cone calorimeter schema [17].

A typical set of test configurations for synthetic turf cone calorimetry test is suggested by Paturel [8]:

- Heat flux: $25kW/m^2$
- Separation distance: 35 mm
- Spark ignitor: yes

Thermal stability: benchtop furnace

The thermal stability of the functional layers of synthetic turf can be assessed by heating them in a bench top furnace from room temperature to a set elevated temperature. The elevated temperature is usually set based on the material thermal stability and ensures the functional layer materials are fully degraded. These tests aim to assess material degradation at high temperatures and determine the percentage of residual mass to evaluate its thermal stability in a simple and rapid way.

Thermal stability: thermogravimetric analysis

Thermogravimetric analyses (TGA) should be carried out to study the thermal decomposition of the functional layer material by determining the weight loss versus temperature. Because of their small size and in order to obtain representative results, the granules of samples, e.g., about 10 mg, could be directly deposited in an open alumina crucible equipped with a gold foil.

The main parameters considered to have information on the thermal stability of the samples are: the temperature at the onset and at the maximum of the degradation, the final residual mass at 800°C and the mass loss rate at specific temperatures.

Water resistance: evaluation of leaching in water

The behaviour of functional layer materials leaching into water is essential to assess if toxic elements could be released into the soil or water system over time. Preliminary lab-scale evaluation could be performed using the immersion method, which immerses functional material in Deionized (DI) water under magnetic stirring at a standard temperature and pressure (STP)_for five days. The pH value of the solution could be measured three times a day at regular intervals, indicating the level of soluble products' extraction by a solvent after the leaching process.

Water resistance: dynamic vapour absorption

It is also common to determine the interactions of vapours with solids using a gravimetric technique such as Dynamic Vapour Sorption (DVS), where a gravimetric vapour sorption analyser could be used to measure the vapour sorption of the functional layer materials. A small amount of sample, i.e., 5 mg, could be placed into a chamber with controlled temperature and relative humidity. The weight gain of the sample subject to the change of relative humidity varying between 0% and 95% could be constantly monitored to evaluate the performance of the material under the sorption-desorption cycle.

3.1.2.For industrial applications

Presently, there is no common international standard for ignition or fire testing of outdoor applications of synthetic turf [7]. Most synthetic turf manufacturers may undertake fire or burning testing, typically using testing methodologies designed for indoor floor coverings, e.g., AS/ISO 9239-1. (*AS/ISO 9239-1 Reaction to fire tests for floorings — Part 1: Determination of the burning behaviour using a radiant heat source*).

AS/ISO 9239-1 specifies a method for assessing the wind-induced burning behaviour and spread of flame of horizontally mounted floorings exposed to a heat flux radiant gradient in a test chamber when ignited with pilot flames.

This method is applicable to all types of flooring, e.g. textile carpet, cork, wood, rubber and plastics coverings, and coatings. This method's results reflect the flooring's performance, including any substrate if used. Modifications of the backing, bonding to a substrate, underlay, or other changes to the flooring may affect test results.

The implications arising from the lack of uniform industry testing standards is discussed further in section 4.2.

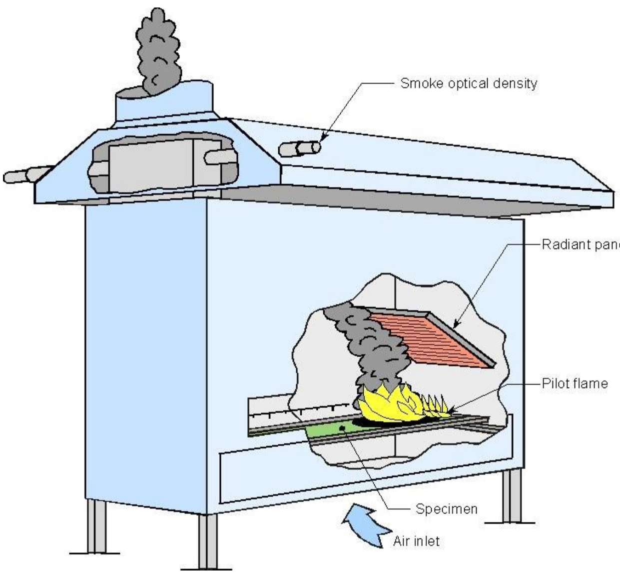

Figure 6. Test equipment for flooring materials according to standard AS/ISO 9239-1 [18].

4. Issues on the use of synthetic turf in bushfire prone areas

On reviewing several journal papers, publicly available industrial reports, and experience gained through numerous testings of polymer-based materials at the ARC Training Centre for Fire Retardant Materials and Safety Technologies, we categorised four challenges for using synthetic turf in bushfire prone areas. These challenges pertained to (a) the material thermal properties and combustion characteristics, (b) toxicology, (c) the durability aspects when the synthetic turf is exposed to elevated temperatures in outdoor environments, and (d) cost analysis. The information is detailed in Table 1 below.

Table 1. Summary of challenges for synthetic turf implementation in bushfire prone areas [7].

Example Material	Thermal/Combustibility properties		Toxicity	Stability	Cost
	Melting point (°C)	Ignition temperature (°C)			
Nylon	160-275	424-575	Carbon monoxide and dioxide Smoke (Particulates) May be more prone to high extractable lead concentrations	Attackts water	Expensive
Polyethlyene	107-140	330-410	Carbon monoxide and dioxide Smoke (Particulates)	UV stable Unable to absorb moisture	Cost may vary
Polypropylene	150-168	>357	Carbon monoxide and dioxide Smoke (Particulates)	Doesn't maintain colour well Prone to UV breakdown	Inexpensive
Rubber	The melting point of crumb rubber is typically not reported	260-316	Carbon monoxide and dioxide Sulfur dioxide Zinc oxide Smoke (Particulates) other ingredients in tyres including: benzene, mercury, styene butadiene, polycyclic aromatic hydrocarbons and arsenic, among several other chemicals, heavy metals and carcinogens.	Unknown	From recycled materials

Low Melting and Ignition Temperatures

The melting and ignition temperatures of polymer-based materials used in the synthetic turf are generally relatively low when compared to the temperature of direct flame attack (above 1000℃) and glowing ember (around 700℃), which can be experienced in bushfire conditions. These elevated temperatures will invariably promote the breakdown of the materials; combustible volatiles will be emitted during the thermal degradation (or pyrolysis) process. As the volatiles react with the surrounding air, they are ignited when the volatile concentration reaches the ignition threshold – above the ignition temperature – and combustion thereafter occurs. It should be noted that TGA testing (described at s3.2.1 above) performed on flame-resistant cork material, being hemicellulose and cellulose in nature, will still degrade, albeit at high temperature ranges of 220-315℃ and 315-400℃, respectively [8].

Toxicity

Combustion products generated during the burning of polymer-based materials used in synthetic turf can be considered toxic. As indicated in Table 1 above, substances include smoke (soot particulates), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), zinc oxide (ZnO), benzene, mercury, styrene butadiene, polycyclic aromatic hydrocarbons (PAH), and arsenic to heavy metals are by-products of the combustion process.

Polymer-based materials, which are derived from petroleum hydrocarbons, yield CO and CO2 predominantly during the combustion process. Other substances highlighted above are due to the additives that are added during the manufacturing of synthetic turf. Assessment and understanding of the toxicity of the synthetic turf subject to fire and the concentrations of toxic release will be essential for the planning of evacuation strategy for the occupants, as well as the selection of adequate PPEs for first responders.

Stability

Synthetic turf installed in outdoor settings over its service life is subjected to various weathering conditions, such as ultraviolet (UV) exposure, alternating extremes of high and low temperatures (thermal-cycling), moisture impact, acidic rain, wind, etc. It is commonly known that weathering will accelerate the aging process of polymer-based materials and alter their physical/chemical properties, making them less fit-for-purpose for the intended application. For example, after exposure to UV and thermal-cycling, pitch materials tend to be less mechanically strong, stiffer, more brittle, and experience a colour change. Infill materials are more likely to be defragmented after weathering and water attack, increasing the possibility of the fragments being washed away, leached or hydrolysed by water. It has been reported that the lifespan of polymer-based materials decreases by 40% when the temperature range is between $30℃$ and $40℃$ when compared to the ambient temperature of $25℃$ [19]. Such extreme weathering conditions could trigger the combined effect of synthetic turf's photo-, thermal-, and chem-degradation. It should be noted that weathering tests carried out in the ARC Training Centre for Fire Retardant Materials and Safety Technologies have revealed that polymer-based materials tend to have a lower degree of polyamidation/crosslink; hence these materials could become more reactive in a bushfire setting, i.e. more flammable, due to prevalence of more monomer chemical structures [20].

Cost

As demonstrated in Figure 1, alternative infill material could significantly reduce the flammability of the synthetic turf – by up to 60% reduction in the heat release rate. However, the cost involved in manufacturing and maintaining these alternative materials remains high compared to the commonly used SBR, which is an infill derived from scrap vehicle tyres. For example, the cost of EPDM, EPDM (flame retardant), TPE and cork per field is around an extra $60000, $70000, $70000 and $40000 Euro compared to SBR, respectively [8].

4.1. Lack of Testing Standards

The proper assessment of the burning behaviour of synthetic turf for outdoor application remains absent, and as noted previously, there are currently no common fire testing standards in Australia or internationally [7].

Some synthetic turf manufacturers have undertaken fire testings by simply applying a blow torch to ignite the pile of a small sample of the synthetic turf and adopting methodologies that are mainly designed for indoor floor coverings such as broadloom carpets, carpet tiles and other internal flooring products. Such fire testings do not address the flammability for bushfire conditions (ember and radiant attack) or the effect of flame spreading over a large field covered with synthetic turf that would ideally be tested in a fit-for-purpose outdoor environment [21].

In Australia, flammability and flame resistance testing for indoor floor covering is undertaken using two testing methods: AS/NZS2111.18:1997 and AS/ISO 9239-1:2003. However, these tests are not fit-for-purpose, as they are carried out in the absence of any wind impact and the floor covering is only exposed to a radiative intensity of $11\ kW/m^2$ compared to $12.5 - 40\ kW/m^2$ typically encountered in bushfire conditions [22]. In attempting to pass and certify the synthetic turf for the above standards, great care must be exercised, and questions must be raised on how the synthetic turf can survive in a realistic bushfire scenario in an outdoor setting, as these standards do not address the fire severity that the synthetic turf would likely to be experienced in a bushfire condition.

4.2. Current Flame Retardant Strategies

One common strategy to improve the flammability resistance of polymer-based materials involves the modification of the matrix via the inclusion of micro-sized fire retardant fillers [23]. In general, many fillers are utilised in combination with other flame retardants to achieve a high level of flammability resistance. Intumescent coatings are comprised of various synergetic active ingredients that will react to heat by swelling in a controlled manner to many times its original thickness [24]. They will produce a carbonaceous char formed by a large number of small bubbles that will act as an insulating layer to protect the substrate, thus retarding heat transfer and improving the fire performance without adversely affecting their mechanical properties.

However, factors such as UV exposure, operational temperature, and the humidity of the environment can affect the fire performance of intumescent coatings. A well-known problem in the deployment of such coatings is that the active ingredients have the propensity to leach out over prolonged periods when exposed to outdoor environmental conditions [25,26]. Once leaching has occurred, the delay of time to ignition is significantly reduced from the initial rating period and may cause health and safety hazards.

Therefore, there is still a great need to utilise non-toxic and durable flame retardants that will be able to fulfil the stability of flame retarded polymer-based materials for outdoor applications. This is particularly the case in Australia given UV exposure, temperature and humidity conditions.

5. Potential Solutions

5.1 Targeted functional layer

Figure 7 depicts the measured heat release rates of (a) backing alone, (b) backing + pile and (c) backing + pile + sand using the cone calorimetry test. It can be seen that the backing + pile + sand revealed the lowest flammability with a peak heat release rate of $\sim 50kW/m^2$. While the pile burnt away, the sand (silica), being an inert material, shielded the backing from burning. Nonetheless, the backing alone and backing + pile, being polymer-based materials, gave peak heat release rates between $225\ kW/m^2$ and $275\ kW/m^2$. From a fire safety point of view, it can be seen that the presence of sand represents an important ingredient in the synthetic turf system.

With reference to Figure 4, the infill that sits above the sand is identified as the targeted functional layer for fire performance improvement. In Figure 1, other alternative materials such as EPDM, TPE or cork in place of SBR have shown lower peak heat release rates, with a reduction of the flammability to be as high as 60%. Also, cork derived from tree bark can be seen to self-extinguish after 500seconds when compared to EPDM after 900 seconds and TPE after 2000 seconds.

Cork is a green and sustainable material. At the end of its useful life, it can be disposed of without environmental damage. We highly recommend the use of cork as a replacement for the current SBR infill material regarding its better fire safety performance.

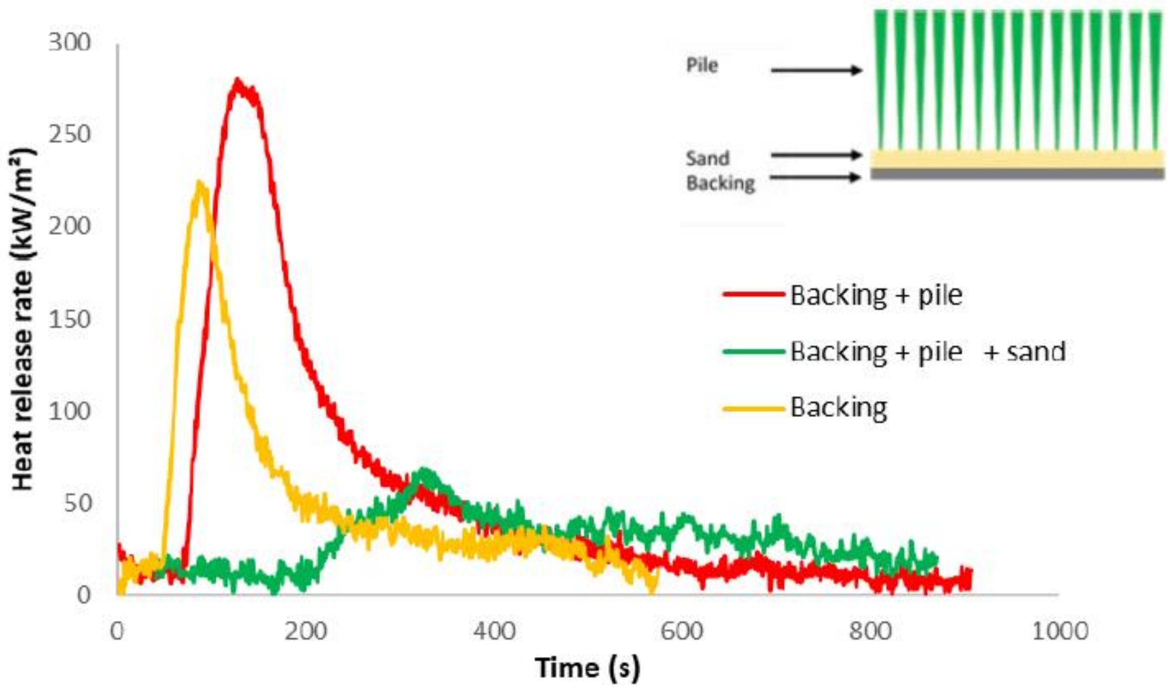

Figure 7. Heat release rates of backing alone, backing + pile and backing + pile + sand [7].

5.2 Conventional flame retardant fillers

To increase the flammability resistance of synthetic turf systems that will be fit-for-purpose in the outdoor environment, non-toxic and durable flame retardants could be introduced to elevate its fire safety performance further when exposed to the harsh Australian condition of increasing bushfire events.

Common flame retardant fillers, such as zinc borate, alumina trihydrate (ATH), melamine, titanium dioxide (TIO_2), graphite etc., have been widely used in both research and industrial communities [27–30] and can be sourced at a reasonable cost for scalable production.

The ARC Training Centre for Fire Retardant Materials and Safety Technologies has successfully implemented these conventional flame retardant filler materials for multiple research and industry projects. However, when implemented for the synthetic turf application, these fillers have limitations, which are discussed in the following sections. The potential solution of using innovative filler materials are also recommended.

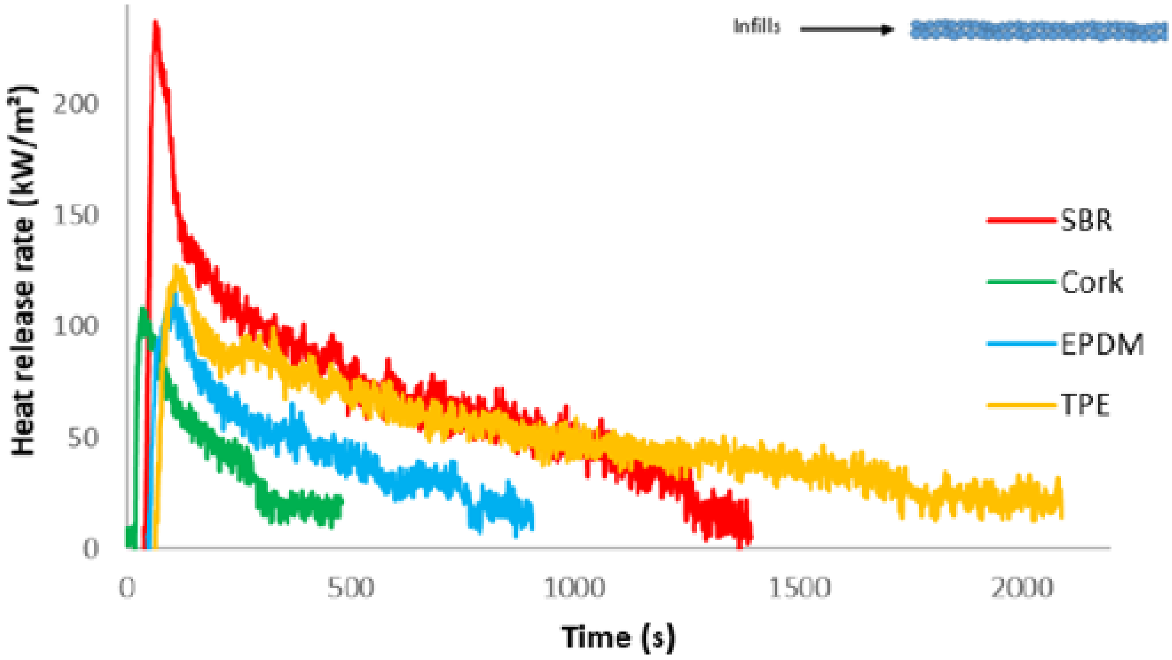

Figure 7. Heat release rates of SBR, EPDM, TPE and corks [7].

Physical appearance: Zinc borate has been found to be unstable under weathering conditions where it was found to leach out, hydrolyze by water or oxidize by UV exposure. Melamine, which is normally used as a pigment and light stabilisation protecting material against fading, was found to experience slight discolouration but leached out during weathering. ATH improved the colour stability. TIO_2 was found to be very effective in preventing discolouration but has the propensity to facilitate chemioxidation. The best protection against the light was the use of graphite. In addition, nano-filler material such as ZnO has been demonstrated as a feasible solution to protect wood based material by increasing the weatherability and leach resistance [25,26].

Mechanical properties: The presence of water generally facilitates the degradation of wood-plastic composites, whereby the mechanical properties decrease during weathering. They can be indicated by the reduction of the tensile strength and modulus, as evidenced by the fibre matrix interfacial bonding degradation and leaching of water-soluble materials from the composites. Overall, the iincorporation of flame retardant fillers increases the strength of the composites. Zinc borate has a positive influence on the flexural/bending strength of the composite. Melamine was found to improve the interfacial interaction in the composite and strength because of three very reactive amine groups. ATH and TiO_2, as fine particles at a high degree of dispersion, can potentially reinforce the material matrix. Studies have also suggested the enhancement of mechanical properties with micro/nanofiller materials such as nanoclay and glass fibre, due to the interlocking bridging effect[31,32]. Nevertheless, care must be taken to ensure that the matrix continuity is not disturbed due to the induced potential microcracks acting as stress concentration on the composites.

Morphology: Figure 8 shows the morphology via scan electron microscopy (SEM) characterization of the composite surfaces. It can be seen prior to weathering, all the surfaces appeared to be smooth. After weathering, cracks can be found which were induced by the expansion/contraction of cellulosic particles within the composites due to water absorption/desorption. The UV radiation could also induce changes in the crystallinity of the polymer matrix, which results in cracks. Elevated temperatures due to photo-, chem- and thermos- oxidation process may contribute to a higher degradation rate where the lifespan of a polymer could decrease by 40% when the temperature range exceeds 30℃ [33]. Among all the flame retardant fillers, TiO_2 appeared to be superior in protecting from UV radiation [19,34].

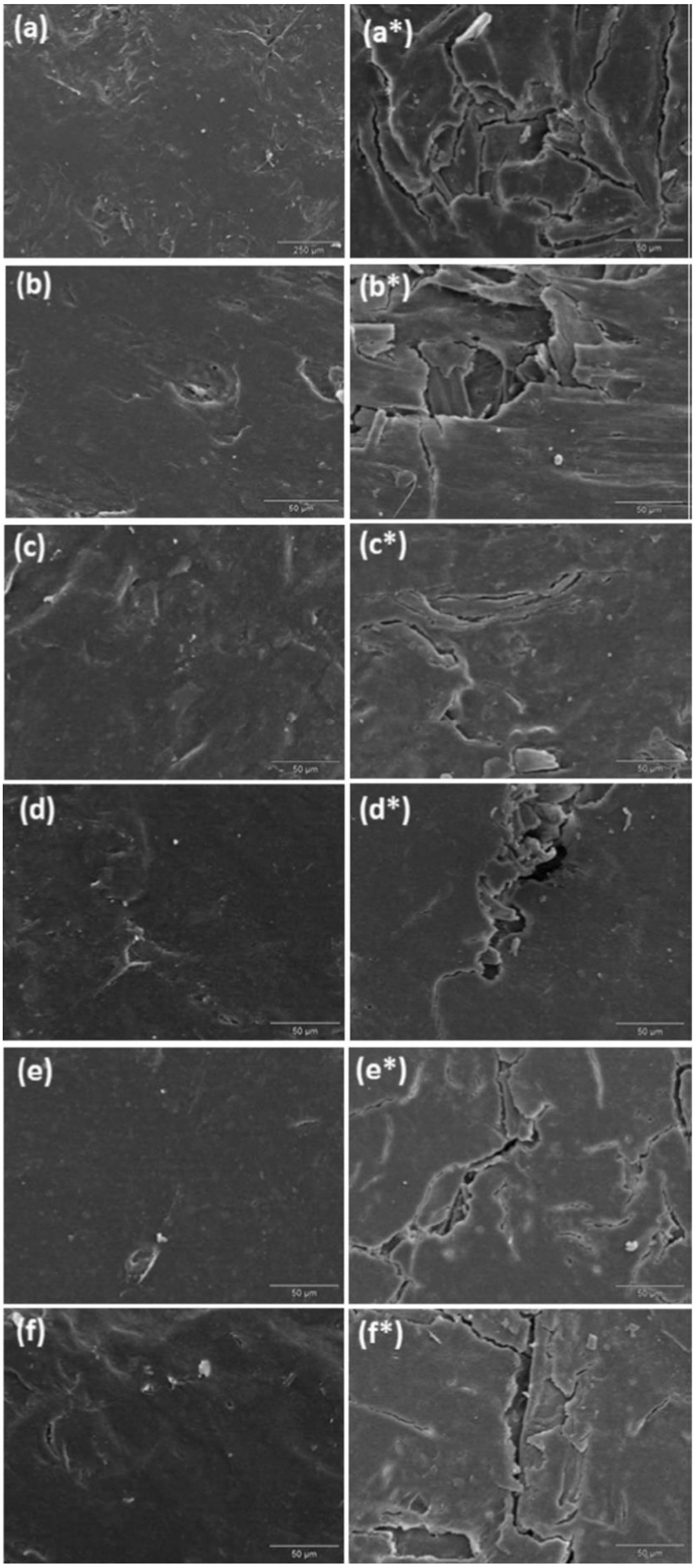

Figure 8. Morphology of composites subjected before weathering: (a) Without fillers, (b) Melamine, (c) Graphite, (d) ATH, (e) Zinc borate and (f) TIO_2 and after weathering: (a*) Without fillers, (b*) Melamine, (c*) Graphite, (d*) ATH, (e*) Zinc borate and (f*) TIO_2 [17].

Water uptake: Water is absorbed by most polymers and is considered to be present in the free volume. It may be attached to polymer chains by hydrogen bonds, resulting in the alteration of physical and chemical properties of the polymer, leading to degradation, swelling, leaching etc. [35]. The following describes strategies to manage water uptake, and therefore, the stability of the material.

The aspect of hydrophobicity can be introduced by adding TiO_2 and nano-clay (see Figure 9). The nano-clay layer provided tortuous paths and increased the barrier property for water transport. The TiO_2 nanopowder also provided a barrier to the passage of water. The increased water absorption and hence reduced diffusion coefficient of water was because of the strong affinity of water molecules towards the nanoparticles that restricted its free motion, and the well distribution nature of the nanoparticles further improved the resistance and retarded the motion of water molecules through the composites; hence the diffusion coefficient of water decreased further.

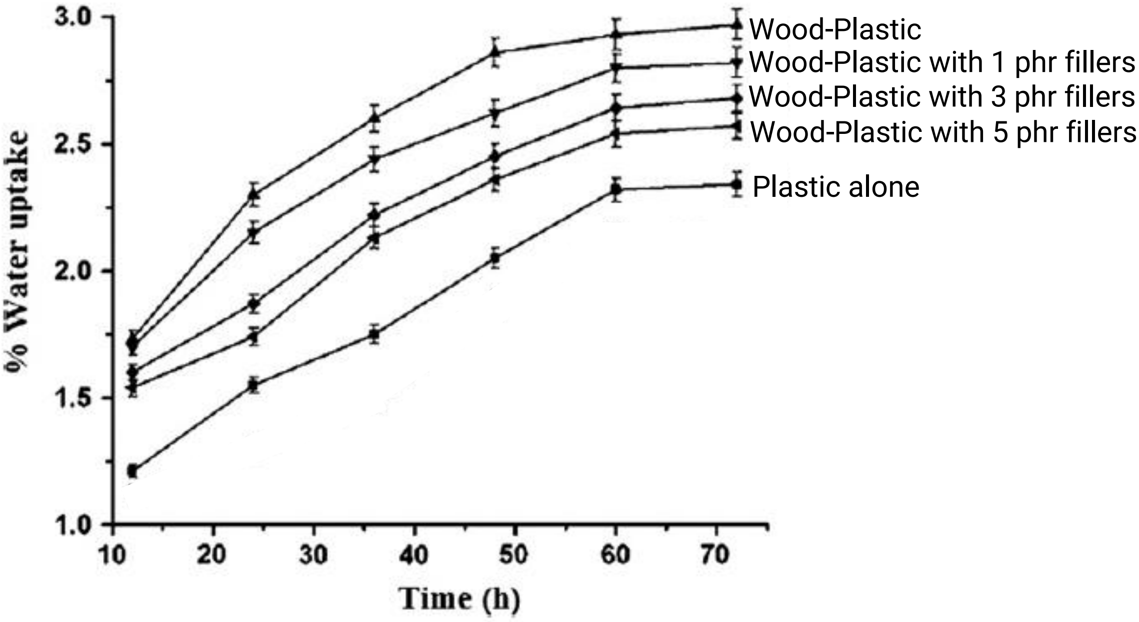

Figure 9. Water update for wood-plastic composites with increasing concentration of fillers. Note that phr refers to parts per hundred rubber [34].

UV radiation: Upon exposing the samples to UV radiation, the degradation of a polymer main chain of the polymer blend occurred, increasing the carbonyl index value. This value has been found to be a major indicator in determining the weight loss of the composites. TiO_2 nanoparticles played an important role; they could act as a screen and delay photodegradation. They absorbed the UV radiation and reduced the UV intensity required for the oxidation of the composite. The nano-clay also worked in the same way as TiO_2. Lower carbonyl index correlates with lower weight loss.

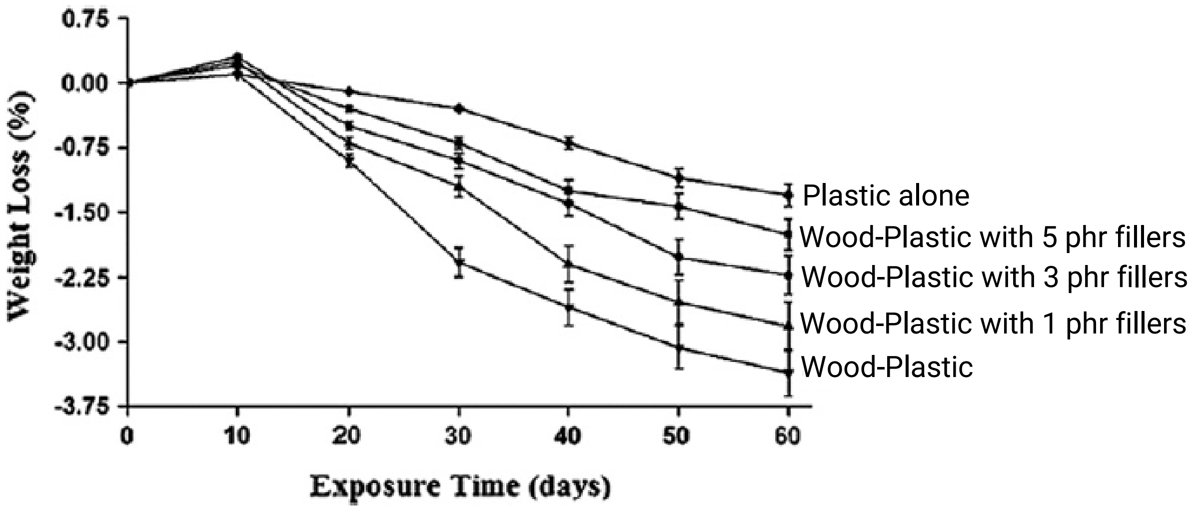

Figure 10. Weight loss for wood-plastic composites with increasing concentration of fillers. Note that phr refers to parts per hundred rubber [34].

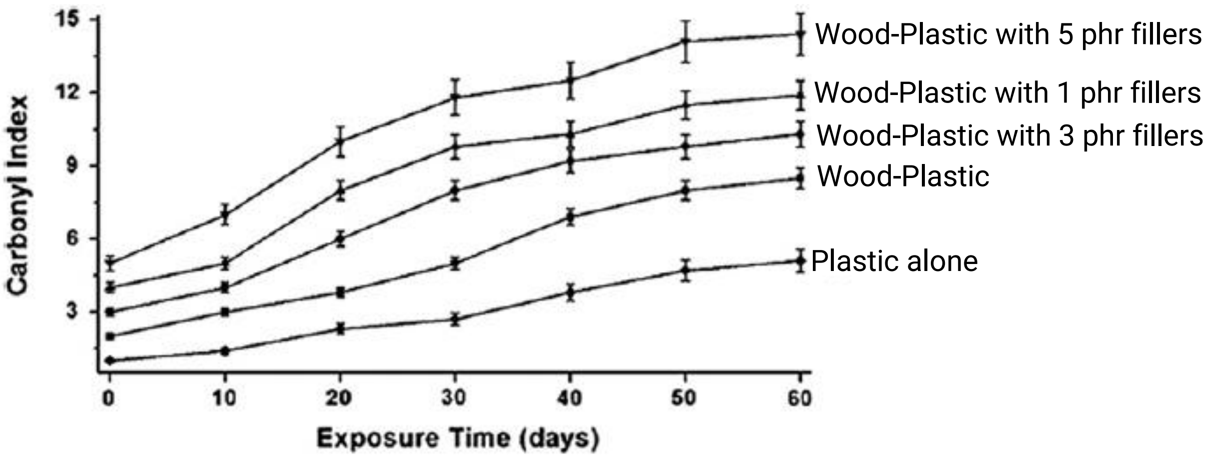

Figure 10. Carbonyl index for wood-plastic composites with increasing concentration of fillers. Note that phr refers to parts per hundred rubber [34].

5.3 Innovative approach

The conventional fillers combined with newly developed materials/binders, as mentioned above, such as ZnO, nano clay, and glass fibre, are proposed as a suitable replacement/ reinforcement for the infills. The fire safety performance, as well as the chemical and physical properties of the improved synthetic turf system (which is similar to the characteristics of wood-plastic composites [27]), will be performed in a future study.

6. Summary

The composition of synthetic turf, most utilised in Australian sporting fields, presents risks in bushfire prone areas. Among the different materials of the synthetic turf system, the composite structure that sits above the shock pad is of significant concern. These layers contain polymers that could be easily ignited and burnt but the infill material that is typically made from scrap tyres (SBR) poses the highest fire risks.

From a bushfire perspective, it is imperative that alternate infill materials such as cork, EPDM and TPE are recommended as they possess higher fire resistance due to their lower peak heat release rates in comparison to SBR.

There is a need for an industry standard to determine the flammability properties and fire spread behaviour in a wind environment for synthetic turf during bushfire conditions. Current industry standards being adopted are not fit-for purpose because the fire testings fail to address the flammability for bushfire conditions (ember and radiant attack) or the effect of flame spreading over a large field covered with synthetic turf, absence of any wind impact and exposure to only low radiative intensity.

There are, however, a number of fire tests adopted in research settings that would be suitable. These include the cone calorimeter which is a device used for predicting real-time fire behaviour and able to determine parameters such as ignition time, heat release rate, mass loss, and other properties relevant to fire characteristics and benchtop furnace to assess material degradation at high temperatures by determining the percentage of residual mass to evaluate its thermal stability in a simple and rapid way.

It is recommended that cone calorimeter is adopted as an industrial standard as the flammability of the different materials of the synthetic turf system would be evaluated close to bushfire conditions.

There are a number of flame retardant fillers that could be applied to further elevate the fire safety performance of synthetic turf when exposed to the harsh Australian condition of increasing bushfire events. However, these fillers have limitations with regards to physical appearance, mechanical properties, morphology water uptake and UV radiation. Among the many flame retardant fillers, TiO_2 has demonstrated great potential to be deployed as a flame retardant filler.

There are many aspects on the flammability of materials of the synthetic turf system that could be further evaluated through the ARC Training Centre for Fire Retardant Materials and Safety Technologies to bridge the knowledge gaps and develop an extensive material database of different flammability limits.

Glossary

Term	Definition
• **critical heat flux (CHF)**	the lowest thermal load per unit area capable of initiating a combustion reaction on a given material; the lowest energy a fire requires to keep burning.
• **bushfire attack level (BAL)**	the severity of a building's potential exposure to ember attack, radiant heat and direct flame contact.
• **time to ignition/ ignition time**	the ease of ignition of the material by defining how quickly the flaming combustion occurs when the material is exposed to a heat source at a given incident heat flux and in an oxygen-controlled environment.
• **heat release rate**	the rate of heat generation by fire - this is also known as power.
• **mass loss**	Weight loss of material outgassed from a specimen that is maintained at a specific operating condition for a specified time.
• **thermal stability**	the ability of the polymeric material to resist the action of heat and to maintain its properties, such as strength, toughness, or elasticity at a given temperature.
• **thermal decomposition**	a chemical decomposition process - the breaking up of large molecules into smaller ones by the action of heat.

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Appendix 11

Smart sensing technology review: Measuring the usage of synthetic and natural turf in public places

Smart sensing technology review:
Measuring the usage of synthetic and natural turf in public places

Submitted to the Office of the NSW Chief Scientist and Engineer
by Dr. Tomonori Hu, Kimi Izzo, Dr. Ayu Saraswati

NSW Smart Sensing Network
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Date: 29 August 2022

Table of Contents

Executive Summary

We review the currently available smart sensing techniques for people counting in the context of measuring sport field usage. Upon reviewing various products, we divide the possible solutions into three broad categories: a *catered product solution* that essentially works out-of-the-box, an *appropriated solution* that requires moderate level modifications to existing products, and *DIY solutions* that builds solutions from ground up. The latter stages of categories incur more development costs but also have the potential to bring in emerging sensor technologies and software capabilities to undertake more intricate tasks for human activity monitoring.

Machine learning plays a strong role in achieving the required results for sport field usage. Without going into detail on the inner workings for each algorithm, we present a high-level overview of what is possible currently, and what is required to enable new capabilities in this space. The following topics have been specifically requested by the Report, with our direct responses provided, and the remainder of the report will elaborate on these answers.

ID	Inquiry	Finding	Relevant sections
2a	Ability to identify individual (bodies) without capturing identifying features (primarily faces) of individuals	Yes – this can be achieved using several ways. Existing camera solutions have an intentionally low resolution that prevents any identifying features to be captured, yet the entire body can be found. An alternative is to perform 'edge-computing' where the processing algorithms are performed on the device, and only statistical information is transmitted. Other sensors such as Thermal and LiDAR sensors also have too low resolution to pick up any features that can trace the individual's identity.	**Section 3 & 4**
2b	Ability to avoid double counting and factors that might influence this e.g., a fast-paced sports match	This will be difficult to achieve in practice. Theoretically, with enough training data, a machine learning algorithm can tell if the same person has appeared twice – but this requires thousands of images of said person, which would create privacy concerns. There are other features that may be detected, such as team uniforms, but this is a specific case. Practically it is best to avoid this by setting up the sensors in a way to have a large field-of-view to minimize double counting. The only way to get an absolute count is to install a radar or infrared beam counter at a gate, where the flow of people in and out of the space is restricted through a specific exit.	**Section 4.1 -4.3**
2c	Ability to distinguish the size and weight of individuals on a field at any point in time, and any limitations of note, including total number of individuals at any one time e.g. ability to distinguish an adult team of soccer or rugby players v one or more groups of 10 year old players	Sizes of individuals may be ascertained through software. Machine learning potentially can perform image segmentation of people from the background, and then these could be converted to real sizes. However, variations in distance could affect the accuracy. Stereo-cameras are becoming more available and can measure this distance to improve accuracies here. Measuring weight presents a more difficult problem. Body sizes could be estimated, but to get an exact weight would be difficult unless certain assumptions are made (body shape, sex, etc) – quickly falling into some privacy concerns. LiDAR sensing technically has the ability to provide a 3D digital twin of the players, and with added data analysis, some estimates may be possible.	**Section 4.3**

		There are no obvious limitations in the number of individuals on a playing field, unless the numbers are so large, they obscure other players behind them.	
2d	Ability to capture intensity of use and factors that might be most relevant e.g. size and speed of players – and whether multiple technologies (e.g. sensor types) might be needed	Calculating player velocities is often done using LiDAR and radar solutions, however converting that into intensity of use (and the subsequent impact on the field) is not well established in the literature. The relationship could be derived but would require significant research and development. Activity recognition, such as being able to tell the difference between standing/sitting and running to imply playing sport, is possible as shown in [11]. There is a repository of activity recognition pre-trained models through the GluonCV toolkit. Separating the spectators from the players based solely on their activity would require non-trivial computation. However, like certain products on the market, areas can be virtually masked in software so that only people on the field are counted.	**Section 4.3**

After comparing the available solutions, we also provide an approximated cost of development for the DIY case should it be pursued in future. We then provide three case studies and recommended sensor solutions for each case. The exact solution ultimately depends on the exact environment and user needs; however, this report should provide a comprehensive survey of the options to consider.

Glossary of Terms

ML	Machine Learning
Sensor Solution	The entire hardware, machine learning and visualiser package
Sensor module	The individual sensor to be integrated with power and data acquisition electronics
YOLO	"You only look once" - a deep learning algorithm that can perform object detection in real time
TRL	Technological readiness level, a scale from 1-10 that describes the maturity of the technology in question, from blue-sky to commercially available respectively
Library	A collection of pre-written code that abstracts algorithms, or software functions into easy-to-use modules
Framework	An online tool that acts as a library for premade machine learning models

1. Introduction

In November 2021 the Hon. Rob Stokes MP, (then) Minister for Planning and Public Spaces requested the NSW Office of the Chief Scientist & Engineer (OSCE) to provide expert advice on the use of synthetic turn in public open spaces. The OCSE is undertaking a review on the design, use and impacts of synthetic turf in public places, exploring its potential risks to the environment and human health. A consideration in deciding whether synthetic or natural surfaces are suitable is the number of hours that a field can tolerate or carry. An issue raised across the course of the review is how use hours are or should be calculated. This is not a trivial consideration as carrying capacity underpins major funding decisions using public resources. This report was commissioned to provide an expert review of the existing and emerging sensing technologies to quantify and capture various sport field activities. This includes investigating the latest software applications with machine learning and AI algorithms.

The aim of the report is to:

1. **Identify** existing technologies suitable to meet requirements.
2. **Compare** the different methods from a technical, operational, and economic view.
3. **Recommend** sensor architectures for various scenarios should a pilot study be required.

This report will begin by establishing the project deliverables, and the associated assumptions made to meet them. A technical outline will be given, followed by a review of existing commercial products and emerging technologies from the literature. The report concludes by outlining the processes and required resources for product development, with a few options to suit a variety of real-world scenarios.

2. Project scope and requirements

From a brief survey (see Appendix - Sydney artificial field survey), synthetic turf fields tend to have a fenced perimeter, sometimes only accessible by gated entrances, and often accompanied by the necessary infrastructure to support sensors such as light poles, connection to mains power, and occasionally Ethernet connection..

As a broad range of environments must be considered, the following table lists the project assumptions made.

Table 1 Assumptions and their corresponding rationale for this project scope

Assumption	**Rationale**
Synthetic turf fields always have an identifiable perimeter	A survey of 37 synthetic sports fields in greater Sydney has revealed only 3 fields have no fencing at all
Light poles or fencing are available and can be used for sensor installation	A survey of 37 synthetic sports fields in greater Sydney has revealed most fields have available infrastructure for the deployment of sensors
There is no restriction of budget, and the judgment of what is too expensive or not has not been made in this report	No budget restriction in given requirements
There is no restriction on council resources (technical capability), the judgment of whether a solution is too complex or not has not been made in this report	No resource restriction in given requirements
Technologies that are not currently available commercially or scientifically will not be considered for scenario recommendation	The report will focus on products currently of the market and literature for recommendation, however some emerging technologies will be mentioned in Section 4.3.

The ideal case of a synthetic sport ground being monitored by a sensing device is shown in **Error! Reference source not found.**. Here sensors (exact type to be later discussed) are mounted onto part of the infrastructure to monitor players in real time whilst processing additional data such as count, velocity, activity type and relevant body characteristics. Deriving such parameters could be possible with the right sensor and algorithm combination, the feasibility of which will be discussed in this report.

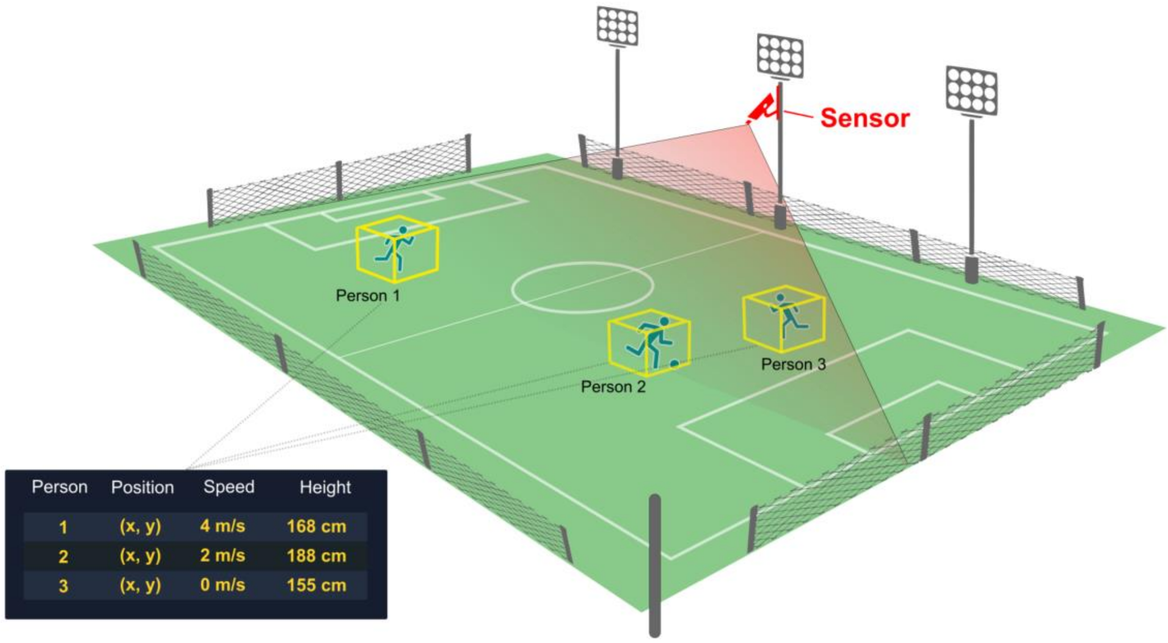


Figure 1: Illustration of an ideal sport field sensing solution. A sensor is placed at a specified location to identify players on the field, with additional information, such as speed and height, being displayed on a dashboard.

The request from the OCSE has sought advice on specific capabilities to support the overall review. It is important to state these questions center on methods for people counting and physical characterisation. The goal is to use this information in conjunction with other sources such as surface maintenance schedules, to better understand how the fields are used over time.

Table 2 Project requirements transformed from the questions posed by OCSE

Requirement	**Rational**
The system will be able to capture all individuals on the playable field space	Fields can be large areas; the sensing mechanism must be able to capture everyone within the defined space at once
The system shall be able to distinguish human beings from objects and animals	There needs to be a method to be able to distinguish between humans, animals, and objects
The system shall be able to count distinct individuals as they move in and out of the field of vision	There needs to be a way of counting distinct people to avoid double counting, making it seem like there are more people than there is
The system shall be able to characterize activity type and body size	Intensity of use may be dependent on body size and activity type
The system shall be able to inform maintenance activities on the field	The purpose of the system is to better maintain synthetic sport turf fields

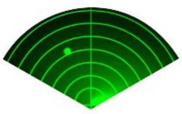
3. Technical background

Before reviewing the latest developments in the research and commercial space, it is important to provide a brief overview of two key building blocks that make up the elements of a desired system – the **sensor** and the **machine learning** algorithm. It is also important to consider the architecture in which these components are put together, as it has implications on the overall system.

3.1 Sensors

We refer to the sensors as the device itself that detects changes in the physical environment and converts it into digital information. Various modes of sensing modalities exist, but in the context of this report, they all detect changes in parts the electromagnetic spectrum caused by human activity.

Table 3 Types of sensors considered in this report

Cameras 	Uses pixel-arrays to build up an image of the environment (looking at the visible wavelengths of light). Digital cameras are a mature technology with a wide selection of pixel resolutions available at affordable prices. It's the primary sensor used for object recognition and image processing. One drawback is the reliance on good lighting conditions, with corrections required for the distorted field of view and lack of depth (sometimes compensated by stereovision cameras).
Thermal vision 	Creates images using infrared radiation (emitted heat), where temperature differences on the order of 0.01C ° can be detected. High contrast can be observed between warm objects and cold backgrounds, with lighting conditions and colours not affecting the output. Thermal cameras tend to be more expensive than visible cameras, with lower image resolution.
LiDAR 	Uses a pulsed laser to measure the distance between the sensor and the target. By measuring a high density of distance points, a 3D 'point cloud' is created to build up a digital twin of the environment. Given it is an active method, it does not rely on environmental conditions such as lighting. One drawback is the data tends to be extremely dense and requires much computation to process.
mmWave Radar 	Uses radio waves (60GHz) to detect motion and track the presence of objects. As 3D imaging from radio wave point data is still in its infancy, the resulting output is usually people represented as dots on a screen, with some additional parameters such as velocity or path tracking lines.
Mobile phone tracking 	An alternative to these direct methods is Wi-Fi and Bluetooth mobile tracking. People are counted as they pass through the detection range of sensors, usually placed on doorways or pathways where foot traffic flow is expected.

One type of sensor not listed in this report are **wearable** sensors (smart watches or tracking devices). If used, this can provide detailed information about velocity, acceleration and position on the field. However, this requires all players to equip certain devices and agree to share this information. In this report we focus only on remote sensing methods that does not require player participation in data collection.

Table 4 compares the abilities of each sensor type at a high level. It is important to note that the exact specifications for each sensor such as range, resolution, and communication method will change depending on the brand and model of each sensor. Such information can be found in their respective datasheets, which if not available on the website, can be requested from the vendor.

Table 4 High level comparison of sensor types

	Thermal Vision	Camera	Radar	3D LiDAR	Wi-Fi/ Bluetooth
					
Can capture physical features	Yes	Yes	No	Yes	No
Area coverage	Dependent on viewing angle and lens size, anywhere between 6-80m for an angle of 103° -7° respectively		$100m^2$	$31400m^2$ (360 ° view)	$400m^2$
Range of detection			10m	50-100m	20m
Resolution	Medium	Medium	Low	High	N/A
Drawbacks	Slow to capture visual data, low resolution feature capture	Dependent on lighting conditions, prone to image distortion	Can only count people passing through its detection zone	Data processing intensive	Can only detect people within its point radius
Ideal use case	Wide area capture for head count analysis	Quick prototyping, complement to thermal vision system	Installed in an enclosed space to get an absolute count in and out	Activity assessment and body size analysis, wide area capture	Count of people passing through the general area, not specifically on the field

3.2 Machine learning

Machine learning (ML) refers to the use of algorithms, that have been trained on historical data, without direct programming or human intervention. Typically, these algorithms are trained to perform a specific task (e.g., classify the presence of an object type in each image) to varying levels of detail. Once the algorithm is trained and evaluated, the output is a model that can be deployed as part of a final product either in the software back end or downloaded as firmware onto a physical device.

The classic example of machine learning is computer vision – analyzing images and videos, as shown in Figure 2. The following are four levels of tasks performed by algorithm:

- Classification – detecting the type of object
- Localisation – ability to locate where on the image an object is present
- Object detection – ability to discern between objects in an image
- Instance segmentation – ability to outline the perimeters of objects from the background

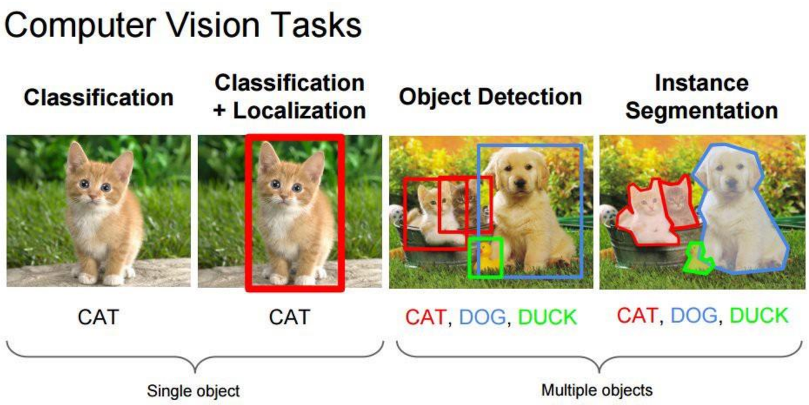


Figure 2: Common machine learning tasks for computer vision, image adapted from [1].

As a rule of thumb, these algorithms are only as good as the amount of training data provided. For instance, a training dataset will include thousands of images of each target (human, animal, object, etc.). It is imperative that the data used to train the algorithm is pertinent to the scenario that is to be detected. At the same time, some variation is needed in the settings, positions, shapes, and colours for optimal performance [2].

Typically, algorithms and models are not made from scratch. A wide variety of frameworks are used to build, train, and deploy machine learning models such as *TensorFlow* – an open-source platform. This simplifies the development process, as these libraries have been developed by the community over many years. The best model for the job depends on the aim of the algorithm, the dataset provided, and the sensors used.

The size of the ML model and memory usage would depend on the algorithm used to train the model. The ML algorithms typically used for the tasks mentioned above are called convolutional neural network-based algorithms. These can range from 30 MB to 500 MB binary files that take anywhere from 2ms- 1s to run a prediction. The deciding factors on which model is tradeoff between performance and runtime. Smaller models may not be as accurate, but they take less computing power and run faster. There are emerging works that tried to push the performance on smaller architecture such as TinyYOLO [3], MobileNet [4], EfficientNet [5], and more.

3.3 Overall architecture

The last important consideration is where the machine learning is performed. Depending on the complexity of the algorithm it can either be performed "on the edge" on the hardware side of the system, or in the cloud – each having its advantages and disadvantages.

If there is enough data bandwidth and storage space to send all the sensor's data to the cloud, then the machine learning algorithm can be potentially run in the software backend rather than requiring additional hardware computing at the edge. The drawback of sending sensor data over the internet is the possible breach in privacy by storing what could be personal data online or providing the opportunity for external threats to intercept the data. Depending on the size of the data sent, and the speed requirements, this would require additional engineering on the hardware, as well as incurring additional monetary costs from the cloud service.

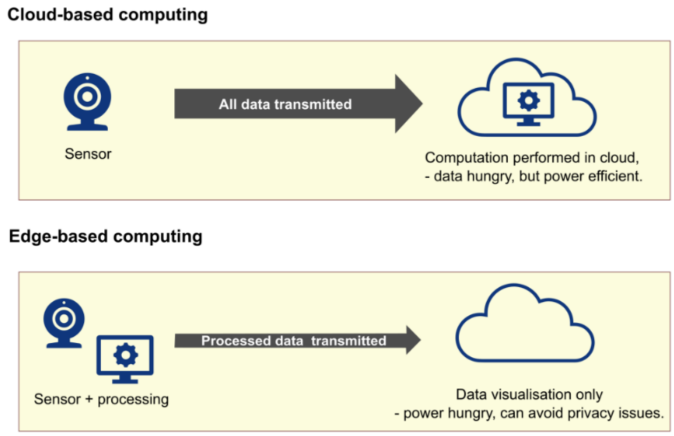


Figure 3: Comparison between edge-computing and cloud-computing architectures. By conducting the processing vs device or online, advantages can be had in power and data efficiencies.

An alternative is to include computational processing at the sensor location - edge-based computing. Suitable devices, such as the Broadcom BCM2711 SoC used in the Raspberry Pi, can run ML models, such as people count or activity type recognition. Although this solution requires some custom development and additional hardware, the advantage here is that much less data is transmitted and stored (labels as opposed to raw images) and the labels can be anonymized – retaining privacy.

4. Technology review: established and emerging

Upon reviewing several existing products on the market, we compared the most relevant features of each sensor for people counting. It is important to note that the exact specifications for each sensor such as range, resolution, and communication method will change depending on the brand and model of each sensor. Such information can be found in their specific datasheet. Based on this, three "tiers" of solutions have been identified:

1. A **catered product solution** is one that already exists on the market and meets the project goals – there is no development time or research required, all time can be focused on deployment.
2. **Appropriated sensor solutions** require modifications to be made to sensor modules to achieve product needs. This may be done through consultation with the vendor or interfacing directly with the sensor with separately made software solution. This might be suitable when minor additional requirements need to be met, where additional development costs can be taken on.
3. **DIY solutions** are made from scratch - an option for where highly specific and niche requirements need to be met. This is the riskiest approach, where major development cost and time needs to be planned and budgeted for.

The companies listed in Table 5 have been consulted and deemed relevant to this application.

Table 5 Companies contacted about their product solutions

COMPANY	EXPERTISE/PRODUCT SECTOR	DESCRIPTION
COMPANY A	Synthetic turf maintenance software	Using cameras and machine learning to provide analytics for sports field use to inform business decisions and maintenance activities
COMPANY B	People counting	A global leader in footfall counting, people tracking and analytics within retail spaces and outdoor zones

COMPANY B	Surveillance solutions	Has a wide variety of sensor types, systems, and software monitoring solutions. Main expertise is thermal vision.
COMPANY C	Surveillance and digital modelling of the environment	Specialized in Lidar sensors and products, has worked with Transport NSW for traffic monitoring over a busy intersection
COMPANY D	People counting	Radar and infra-red based people counting solutions for indoor and outdoor environments

4.1 The catered product solution

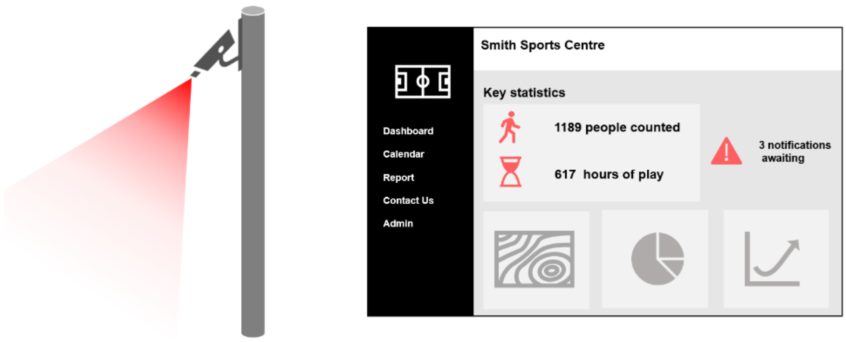


Figure 4: Solution offered from Company A – a pole-mounted visible camera system monitor players on a field. The software includes a dashboard with usage statistics and heatmaps to inform field occupancy.

Company A offers a product directly suited for synthetic turf monitoring and maintenance. The product is a camera-based system with deep learning capabilities. The shoebox-sized device is designed to be mounted onto a lighting pole, Figure 4.

The primary focus of this product is to calculate use-rate statistics to inform and monitor turf maintenance activities, whilst providing technical evidence to back up a business case for field upgrades or additional turf installations in the area.

The key features of the system are:

- Ability to count individuals without capturing identifying features
- Provides an average count of people at specified time periods (hourly, weekly, monthly)
- Can discern between peoples, animals, and objects on the field
- The playing field is virtually masked in the software, so there is no need to be able to distinguish between spectators and players
- Creates usage heat maps of each field, based on people count and dwell time
- Triggers alerts for field maintenance activities based on heat map data
- Recognizes turf cleaning machines and tracks their motion to determine if maintenance has been completed
- Ability to take live camera snapshots of the field at peak usages or on a user prompt. Images are stored within the dashboard.
- Provides reports with calculated use statistics for each field in the user's system

However, the system cannot identify individual people (the height of the camera and the resolution does not permit this). As such double counting would take place, for example if the players walked off the field during half time and walked back on, they would be counted twice. Company A has remarked that they have a way of compensating for this in the software, but the numbers recorded should not be taken as absolute counts.

Additional characteristics such as age, weight, player size or gender are not calculated. It has been stated that such data is not legally allowed to be identified. Recognition of activity (sport type) is not performed, as they assume the field type would already determine this, and velocity/intensity of usage is not calculated.

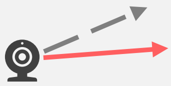
The required number of devices differs by field type, for example soccer pitches would require at least two sensors (at opposite corners), whilst AFL fields may require up to five. For each set up the precise required number of sensors is simulated from a Google Maps image. A typical cost for procuring and installing the system for one soccer-sized pitch, with a ten-year software service, is $60,000 AUD.

4.2 Appropriated sensor solutions

Four companies with extensive product lines and solutions in each of the main sensing domains have been contacted for this project, all information below has been collected through video calls, emails and their respective websites and datasheets. Of course, the company list extends past this with pure sensor module options available as well.

Table 6 Appropriated sensor review

COMPANY & PRODUCT	**QUOTE**	**DESCRIPTION**
COMPANY B (Product – unspecified) 	N/A	Company B is a leader in footfall systems and has a wide portfolio of corporate retailers in multiple countries. It specialises in people counting specifically within retail and public spaces. These camera-based sensors are typically installed above doorways looking down, or at key zones where people are expected to flow in and out of, such as ticket gates. These are backed with powerful analytics and a visualizer with the end goal of evaluating retail brand strategy and impact on customers. Such solution is relevant, but discouraged for the following reasons: • It operates based on flow of people in and out from a specified virtual zone. This means double counting will occur. • Additional analytics such as size, and speed of the person are not calculated. • Depending on the angle, and the required distance, the furthest corners of the field of vision will experience degradation in accuracy and resolution • The large area of most pitches, and required infrastructure would incur high costs **Not recommended as an appropriated sensor solution for this specific use case (long term and scalable data collection).**
Company C 	$6000-7000	Company C is specialized in thermal imaging sensors but also sport digital camera and radar-based surveillance products as well as stereovision people counter for retail spaces. Their recommended product is the fixed thermal camera, with the option of having a dual optical/thermal set up. Software solutions can also be provided but the analytics are surveillance-focused and do not include people counting.

		As these cameras cannot rotate, and optical zoom is not possible with thermal vision, the positioning of the angle and height will be crucial with deployment. Calculations will need to be made to ensure the field of vision according to the purchased lens is appropriate for the field area. **Not recommended as an appropriated sensor solution for this specific use case (long term and scalable data collection).**
Company D 	\$13,500 per sensor \$7000 for LIDAR processing box	Company D is a key player in the LiDAR field providing a suite of sensors, with the accompanying software control and analytics also provided. Flexible when it comes to analytics, people counting is an offered feature, with other options up for discussion with the technical support team. During the consultation process, a digital twin of the intended environment can be made with a simulation of how many sensors would be required in the space to be able to compute the required analytics. Up to 120 people can be tracked at one time with velocity and people tracking within the field of view as potential outputs of the system. A minimum of two sensors is recommended for a soccer field to obtain the proper depth of field. The resolution is high enough to distinguish people who are close together, and for large areas is more economic than CCTV options. The vendor claims that only five LiDAR sensors were needed to cover a building floor, which would have otherwise required 120 CCTV cameras. However, similar to other options double counting will still take place once someone exits the field of view. **A good option for large-scale monitoring and high-resolution analysis**
Company E 	780 EUR	Company E sells a range of mmWave radar and infrared beam people counting products. Made to be installed in retail areas and streets, these products have the benefit of guaranteeing privacy as no physical features are captured. The radar-based product has a field of vision like a camera, with a maximum area of $100m^2$, and a 120° degree viewing angle. This sensor is placed at pinch points or doorways to track and count the amount of people moving in and out of the detection zone. Additional features include speed estimation up to 35km/hr, total occupancy counts and timestamped statistics in a real time online portal. Occupants are represented as individual dots on a screen, where user defined zones can be set up for counting to be triggered. Where light post mounting is not possible, an infrared beam product that can be installed at the gate which counts people as they traverse the beam. **Recommended solution: installation at the gates of high fenced fields to get absolute count of players.**

4.3 DIY solution

Up to this point we believe that the Company A system, or an appropriated system such as the Ouster product meets most requirements for people counting on sport fields. If the unmet requirements such as body size, no double counting and activity analysis are still desired or there is a change in scope, then custom development is required in the hardware and/or machine learning domain.

In this section we looked to the literature for new and emerging technologies to further explore the capabilities of machine learning and whether up and coming novel solutions can provide clarity on the feasibility of achieving such requirements. The following hardware and machine learning sections discuss what steps and resources are required to develop systems from the ground up.

Emerging sensing techniques

The solution from Company A uses Machine Learning algorithms on images which is a two-dimensional problem. Though extremely matured, to get information such as size and weight there is a need to move into three-dimensional data sets. Significant leaps and bounds have been made in the last decade in 3D imaging from sensor data, object recognition and machine learning tools and analytics. Considerable progress in contribution to visual datasets acquired from security systems, traffic cameras, and publicly gathered images (citizen science) has advanced the field of object recognition with machine learning [6, 7].

Stereo-cameras use two or more imaging sensors that are displaced from one another to capture differing angles of the same scene. Combining these images can the reveal a 3D environment, like that of a LiDAR point-cloud, but from a completely passive imaging system - Figure 5. The hardware is available from 500 USD on upward, but much of the processing algorithms are not yet readily available for custom usage at this stage. A limiting factor is that the maximum range is rated to only 20 meters but with custom optical devices this potentially could be increased.

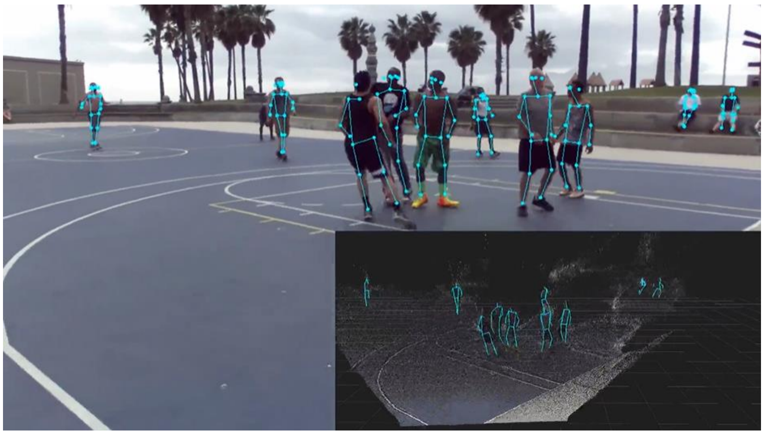


Figure 5: Stereocamera vision of a basketball match. A two-camera system fuses images to create a 3D perception of the environment. Targets in view can be classified and tracked. Image adapted from [15].

On the other hand, techniques such as LiDAR, thermal Imaging and radar have limited datasets which have limited their commercial usage. Thermal imaging has increased in usability as the resolution has improved enough where the contrast can supplement digital camera imaging in low light conditions, improving the precision of capture. Though certain vendor offers some software for detection, the labels are generic (person, bike, car…. etc.) and not at the level of identifying more detailed information such as player type, activity, size, and so on. In these cases, a new dataset for training and validation will have to be made by taking images of the same objects of interest [8].

Figure 6: A thermal image taken from inside a car. Human bodies appear as bright objects even in difficult conditions, and can be identified (at a basic level) using machiine learning. Image adapted from [8].

3D image generation from mmWave radar is possible, where machine learning is used to optimise image creation from the dataset, however images are blurry and the echoes from the environment the radar is operated in effects the crispness of the image [9]. Dealing with the vast amounts of data gathered by LiDAR and Radar requires the use of compressed sensing algorithms to achieve high sampling rates at a fraction of the computing power, however this technology is still emerging.

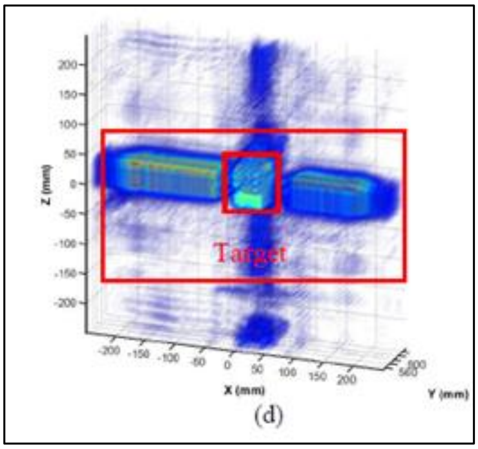


Figure 7: 3D mmWave radar high resolution imaging of a model target (4.9 cm x 6.1 cm x 6.8 cm) placed 56 cm from the sensor. Such techniques could be used to image at much longer ranges for larger targets – image adapted from [9].

Emerging analysis techniques

Player detection and analysis on the sports field comes with a wide array of difficulties such as similar appearance of players, changing background, unpredictable human movements, motion blur and low resolution in faraway players. Significant work goes into "playfield detection" (isolating the field from the advertisements and spectators) to reduce the number of pixels processed. Other aspects of a camera system that can affect performance include player shirts, shadows on the field, varying field colors between stadiums and weather conditions. A plethora of image filtering and processing algorithms are required to take frames of players in motion to recognise and follow their movements throughout the game [10, 11] .

Generic human actions such as running, jumping (and a multitude of others) can be classified successfully when static images of people on a uniform background are take and processed. In future should this be applicable to fast moving players on a field, rudimentary actions such as standing still, jumping, and running could be a function of intensity of use [12]. Correlating such actions to the degree of synthetic turf wear and tear would be a project in itself.

In a similar vein, silhouette images rendered from high contrast images taken on a unform background can be used to estimate BMI with reasonable success (correlation coefficient of 0.73 for females, and 0.61 for males). Performance was affected by shadows, a small dataset, and clothing on participants affecting their silhouette perimeter. Like with human action recognition, applying the techniques used to moving players, clothing variations and field of view distortion will be challenging [13].

Sports analysis and size estimation using digital images is an emerging field with a variety of challenges to be faced. Research in using data from sensors beside digital cameras is still ongoing but is limited due to lack of public datasets for algorithms to be trained on. Though data collection exercises can certainly be undertaken they tend to be costly and time-consuming tasks. Only when there is enough incentive, or a market for commercial players, would they be undertaken.

4.4 Building the system

From a hardware standpoint, a DIY system can be approached in two ways:

1. Purchase an all-encompassing sensor system, so that only the software aspects need to be developed. This simplifies the process, reducing development team size, cost and deployment time, but there are only a few options available on the market to do this.

2. Purchase an individual sensor module (A table of **Error! Reference source not found.** identified in the course of the review is available on request from NSSN) and design the power, control, and data acquisition electronics around it. This allows for more design flexibility, or if the aim is to develop a new proprietary system. This will result in increased to complexity, time required for machine learning development and testing, and will incur large prototyping and development costs.

The complexity of machine learning development is highly dependent on the sensor used and the analysis to be performed. For example, if a thermal sensor is chosen, one will need a thermal image dataset of people playing sports on a field. If such datasets do not exist, it will need to be gathered by taking thousands of images in various conditions. Acquiring this data, the additional cleaning, labelling, and storing to build a dataset that will result in statistically significant predictions from the algorithm may take a great deal of time as illustrated in Figure 8 [14].

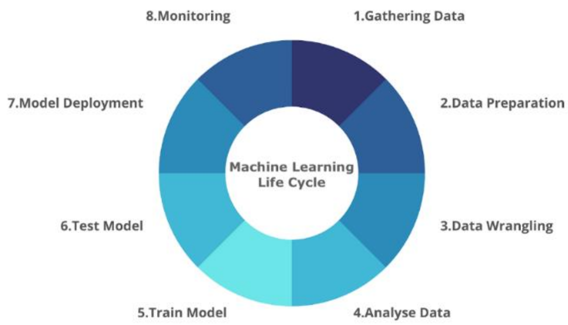


Figure 8: Steps involved in the ML life cycle – image adapted from [14].

After a model has been made, it needs to be deployed onto the system. As previously mentioned, this could be done on the edge or entirely in the cloud, each with its pros and cons, where the ultimate decision depends on the user needs.

Estimated development cost and time

To give an idea of development cost, we lay out all the considerations below. In the case that hardware solutions are required from scratch (worst case scenario), it is recommended for the task to be carried out from an electronics consultancy. This may require a minimum of four people (electronics engineer, industrial designer, firmware engineer, project manager) at a minimum charge out rate of $150/hour, with a project duration of up to four months. On hardware alone this adds up to $240,000 in development costs.

The development of the machine learning solution depends on the complexity of the design, and the availability of an existing dataset for training the algorithm. For the worst case (no dataset) the activities would include gathering and labelling data, processing, research, testing, and final deployment. This is likely to require a team of 3-4 full time ML engineers, 1-2 software engineers for visualizer design and a small team for manually annotating for an 18-month development effort. This be undertaken by either industry and/or academia.

5. Recommendations: Real world use-cases

After considering numerous sensor systems and approaches, we now examine three indicative sport fields and make recommendations for development. The following are three environmental scenarios based on real football fields in Sydney. It is worth mentioning that all the sensor modalities described in Section 4.2 can adequately count people when configured correctly. The following recommendations are based on overall considerations around performance and ease of setup, and ability for the technology to be as scalable long-term solutions. In each case the **sensor type** is the bottle neck as to whether certain requirements can be met, despite whether it would be an appropriated or DIY solution.

Scenario 1: High fenced, individual fields.

Figure 9: Fairfield - Ultimate Soccer

There are multiple sport centers in Sydney where futsal and soccer pitches are close together, with high fences where entry is only permitted through a gate, with no room for spectators within the pitch. Under these highly controlled circumstances, where it is fair to assume only players enter the field. This would be an ideal case for **infrared** or **radar-based people counters** installed at the gate for an absolute count for people going in and out of each pitch. This would be a low-cost solution for a multi pitch area.

Scenario 2: Low fenced, restricted entry fields

Figure 10: Majors Bay Reserve

Synthetic turf fields are often built into stadium like infrastructure, with high external gates, with stands available for spectators. This prevents casual use of the field such as casual park goers, gatherings, dog walking or picnics. It’s most likely that anyone on the field is using it to train or play the relevant sport. Like the high fenced option, this presents a restricted domain with a clear perimeter aiding in the machine learning aspect, whilst keeping the area relatively small as there would be only one football pitch per complex.

Thermal vision cameras could be installed in the space, with flood lights allowing for a large field of vision over the entire pitch. The high contrast between players and the low inner fence presents an adequate foreground to simplify analysis for count, velocity, and distinction between players and spectators. For an additional metric, a radar/infra-red beam could be installed across the perimeter, or even just at the gate for an absolute count of players within to prevent double counting. Alternatively, during half-time sessions when players enter/exit the field, a timing function within the software can discern if that means a new game has started with new players, or if the same players are returning to the pitch where the additional counts can be discarded.

However, these analytics would require a custom machine learning environment which will require development time and personnel. Although a onetime cost if this solution is to be used at scale, may require months of development at high cost.

Scenario 3: Low fenced or no fenced, un-restricted fields, multiple pitched fields in close proximity, or multi use sports centers

Figure 11: Examples of low-fenced fields: Charles Bean Oval (left), Jamison Park Penrith (middle) and Hensley Athletics Field (right)

The last category of field types involved large, unrestricted areas where multiple activities may be occurring in the surroundings outside the pitch, requiring more precise sensing to determine if the field is being used, and in what way.

As there is no infrastructure that restricts the flow of people into the area (such a gate) this eliminates radar and infrared beam people counting solutions, additionally the large area to cover and the processing required to discern between field use and not would be complex for a DIY ML algorithm that would be required by a thermal sensor.

In this case, a **LiDAR** solution may be considered. A LiDAR sensor such as that recommended by Ouster would be able to cover a large area with a high enough resolution to determine the speed and size of moving people. This would be especially useful for the athletics field case where people running around the track would show an evident circular pathway around the field. Virtual perimeters can also be drawn in the analytics software, facilitating analysis for fields with no physical boundary, or where multiple pitches are merged allowing for the possibility of a rate of use heat map where one field may be more utilised than the other.

See Table 7 below for a summary of appropriated/DIY solutions suggested for each scenario and how they meet requirements compared to using Company A. As shown in the table, only one solution can determine wear of the field. Every other appropriate/DIY option will require this body of work, separate from the already discussed hardware and machine learning activities.

Table 7 Summary of the scenario and requirement comparisons

Req. ID	**Requirement**	**Scenario 1: radar/infra-red beam**	**Scenario 2: thermal vision and counter at gates**	**Scenario 3: Lidar system**	**All scenarios: Company A offering**
1	The system will be able to capture all individuals on the playable field space	✓	✓	✓	✓
2	The system shall be able to distinguish human beings from objects and animals	?	✓	✓	✓
3	The system shall be able to count distinct individuals as they move in and out of the field of vision	✓	✗	✗	✗
4	The system shall be able to characterize activity type and body size	✗	✗	✓	?
5	The system shall be able to inform maintenance activities on the field	✗	✗	✗	✓
	Rational for unmet requirements if any (marked with "?")	Not necessary as fields are gated and only sport players would be entering the premises.	Would require significant machine learning development, may involve complex/costly development		Vendor chooses not to collect this data as it leads to legal issues.
	Additional notes	Low cost, Wi-Fi based solution	Risky as it requires DIY analytics	High cost and requires additional development	

As can be seen from these three examples, the exact sensor solution heavily depends on the environment and user needs. These case studies are only meant to serve as a suggestion and each scenario needs to be assessed individually. This report should serve as a comprehensive guide of all considerations when deploying a human counting smart sensor for sport fields.

6. Study: TOR 4 – Study Design Approaches

Based on the previous analysis in Section 5, here we look towards what would be the lowest cost count solution to be recommended as a pilot study. This would serve as a short-term data collection exercise to provide some quick information about field usage.

In cases such as Scenario 1 or 2, a simple approach would be to use infrared or radar gate counters to track people entering and exiting the fields. It would be best to reference these detections with existing booking systems to ensure correlation – both booking size and event type (whether adult/child activities can be ascertained). Since the sensor system cannot determine activity type, care would also be needed to ensure any maintenance schedules are omitted from the detections.

To ensure good data sampling, it would be best to collect data on both synthetic and natural fields within proximity. This would ensure that similar conditions (weather and population demand) are faced on both fields.

For the pilot study (3-4 months of data collection), the requirements would be:

- Two fields (synthetic and natural) in the same suburb/locality
- 1.0 FTE Electronics Engineer to develop the data gathering hardware
- Local council involvement (assets team) to arrange the fitment of hardware to public spaces
- Access to existing sport field booking system for referencing

Though this is not a completely robust and scalable sensor system for long term use, it can be the cost-effective solution to test basic assumptions about sport field usage and its effect on the surface quality.

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Appendix

1. Sydney artificial field survey

Park Name	Restricted access to complex	Restricted access to turf	Immediate surroundings
Moore park	NA	High gate	Natural parkland and other sport courts
Waverly	NA	Low gate	Natural parkland and other sport courts
Heffron Park	NA	Low gate	Natural parkland and other sport courts
Pennant Hills Park Field 3	No	Low gate	Stand alone
Majors Bay Reserve	High outer gate	Low gate	Natural parkland
Kareela Oval	NA	Low gate	Natural turf field
Mason park 1	NA	Low gate	Natural parkland
Arlington Oval	High outer gate	Low gate	Stand alone stadium
Hensley Athletic Field, Eastgardens	High outer gate	None	Athletics stadium with track
Northbridge Oval	High outer gate	High gate	Stand alone stadium
Cromer Park	High outer gate	Low gate	Stand alone stadium
Ultimate Soccer Fairfield	NA	High gate	Multi pitch complex
Melwood Oval	NA	Low gate	Natural parkland, this is an AFL field
Fraser Park 5 Aside	NA	High gate	Multi pitch complex
UNSW David Phillips Field	NA	Low gate	Multi pitch complex
Blacktown City Football Center	High outer gate	Low gate	Stand alone stadium
North Turramurra Recreation Area	NA	Low gate	Natural parkland
Blacktown Football Park	High outer gate	Low gate	Stand alone stadium
Centennial Parklands Sports Center	NA	High gate	Multi pitch complex
Peakhust park	NA	Low gate	Natural parkland
Valentine Sports Park, Glenwood	NA	Low gate	Multi sport center
Charles Bean Oval Lindfield	NA	None	Natural parkland
Brighton Memorial Playing fields	NA	Low gate	Natural parkland
KIKOFFf Canterbury	NA	High gate	Multi pitch complex
Andrew Petrie Oval Woollahra	NA	Low gate	Stand alone stadium
Jensen Park Regents Park	NA	Low gate	Stand alone stadium
Fraser Park Football Club Marrickville	NA	High gate futsal Low gate full sized	Multi pitch complex
Seymour Shaw Stadium	NA	Low gate	Stand alone stadium
Wanderers Football Park	NA	High gate	Multi pitch complex
Bankstown Community Football 5 a Side	NA	High gate	Multi pitch complex
Rockdale Llinden Sports Centre	High outer gate	Low gate	Stand alone stadium
Strathfield Park	NA	Low gate	Natural parkland
Lantham Park	NA	None	Natural parkland
Waverly Oval	High fence	Low gate	Natural parkland
Arncliff Park	NA	Low gate	Natural parkland
Poulton Park	NA	Low gate	Natural parkland
The Ponds Stadium	High	Low gate	Stand alone stadium

Percentage of gate access only complexes (individual fields within complexes not counted)	24

Appendix 12

National Sports Injury Data Strategy

Appendix 12: Response to NSW Office of the Chief Scientist review on use of synthetic turf in public spaces in NSW

1.1 The project

The Australian Institute of Health and Welfare (AIHW) is working on a National Sport Injury Project, which aims to improve and develop national sport injury data to inform injury prevention and increase participation. The project will also perform an economic analysis on sports injury and participation.

This project is funded by Sport Australia and was allocated $2.8 million in the 2022-23 Australian Budget. The project is led by a project team of staff across the AIHW, Sport Australia and the Australian Institute of Sport. A Steering Committee provides advice from experts in sports injury epidemiology and representatives from key stakeholders, including major sports organisations and the Department of Health. The committee meets quarterly to review the long-term work plan for the project and provide strategic advice.

In February 2022, the AIHW published a draft *National Sports Injury Data Strategy* following extensive consultation with:

- Health and technology experts
- Government and industry bodies
- Insurers
- Sports trainers and first aid providers
- Sporting organisations (national and state/territory)

The draft *Strategy* outlines the proposed approach to develop a National Sports Injury Data Asset (NSIDA). Online consultation sought additional feedback which will be incorporated in an updated *Strategy*. Further knowledge gaps identified in the feedback included:

- Injury impacts
- Treatment outcomes
- Dental and eye injuries
- Injury severity
- Protective equipment and
- Participation data.

1.1.1 Data capture

A number of sources are being investigated for use in a NSIDA, and include existing data already collected by sporting organisations and sport insurers. If these data sources include information about the playing surfaces, then this data can be reported at an aggregated level if there is sufficient data to aggregate.

A question on playing surface is included in a simple and anonymous sports injury data collection tool being piloted by the AIHW to collect new sport injury data.

The AIHW is also working with organisations to obtain existing data and to encourage data reporting as described in the draft strategy. Some timelines provided in the draft strategy have been impacted by COVID and wet weather affecting on numbers of participants, games played, volunteer numbers and the capacity for organisations to absorb changes to existing procedures.

1.1.2 Future Directions

The updated *Strategy* is anticipated to be released in late 2022. Implementation of the final *Strategy* will depend on funding decisions on the new Federal Government.

Appendix 13

Per- and Poly-fluoroalkyl Substances (PFAS)

DOC22/729022-1

Dr Suzanne Pierce
Director Policy, Science & Research
Office of the Chief Scientist and Engineer
GPO Box 5477
SYDNEY NSW 2001

By email: suzanne.pierce@chiefscientist.nsw.gov.au

Dear Dr Pierce

NSW Technical Advisory Group
Synthetic turf in public spaces - risk of per- and poly-fluoroalkyl substances (PFAS)

I refer to the Office of the Chief Scientist and Engineer (OCSE) letter dated 20 July 2022 requesting advice from NSW Government agencies and entities on the potential risks to the environment and human health from the use of synthetic turf in public spaces.

Specifically, OCSE has requested advice from the NSW PFAS Technical Advisory Group (TAG) on potential impacts of per- and poly-fluoroalkyl substances (PFAS) from synthetic turf.

Your request has been reviewed by the members of the TAG including the Environment Protection Authority (EPA), Department of Planning and Environment – Science, Department of Primary Industries, Department of Planning and Environment – Water, and NSW Health.

The TAG has provided a response to each of your seven (7) questions and general comments in **Appendix 1**. Please note, this response is in addition to advice that was provided directly to your office from NSW Health and Department of Primary Industries – NSW Food Authority.

If you have any further questions about this issue, please contact Maria Moreno, A/Unit Head Operations Metro North, on 02 9995 5169 or at Maria.Moreno@epa.nsw.gov.au.

Yours sincerely

30 August 2022

David Gathercole
A/Director Regulatory Operations Metro North
Environment Protection Authority

Appendix 1

NSW PFAS Technical Advisory Group advice to Office of the Chief Scientist and Engineer on PFAS exposure from synthetic turf in public spaces-August 2022

Please find a response to questions on notice below.

This response should be read along with the information provided in **Attachment A** of Office of the Chief Scientist and Engineer correspondence dated 20 July 2022.

a. Is the information set out in points 1-11 below accurate and/or have there been changes of note that the Review should be aware of, including research priorities and programs?

Point 1:
enHealth guidance on risk assessment provides a framework for assessing human health risks. We also note that there is a potential for contaminants to leach into stormwater and otherwise into the environment (i.e., implications for ecological and environmental risks), and therefore a reference to the Australian Water Quality framework for assessing contaminant risk to aquatic ecosystems is also recommended.

Point 2, 3 and 5:
As point 1 indicates, the process for undertaking a human health risk assessment is based on enHealth guidance. As such, the TAG suggests that the focus for any human health assessment of risk from PFAS needs to use the tolerable daily intake (TDI, FSANZ) - rather than the inclusion of point 2, 3 and 5 which are communication points from Health Organisations on the potential health effects of PFAS. The TDI is designed to be protective of these health effects, and thus we suggest this is referred to instead.

Point 4:
The PFAS Health Study (December 2021) investigated the health effects of PFAS of three Australian communities exposed to historical fire-fighting foam products used on Defence bases. It is unlikely that PFAS from the pile blades of synthetic turf would reach those contamination levels and therefore from a risk communication perspective, those studies need to be interpretated appropriately within the context the synthetic turf review.

If the purpose of this point is to link PFAS exposure with health risks, we refer to the process of a risk assessment using the TDI above.

Point 7:
The reference to human health and ecological guideline values for soil and biota guideline values are not relevant for the purpose of synthetic turf. The way these guidelines are determined do not apply in this instance, and it would be inappropriate to apply these guideline values to PFAS concentrations in synthetic turf (e.g., synthetic turf exposure is not the same as soil exposure, and wildlife criteria are for food that wildlife eat). The ecological water quality guidelines referred to in point 7 however would be useful if risk from PFAS leaching from synthetic turf and rubber infill or monitoring of stormwater/waterways downstream from synthetic fields was undertaken.

Point 8:
Comparison of PFAS in synthetic turf with soil is not appropriate, given that PFAS is not naturally occurring, and soil is not a 'product.' It could be more useful to compare PFAS levels in synthetic turf with other products that have deliberately had PFAS added for water resistance/surface protection etc. purposes (e.g., raincoats and other plastics) as a comparative level.

The comment on leachability is valid and applies to all potential contaminants that could leach from synthetic turf (noting we believe there are likely to be more relevant contaminants of concern other than PFAS based on a hazard and concertation basis). This part of the comment could be separated from the soil comment and linked with water quality guideline values.

Point 9:

The TAG is not sure of the purpose of this statement.

It could be useful to recognise that synthetic turf sporting fields generally fall under council's jurisdiction. Further, it could be useful to investigate if PFAS has been on the radar for any councils with synthetic turf sporting fields. Especially given that some have stormwater monitoring projects that address potential contaminants of concerns from synthetic fields.

Point 10:

The TAG is not sure the relevance of singling PFHxA out from all the other PFAS, given that you may wish to identify first if PFHxA is even present in synthetic turf and plastics. Also, other PFAS have already been listed in the Stockholm convention and therefore should be phased out with time as well. This leads to 2 points:

- not all countries that manufacture PFAS and products that contain PFAS are registered to Stockholm or the European system. Therefore, this is unlikely to directly translate to PFAS presence synthetic turf globally; and
- this assumes that the presence of PFAS in synthetic turf and rubber infill is a deliberate addition into the articles. To get a feel of the likelihood of this, we recommend a scan of the literature on PFAS concentrations in articles that deliberately have PFAS added as a comparison to those levels identified in synthetic turf. It is also likely that PFAS in synthetic turf is due to the feedstock used to make the products, and/or the materials used in the recycling process. This also means that depending on the feed stock, there is likely to be high variability in potential contaminant concentrations.

Point 11:

As in comment on point 10, we are not sure how US EPA chemical regulation translates to PFAS in synthetic turf in Australia. The Australian government via AICIS and the IChEMS also have reporting requirements for importing chemicals into Australia. Would it be more useful to explore if and how these may have influences on contaminants of concern in products/synthetic turf? The statement listed further seems to be related to the importation of PFAS chemicals, rather than PFAS contained in articles/products. It should be established whether this is relevant in the context of synthetic turf used in Australia. Is the turf produced in Australia or is it produced overseas (and where) and then imported into Australia in its final form?

b. Is the TAG aware of other literature (not referenced above) or literature searches specific to the use of synthetic turf and impacts on human, environmental or ecological health that may be relevant to the Review Terms of Reference?

Specific to PFAS in synthetic turf, the TAG is aware the following paper, although note, we have not undertaken a review for papers specific to this request):

> Mélanie Z. Lauria, Ayman Naim, Merle Plassmann, Jenny Fäldt, Roxana Sühring, and Jonathan P. Benskin. Widespread Occurrence of Non-Extractable Fluorine in Artificial Turfs from Stockholm, Sweden. *Environmental Science & Technology Letters* 2022 9 (8), 666-672. DOI: 10.1021/acs.estlett.2c00260

The paper seems to be the publication connected to the Master's thesis that was referenced. Comparisons of the different analytical techniques employed are also in this paper.

c. **Could the TAG comment on the values found in the limited studies and samples referenced above relative to other values observed in priority PFAS-affected sites in Australia, potential routes of exposure and implications, if any, in light of current knowledge and evidence?**

Expected pathways are accidental ingestion and dermal contact, however, we are not aware of any PFAS exposure pathways being assessed for users of synthetic turf fields. Based on the current knowledge on concentrations of PFAS in synthetic turf and its contribution of exposure pathways, the resultant health impacts would be minimal.

Additional points of note:

- The study mentioned above listed concentrations of PFOS in the sporting field in the range of 84-118 pg/g (0.084 ug/kg - 0.118 µg/kg) and PFOA in the range of 46 – 96 pg/g (0.046 µg/kg – 0.096 µg/kg). This is lower than the typical laboratory reporting limits in many matrices.
- Comparing the concentration of PFOS/PFOA in the sporting field to the concentration of PFOS/PFOA in other plastics or food packaging materials may be a more useful approach in this instance. We suggest a review of such data is undertaken, but as an example, a study of PFAS in popcorn bags found concentrations of PFOS up to 7.7 µg/kg (Mortera and Tena 2013). The Australian packaging Covenant also tested Australian popcorn bags and found concentrations of total PFAS (sum of 28 targeted PFAS) up to 69 µg/kg.
- There are also measurements of total fluorine concentrations for some materials, but we note care must be taken when comparing such data because the lab methods used for total fluorine measurements may not be the same and as such may not be comparable.
- References:

APCO Report: PFAS+in+Fibre-Based+Packaging (packagingcovenant.org.au)
Moreta, C. and Tena, M.T., 2013. Fast determination of perfluoro compounds in packaging by focused ultrasound solid–liquid extraction and liquid chromatography coupled to quadrupole-time of flight mass spectrometry. *Journal of Chromatography A*, *1302*, pp.88-94.

d. **Is the TAG aware of any testing of synthetic turf materials in Australia?**

We are aware of some research on chemicals in or leaching from synthetic turf fields by Macquarie University, but we are not sure if PFAS is one of the chemicals of concern that are being investigated. The study is investigating the leachability of chemicals from synthetic turfs and their effects on ecosystems.

e. **Could the TAG comment on the use and value of fluorine testing for the presence of PFAS? The context for this question relates to material provided to the Review regarding the presence and markers for various chemicals of concern, including PFAS, particularly by members of the community, versus data on the effects at various concentrations and exposure pathways (per point 1 below).**

There are many different ways to test the presence of PFAS i.e., targeted measurement of specific PFAS, non-target analysis for unknown PFAS, total oxidisable precursor assay (a measure of the presence of PFAA-precursors), total organic fluorine testing, extractable organic fluorine testing. These are all likely to give very different results, an example of such a study can be seen in the paper listed above.

Understanding what the objective is for using fluorine testing, what types of fluorine are captured/not captured by specific methods (and if these are comparable) and if there are other fluorine compounds that may be present in synthetic turf other than PFAS that could influence results are important to consider.

Importantly, sound sampling strategy and appropriate study design (i.e., approaches to understand leaching potential to water and soil matrices in rainwater) are required to interpret chemical testing for PFAS meaningfully.

f. Over the course of the project, the Review was advised, including by industry stakeholders, that unless tested themselves, the composition of imported products was unknown, and that there is a need for standards.

i. The Review is considering recommendations to improve data collection, reporting and sharing. This includes for example, declaration and testing (validation) of the chemical composition of synthetic turf materials imported or manufactured. Could the TAG provide comment on the potential approach, including the parameters that might usefully be covered and/or any barriers to implementation of such an approach.

The presence of PFAS in synthetic turf maybe due to the chemical being added as an extrusion aid during the making of the pile blades, or due to contamination from other environmental sources. If the presence of PFAS in synthetic turf is very low, then routine testing for them is costly, in the context of other more prioritised chemicals such as PAHs and some heavy metals.

Additionally, it would be important to establish a list of chemicals of concern, and these will likely differ when considering human health and potential ecological/environmental risks. From this is can be systematically established if PFAS is of concern (this may already have been done by OCSE, but noting the approach we would take in general, as this information was not available to TAG).

The data collection, reporting and sharing on the chemical composition imported of manufactured, would this be voluntary with industry? Who would maintain this?

ii. The Review is also considering establishment of a sample library to promote research and the ability to compare research outcomes of different products and surfaces (e.g., performance under different conditions). Could the TAG comment on what any parameters for such library e.g., number and size of samples, etc.

If a library is established, we suggest considering different types of synthetic turf (i.e., virgin turf, newly laid and different states of weathered turf), age of the field, and environmental conditions. Where possible these samples should be collected together with stormwater to allow an investigation into chemical run-off from synthetic sporting fields.

g. Does the TAG have any views on future data collections or research priorities relevant to the Review TOR 4 more generally?

Based on above we highlight the importance of including the following in any assessments around synthetic turf:

- Environmental exposure (not only human health)
- microplastics
- identifying the key chemicals of concern

Additionally, it is recommended that testing for PFAS be considered in the context of testing for other more prevalent chemicals such as PAHs and some heavy metals.

General Comments

1 – Remaining questions relating to PFAS contamination from synthetic turf

It would seem as though there is not a currently strong understanding of the full chemical composition and stability of the chemicals in the synthetic turf matrix. There are several questions to be answered before the TAG can fully consider the issue, for instance;

- What exactly is in the turf (including raw materials) and are synthetic turfs all the same?
- Does it leach?
- How much does it leach?
- How is it transported through environmental media?
- What concentrations get into the waterways?
- Do animals take it up in any quantity?
- Does it affect fish health?
- Does contamination of fish present a significant exposure pathway for humans?

It is important to note that, in the context of aquatic fauna, the chemicals can accumulate and some of them may create risk if they reach the waterways in high enough concentrations. As to whether contaminants originating from turf is more or less significant in the context of the large stable of diffuse contaminant sources across our urban landscape, we can't say.

2 – Contaminant testing for synthetic fields

The TAG feel that there would be benefit in including PFAS in the suite of potential contaminants that are routinely investigated at synthetic field sites.

Additionally, the TAG feel that each site would been to be considered with regard to the contaminant and the surrounding environment. For instance, it would be important to identify sites where there is a risk to a particularly sensitive ecosystem or critical habitat, or where there might be cumulative contaminant pressures such as where the site is located on other known contaminated sites (i.e., sites within an existing PFAS contamination zone).

3 – Synthetic turf regulation in NSW

Synthetic turf and potential PFAS contamination of synthetic turf are not currently regulated by the EPA. Additionally, there are currently no limits on PFAS levels for synthetic turf or recovered wastes applied to land.

No data is held by the EPA regarding the potential contamination of synthetic turf, recovered wastes, and no literature reviews have been undertaken.

Mr David Gathercole
Chair, NSW PFAS Technical Advisory Group
NSW Environmental Protection Authority
Locked Bag 5022
PARRAMATTA NSW 2124
Email: David.Gathercole@epa.nsw.gov.au

Dear Mr Gathercole

**Re: Request for Advice on Per- and poly-fluoroalkyl substances (PFAS)
Review of the use of synthetic turf in public spaces**

I write in relation to a review being undertaken by the NSW Chief Scientist & Engineer into the potential risks to the environment and human health from the use of synthetic turf in public spaces (the Review). The Terms of Reference can be found here.

We are seeking assistance from NSW Government agencies and entities that may have expertise, data and/or literature related to the use of synthetic turf relative to natural surfaces. This includes the potential impacts of chemicals which may be released from synthetic turf surfaces and in-fill materials, or which may be contained in any water run-off.

PFAS has been raised with the Review as a potential series of chemicals of concern – either contained in the materials themselves (see Attachment A) or as an aid in the extrusion process (see for example Gluge et al 2020).

Attachment A contains information identified by the Review and questions that we would appreciate advice from the Technical Advisory Group. If possible, I would be grateful for a response by Friday 12 August 2022.

Should you or other members of the TAG have any questions, please do not hesitate to contact me at suzanne.pierce@chiefscientist.nsw.gov.au or phone 0428 091 861.

Yours sincerely

Dr Suzanne Pierce
Director Policy, Science & Research

20 July 2020

cc. Mr Edward Jansson, Senior Manager OCSE
Mr Kishen Lachireddy, Manager, Surveillance and Risk Unit, Health Protection NSW
Dr Pip Brock, A/Principal Project Officer, DPI
Ms Janina Beyer, A/Team Leader DPE Science
Dr Tina Jafari, lead hydrogeologist, DPE Water
Ms Alison Imlay, Manager Food Science, DPI Food Authority
Dr Matt Taylor, A/Director Fisheries Research, DPI Fisheries

Attachment A
Request for advice to the NSW PFAS Technical Advisory Group (TAG)

Background: literature

The Review team as well as independent scientific experts commissioned by the Review have undertaken searches on the presence and concentrations of PFAS in synthetic surface sporting fields. The literature relevant to synthetic turf surfaces appears limited, having reviewed Scopus, ProQuest Science and Technology databases, Web of Science and Springer Materials. Relevant information identified (including grey literature) included:

- A Masters degree thesis (Stockholm University), which sampled 18 fields, finding PFAS in 76 percent of the backing samples (concentrations ranging from 0.04 to 0.89 µg/kg) and in 18 percent of infill samples (concentrations ranging from 0.03 to 0.21 µg/kg). One sample identified PFAS in the surface blades. Concentrations appear highest In Ethylene Propylene Diene rubber (EPDM) and Styrene Butadiene Rubber (SBR) fields. Note that in Australia, the majority of fields currently installed utilise SBR products from recycled tyres.
  Source: Naim, A (2020) An Investigation into PFAS in Artificial Turf around Stockholm, in Department of Environmental Science
- A review by TRC for the City of Portsmouth, which detected very low levels of a limited number of PFAS in the synthetic turf samples, concluding the levels detected did not represent a human health risk to those using the synthetic turf
  Source: TRC (2022) Technical memorandum: Evaluation of PFAS in Synthetic Turf (attached)
- Advice to the Martha's Vineyard Commission and Oak Bluffs Planning Board on testing for PFAS in synthetic turf fields from the Ecology Centre
  Source: Ecology Centre (2020) Memo on PFAS-free Synthetic Turf Standards and Testing
- An information sheet from the Toxics Use Reduction Institute (TURI) including reports of NGO tests on field samples.
  Source Massachusetts Toxics Use Reduction Institute (2020) Per- and Poly-fluoroalkyl Substances (PFAS) in Artificial Turf Carpet.

The Review also identified a position statement from the Mount Sinai Children's Environmental Health Centre (2017) Artificial Turf: A Health-Based Consumer Guide. The primary focus of the document is on the risks of rubber crumb, although it references chemicals of concern in the blades and leaching from the product. The Guide makes suggestions for safer play on artificial surfaces. Note that NSW Health has undertaken a literature review on the health impacts of synthetic turf that encompasses rubber crumb.

Request for advice

a. Is the information set out in points 1 -11 below accurate and/or have there been changes of note that the Review should be aware of, including research priorities and programs?

b. Is the TAG aware of other literature (not referenced above) or literature searches specific to the use of synthetic turf and impacts on human, environmental or ecological health that may be relevant to the Review Terms of Reference?

c. Could the TAG comment on the values found in the limited studies and samples referenced above relative to other values observed in priority PFAS-affected sites in Australia, potential routes of exposure and implications, if any, in light of current knowledge and evidence?

d. Is the TAG aware of any testing of synthetic turf materials in Australia?

e. Could the TAG comment on the use and value of fluorine testing for the presence of PFAS? The context for this question relates to material provided to the Review regarding the presence and markers for various chemicals of concern, including PFAS, particularly by members of the community, versus data on the effects at various concentrations and exposure pathways (per point 1 below).

f. Over the course of the project, the Review was advised, including by industry stakeholders, that unless tested themselves, the composition of imported products was unknown, and that there is a need for standards.
    i. The Review is considering recommendations to improve data collection, reporting and sharing. This includes for example, declaration and testing (validation) of the chemical composition of synthetic turf materials imported or manufactured. Could the TAG provide comment on the potential approach, including the parameters that might usefully be covered and/or any barriers to implementation of such an approach.
    ii. The Review is also considering establishment of a sample library to promote research and the ability to compare research outcomes of different products and surfaces (e.g. performance under different conditions). Could the TAG comment on what any parameters for such a library e.g. number and size of samples etc.

g. Does the TAG have any views on future data collections or research priorities relevant to the Review TOR 4 more generally?

Review observations and assumptions relevant to this request for advice

1. The Environmental Health Standing Committee (enHealth) is a standing committee of the Australian Health Protection Principal Committee (AHPPC). enHealth guidance on undertaking environmental (EHRA) and human health impact risk assessments include the following: consideration of sources of issues, data on the dose or concentration of a pollutant/hazard to have an effect, the source, timing frequency and consistency of exposure among different populations, and the potential for adverse health effects, including severity and reversibility of health effects.
2. Advice by enHealth on per- and poly-fluoroalkyl substances (2019) includes that
    - *In human studies, the Expert Health Panel for PFAS found that a number of health effects (such as slightly high blood cholesterol) have been associated with PFAS exposure but these health effects are generally small and have not been shown to be clinically significant. More research is required before definitive statements can be made on causality or risk but, currently, there is no evidence of a significant impact on human health.*
    - *Although there is still uncertainty around the potential for PFAS exposure to cause significant adverse human health effects, we do know that some long chain PFAS, such as PFOS and PFOA, can persist for a long time both in the environment and in humans. Therefore, it is prudent to reduce exposure to PFAS as far as is practicable. Action should be taken to address the source of the exposure and interrupt known human exposure pathways. Determination of human exposure pathways is best achieved through a full human health risk assessment that examines all potential routes of exposure.*
    - *enHealth considers ingestion of food and drinking water contaminated with PFAS to be the major human exposure pathways. Inhalation of dust contaminated with PFAS and dermal (skin) contact with PFAS are considered to be minor exposure pathways.*
3. Australian Government Department of Health (DOH) advice includes that:
    - *There is no current evidence that supports a substantial impact on an individual's health from PFAS exposure. A number of studies show a link between PFAS exposure and several health effects, however there is limited or no evidence of human disease accompanying these health effects.*
    - *People can be exposed to PFAS in their workplace if they are involved in the manufacture or use of PFAS. Outside of the workplace, exposure to PFAS can occur from food, water (ground and surface water) and various consumer products. Dermal (skin) contact with PFAS is not considered a significant exposure pathway.*
4. The Australian National University was commissioned by the DOH to undertake research into three communities affected by PFAS contamination as a result of firefighting activities in nearby Defence Force bases. The overall ANU study findings released in December 2021 include:

- *There was clear evidence of elevated blood serum concentrations of PFAS in residents and workers in the PFAS-affected communities and increased psychological distress in the three exposed communities.*
- *The evidence for other adverse health outcomes was generally limited. For most health outcomes studied, we did not find evidence that health was worse in PFAS-affected communities than non-affected communities. Rates of some adverse outcomes were higher among people in individual PFAS areas, but this does not necessarily mean that PFAS was the cause. Overall, our findings were consistent with previous studies that have not conclusively identified causative links between PFAS and adverse health outcomes. The association between higher PFAS levels and elevated cholesterol levels was consistent with the previous evidence.*

5. NSW Health advice includes that
   - *There is currently no consistent evidence that exposure to PFOS and PFOA causes adverse human health effects. However, based on the evidence from animal studies potential adverse health effects cannot be excluded*.
   - *In humans, there is no conclusive evidence that PFASs cause any specific illnesses, including cancer.*
6. The PFAS National Environmental Management Plan (NEMP) provides nationally agreed guidance on the management of PFAS contamination in the environment, including prevention of the spread of contamination. It supports collaborative action on PFAS by the Commonwealth, state and territory and local governments around Australia. The NEMP is an Appendix to the Intergovernmental Agreement on a National Framework Responding to PFAS Contamination established in 2020. The NEMP sets out agreed definitions, primary indicators of the presence of PFAS compounds, primary and secondary sources of contamination, analytical and risk assessment methods, monitoring and management approaches. NEMP does not address current use and management of PFAS-containing products and articles. A framework for future work is organised into six themes: PFAS chemicals including analytical methods, environmental data and monitoring, water, soil, resource recovery/waste management and site-specific application of NEMP guidance.
7. The second version of NEMP released in 2020 provides updated advice on environmental guideline values for human health investigation levels for soil, including for public open space (Table 2) and ecological values including exposure scenarios for soil (Table 3), biota (Table 4) and ecological water quality (Table 5).
8. Work undertaken by the UNSW Water Research Lab for the Review notes that the levels reported (Naim, 2020) are lower than median levels reported in a global survey of PFAS in soil (Brusseau et al (2020) PFAS concentrations in soils: Background levels versus contaminated sites. However, leachability remains unknown and transport in runoff also requires testing to understand possible threats to nearby ecosystems. This approach appears consistent with exposure pathways for ecological assessments set out in section 8.6 of the NEMP.
9. The NSW Environment Protection Authority leads the NSW Government PFAS Investigation Program. Current investigations are focused on sites where it is likely that large quantities of PFAS have been used.
10. At its meeting of 21 December 2021, the EU Committees for Risk Assessment and Socio-Economic Analysis supported Germany's proposal to restrict the use of undecafluorohexanoic acid (PFHxA) and related substances. This would prohibit manufacture, production or placement on the market.
11. In June 2021, a US Environmental Protection Agency rule change requires all manufacturers (including importers) of PFAS in any year since 2011 to report information related to chemical identity, categories of use, volumes manufactured and processed, by-products, environmental and health effects, worker exposure, and disposal.

Appendix 14

Odour of synthetic turf and its relationship with local communities

The odour of synthetic turf and its relationship with local communities

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1. Introduction

The rate of uptake of synthetic turf fields for a variety of applications continues to increase in Australia and abroad (Fleming, 2011, Holderness-Roddam, 2020, Madden et al., 2018). Numerous concerns regarding synthetic turf fields have had some degree of investigation- these concerns are based around maintenance, sports injuries, ecological impacts, as well as health concerns (Brooks and Francis, 2019, Claudio, 2008, D'Andrea, 2020, Cheng et al., 2014, Wellings, 2013). Less studied however, is the impact of the odours emitted from synthetic turf fields.

A critical aspect which will determine some of the major controlling factors for the emission of odorants from synthetic turf fields is the origin of each compound, specifically, whether they are adsorbed to the turf materials already in their original form, or they are produced/modified “in-situ” by chemical, photochemical, and biochemical reactions. It is possible that different compounds may originate via different processes.

In the case of volatile organic compounds (VOCs) (i.e. compounds that elicit an odour) that do not undergo chemical transformations within the turf material, their emission rate (how much is emitted to the air within a time interval) will be controlled by:

- The dynamics of desorption (which is highly dependent on temperature),
- The diffusion of the compounds through the turf material, and
- The extent of turbulence affecting transport over the field.

In contrast, the emission rate of compounds produced by reactions will be primarily dependent on the reaction rates, which in turn may be controlled by factors including temperature, humidity, age of the material and exposure to UV radiation.

In addition to the emission rate, the concentration of odorants from synthetic turf fields to which communities are exposed depends on the dispersion of these compounds in the local atmosphere. This dispersion is highly site-specific, varying from relatively simple situations, such as if the fields are located in open parks with flat terrain and few obstacles, to very complex ones, in cases with fences and multiple buildings surrounding the field. Furthermore, atmospheric dispersion is controlled by a variety of other factors, the main ones being wind speed and direction, meandering (oscillations of the axis of the dispersed plume), and atmospheric stability (i.e., if vertical temperature and humidity differences favour or hinder mixing). Some odorants may also be susceptible to transformations as they disperse, due to chemical and photochemical reactions.

Odours play a subtle but powerful role in our perception of the world; its hidden nature and complexity makes adjudicating and assessing odour impact far more challenging than a visual or aural impact. Regardless, malodours have potential to cause considerable community dissatisfaction that can result in severe ramifications. To that end, analysis of odorants (chemicals that have an odour) and community engagement regarding malodour often requires specific and targeted methodologies and strategies to ensure accurate representations. Odours emitted from synthetic turf have yet to be formally explored and as such current research is left to extrapolate as well as provide recommendations for future investigation. From what evidence that has been collected from previous research, some potential odour culprits have been identified; however, a more stringent approach to both the chemical analysis of, and community engagement regarding, synthetic turf odour is recommended based on synthetic turf's distinctive qualities.

2. Current literature on synthetic turf

Within the domain of synthetic turf, odorants and their varying qualities have had very little investigation. With that consideration, multiple sources have cited "offensive" odour as a limiting factor for the adoption of synthetic turf, but very little information is provided beyond the odour being offensive, and that there is anecdotal understanding that this odour is stronger in synthetic fields that have a crumb rubber base and that temperature increases exacerbate the odour (Government of Western Australia, 2011, Wellings, 2013). Nillson et al. (2008) goes a little further by stating that artificial turf suffers from a "rubber smell" caused by some sulfur compounds, butyric and valeric acid, among other odorants. Further, that these claims are somewhat supported by other research (Nilsson et al., 2008, Cheng et al., 2014). Sulfurs, valeric acid, and butyric acid are well known odorants of concern and have far reaching impacts (Hayes et al., 2020). However, assertions are largely unsupported and somewhat inconsistent with information on VOCs that were able to be gleaned from other synthetic turf research. It should be kept in mind however, that the current research techniques are far from optimal to determine odorant qualities, and that these studies have predominantly focused on determining a specific class of chemicals separate from sulfurs and acids. For example, recent research by Schneider et al. 2020b and Donald et al. 2019 are concerned with toxicity levels of specific classes of chemicals- in particular Polycyclic Aromatic Hydrocarbons (PAHs) but other chemicals including other VOCs were also investigated. The differences between what is required for odour research and current synthetic turf research results in further complications. This includes deficiencies with current synthetic turf research in determining odour concentration, expected exposure to community, as well as deficiencies as to determining odour qualities (Vetrano, 2009).

In addition to the paucity of literature on odour concentrations from synthetic turf, there is little consensus on chemical measurement techniques. Variable factors in the literature include what is sampled, how the samples are prepared, measurement methodologies, as well as the ways in which that data is presented (Donald et al., 2019, Schneider et al., 2020b, Celeiro et al., 2018). To our knowledge there has been no analysis of synthetic turf that is suitable for the investigation of detection and concentration of odorants. Instead, chemical analysis of odour has centred around evaluating toxicity; the results which predominantly indicate negligible risk (Donald et al., 2019, Fleming, 2011, Marsili et al., 2014, Schneider et al., 2020b, Shalat, 2011, Smetsers et al., 2017). Nevertheless, for the purposes of determining potential odour impact of synthetic turf, there is some indication of the sorts of odorants that could be encountered. Table 1 compares chemicals detected within synthetic turf via two current studies and extracts known odorants and their odour qualities (Schneider et al., 2020b, Donald et al., 2019). However, there are several limitations with this comparison. With current research practices, this probably represents the most accurate method to determine odorous compounds but has little or no utility in terms of odour research. To begin with, extrapolating odour concentrations, especially with regards to what may be experienced by an individual, is essentially impossible in these methods. This sort of analysis also does not lend itself to recognising synergistic or antagonistic relationships between compounds which may express as different odours (Hayes et al., 2014). Another issue is that the qualities of odours detected (such as what it smells like) is circumspect. As with all research on odours, descriptions are best established through hands-on testing as descriptors of specific compounds are rare within the literature, and may be interpreted differently according to the individual detecting them (Hayes et al., 2014). Additionally, as already stated, these methods do not focus on a broad spectrum of odorants that may exist in synthetic turf; however, some research may provide indications of likely culprits.

Table 1: Chemicals detected in synthetic turf samples that elicit odour. Odour references were taken from appropriate sources (Ruth, 1986, Kim et al., 2016) unless otherwise stated.

Chemical	Odour	Zone tested	Source
1,2-dimethylnapthalene	Napthalene-like (Wiedmar et al., 2017)	Passive air sampling	Donald et al. 2019
1-Methylnaphthalenes	Not stated but low threshold- likely naphthalene-like	Passive air sampling	Donald et al. 2019
2-Methylnapthalenes	Not stated but low threshold- likely naphthalene-like	Passive air sampling	Donald et al. 2019
1,2,4-trimethylbenzene	Aromatic	Emission test chambers	Schneider et al., 2020b
1,4-dimethylnapthalene	Napthalene-like (Wiedmar et al., 2017)	Passive air sampling	Donald et al. 2019
1,5-dimethylnapthalene	Napthalene-like (Wiedmar et al., 2017)	Passive air sampling	Donald et al. 2019
1,6-dimethylnapthalene	Napthalene-like (Wiedmar et al., 2017)	Passive air sampling	Donald et al. 2019
1-methylnapthalene	Mothballs	Passive air sampling	Donald et al. 2019
2,6-dimethylnapthalene	Anise-like (Wiedmar et al., 2017)	Passive air sampling	Donald et al. 2019
2-ethyl-1-hexanol	Aromatic	Emission test chambers	Schneider et al., 2020b
2-ethylhexanoic acid	Mild	Emission test chambers	Schneider et al., 2020b
2-heptanone	Fruity, spicy	Emission test chambers	Schneider et al., 2020b
2-hexanone, 5-methyl	Fruity	Emission test chambers	Schneider et al., 2020b
2-methylnaphthalene	Threshold reported	Passive air sampling	Donald et al., 2019
4-*tert*-butylphenol	Disinfectant, leathery	Rubber matrix	Schneider et al., 2020b
Acenaphthene	Detected but uncharacterised (although an irritant)	Rubber matrix, passive air sampling	Schneider et al., 2020b Donald et al., 2019
Aniline	Rotten fish	Emission test chambers	Schneider et al., 2020b
Anthracene	Weak aromatic	Passive air sampling	Donald et al. 2019
Benzo[*a*]pyrene	Faintly aromatic	Rubber matrix	Schneider et al., 2020b
Benzo[b]fluoranthene	Chlorine-like (Ag2019)	Passive air sampling (Donald et al., 2019)	
Benzothiazole	"unpleasant", car tire-like (Wiedmar et al. 2017)	Rubber matrix and emission test chambers	Schneider et al., 2020b
BHT	Slight phenolic	Rubber matrix	Schneider et al., 2020b

BPA	Slight phenolic (Ma et al., 2019)	Rubber matrix	Schneider et al., 2020b

Chemical	**Odour**	**Zone tested**	**Source**
Cyclohexane, propyl-	Sweet, aromatic	Emission test chambers	Schneider et al., 2020b
Cyclohexanone	Sweet, pepperminty	Emission test chambers	Schneider et al., 2020b
Cyclohexylamine	Fishy, ammonia	Emission test chambers	Schneider et al., 2020b
Cyclopenta[cd]pyrene	Potentially tar-like or asphalt-like (Morgan et al., 2015)	Passive air sampling	Donald et al. 2019
Decahydronaphthalene	Aromatic	Emission test chambers	Schneider et al., 2020b
DIBP	Slight ester	Rubber matrix	Schneider et al., 2020
DINP	Slight ester	Rubber matrix	Schneider et al., 2020b
Ethylbenzene	Gasoline	Emission test chambers	Schneider et al., 2020
Fluorene	Mothballs (anecdotal), detected but uncharacterised	Rubber matrix, passive air sampling	
Formaldehyde	Pungent, hay	Emission test chambers	Schneider et al., 2020b
Isobutanol	Sweet	Emission test chambers	Schneider et al., 2020b
MBT	“unpleasant”	Rubber matrix	Schneider et al., 2020b
MIBK	Sweet, sharp	Emission test chambers	Schneider et al., 2020b
Napthalene	Mothballs, ,mouldy (Wiedmar et al. 2017)	Rubber matrix and passive air sampling	Schneider et al., 2020b Donald et al. 2019
n-heptane	Gasoline	Emission test chambers	Schneider et al., 2020b
Phenanthrene	Faintly aromatic	Rubber matrix, passive air sampling	Schneider et al., 2020b Donald et al. 2019
Styrene	Solventy, rubbery	Emission test chambers	Schneider et al., 2020b
Tert- butylamine	Ammonia	Emission test chambers	Schneider et al., 2020b
Toluene	Rubbery, mothballs, floral, pungent	Emission test chambers	Schneider et al., 2020b
Xylene	Sweet	Emission test chambers	Schneider et al., 2020b

3. Odours and components of synthetic turf

Current literature regarding the odorants emitted by applications that are situationally and chemically related to synthetic turf such as playgrounds and other facilities that may use crumb rubber are either less researched than synthetic turf with regards to odours, or can occasionally indicate consensus with synthetic turf research. Benzothiazole appears to be an ubiquitous odorant detected both in synthetic turf and crumb rubber studies, has a reasonably low odour threshold (therefore easier to smell) and its “tire-like, unpleasant” quality may be what was noticed by Nillson et al. 2008 (Wiedmar et al., 2017, Kim et al., 2016).

This unanimity provides only a direction for future research however and should not be seen as a finished outcome given the lack of knowledge regarding odour qualities and concentrations. With every study looking at specific components, there is no accounting for the influence of factors relating to synthetic turf field in its entirety; as such the overall profile may be compromised if too much emphasis is placed on this research.

3.1 ***Odour and crumb rubber***

The crumb rubber component of synthetic turf fields has been cited as the likely culprit for objectionable odour (Cheng et al., 2014). However, studies have focused on odours from processing and vulcanization of rubber. Far less research has investigated crumb rubber. One study conducted by Li et al. (2010) investigated crumb rubber material for use in synthetic turf and produced intriguing findings; namely that benzothiazole was present in all tested chemicals, and that VOC concentrations appeared to decrease in intensity within fourteen days to a consistent state thereafter. Other odorants of interest appear in Schneider et al. 2020b and Donald et al 2019. Donald et al.'s (2019) findings including naphthalene, 1-methylnapthalene, 2-methylnapthalene, BHT, 4-*tert*-octylphenol, as well as phenanthrene (Li et al., 2010). Gomes et al. (2021) indicates similar results using a database extracted from multiple sources (Gomes et al., 2021). These papers are promising with regards to methodologies as they often use more broad-spectrum measurement techniques. At the same time, care must be taken not to over-extrapolate. Crumb rubber has a variety of applications and scenarios as well as being in a variety of concentrations and forms. These variables will have a profound impact on the concentration and quality of the VOCs emitted. As a result, while a lot of research is centred in this area it is unlikely that meaningful information will be gleaned from investigation too far afield. As with synthetic turf studies, crumb rubber studies are a missed opportunity in that they do not accommodate for odour assessment.

3.2 ***Odour and synthetic turf adhesives***

A variety of adhesives are used for synthetic turf and may be the origin of potentially poor odours. Polyethylene and polypropylene possess a variety of VOCs such as 2,3-butandione ("butter, fatty, sour milk"), Nonanal ("moldy, goat-stable"), and heptanal ("fatty, stink bug", soapy"). The odour thresholds for the majority of these odorants is very low and therefore more susceptible to being malodour culprits (Hopfer et al., 2012, Bravo et al., 1992).

Polyurethane, another adhesive used in synthetic turf, is more difficult to pin down with regards to the sorts of VOCs emitted, as there is a vast amount of research that is unrelated to its application in synthetic turf and as such hypothesizing VOCs from these studies would be misleading. What is typical of most VOCs is that they become more active with increases in temperature and those found in adhesives were no different (Bravo et al., 1992). These articles also have some indicators as to what may be causing malodour but there are additional disadvantages with regards to methodology in that the amount and constitution of the adhesives being studied vary wildly and as such comparisons with synthetic turf usage should be carefully considered.

4. Impact of other factors on the way odours could be perceived with synthetic turf

Our review of the literature did not identify specific studies that investigated the origin of odorants within the synthetic turf, which, as mentioned in Section 1, can determine which processes control the emission rates of these compounds. However, we can hypothesise two possible mechanisms and discuss their implications, - desorption and in-situ production.

4.1 ***Desorption***

In this hypothetical route, the odorants are present as original components (or impurities) of the materials that make the synthetic turf. There is a natural equilibrium between the synthetic turf matrix and the air layer immediately in contact with it (which can happen on the surface and/or in pores and cavities in the material), characterised by a “saturation” concentration. This saturation concentration can be defined as the concentration of the desorbed compound in the air that is in equilibrium with the solid matrix. For a fixed temperature, the saturation concentration will be proportional, within a range, to the amount of the compound contained per meter square of material. Typically, for the same amount of compound adsorbed, this saturation concentration increases with the temperature, i.e., there is relatively more desorption at higher temperatures and explains why odours may be detected at these ranges.

The emission rate of compounds will be determined not only by the saturation concentration, but also by the conditions that promote the transport of the compounds from within the synthetic turf matrix to the air over the field. In case the material is porous and most of the desorption takes place within the pores, an important transport process is the diffusion of the odorants through the porous media (example schematics in **Figure 1**). This is controlled by each compound's molecular diffusivity in the air (D_G), and the size and tortuosity of the pores. Once the odorants reach the surface of the synthetic turf (or if they are primarily desorbed from the surface), another potentially controlling step is their transport within the wind boundary layer over the field, which can be characterised by an "aerodynamic conductance" or "gas-phase conductance" (k_G). In general terms, the more turbulence over the field, the more efficient is the transport of the desorbed compounds from the surface to the atmosphere. This turbulence depends on a variety of factors, but primarily the wind speed and the stability of the boundary layer. Higher temperatures near the surface favours mixing, since air parcels near the surface become "buoyant" and tend to move upwards. The size of the field may also play a role, especially if the terrain upwind has higher roughness or some kind of barrier. In such a case, a larger field would allow an internal boundary layer to develop further, with more intense turbulent friction (Savelyev and Taylor, 2005, Markfort et al., 2010).

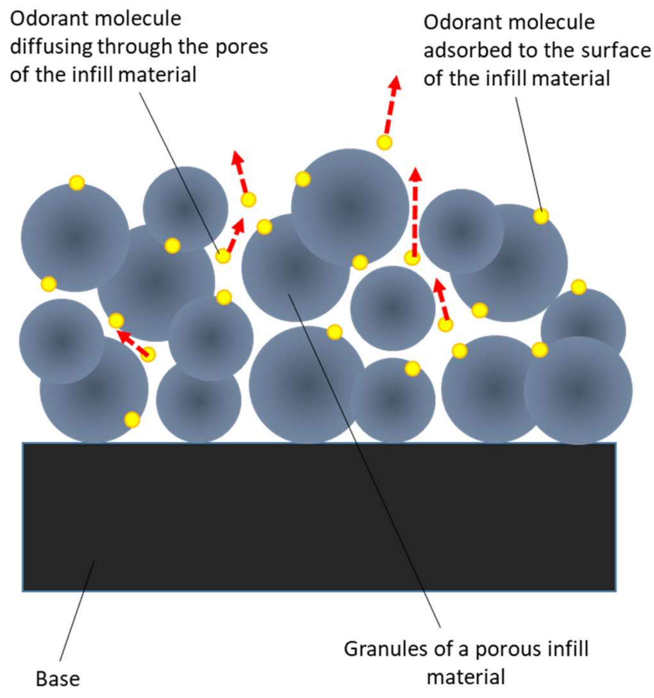

Figure 1. Schematics of a hypothetical case where odorant molecules (yellow) are adsorbed to the granules of a synthetic turf's porous infill and are diffusing through the pores of the infill layer.

4.2 *In-situ production*

Rather than being simply desorbed, the odorous compounds may be produced by reactions that transform molecules originally present in the turf matrix into the odorants of concern. The nature of these reactions can be varied, including chemical, photochemical and/or biological processes, and may be different for each compound. The emission rate of compound originated by this hypothetical route will be dependent mostly on the rate of production/transformation (that is, the reaction rates). Controlling factors for this rate may vary according to the mechanisms involved but may include one or a combination of the following (example schematics in **Figure 2**): temperature of the turf material; water content; age of the turf and/or exposure to damage; exposure to other chemicals; and intensity and duration of solar radiation.

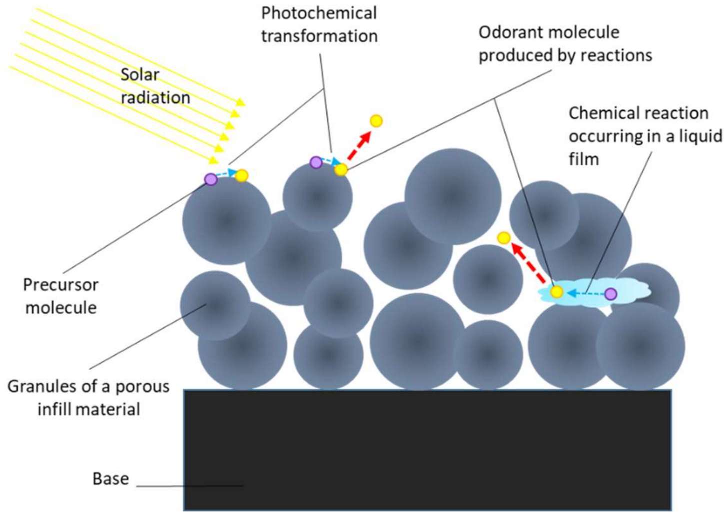

Figure 2. Schematics of a hypothetical case where odorant molecules (yellow) are produced by photochemical reactions on the surface of the infill layer and chemical reactions within a water film inside the pores of the infill material, then diffuse through the air.

4.3 ***Dispersion of odorants around synthetic turf fields***

The exposure of neighbouring communities to odorous emissions from synthetic turf fields will also depend, in addition to the emission rate, on the dispersion of the odorants in the atmosphere. In turn, the dispersion will be highly specific according to the meteorology, terrain, landscape, and layout of each site. In principle, synthetic fields may be located in a variety of terrain configurations; a main distinction that can be made is between “simple” and “complex” terrain. One of the simplest and most straightforward situations would be a field in an open park with flat terrain and few obstacles (trees, bushes, sparse buildings far from the field). In such a case, the dispersion would, on average, approach a “classical” Gaussian plume (with concentrations following a normal distribution in the span wise direction, with peak at the plume's centreline), mostly controlled by wind speed, terrain roughness and atmospheric stability (Huang, 1979; Seinfeld and Pandis, 2016). The presence of hills, forests or woods, buildings close to the field and an urban landscape will add complexities, and the specific characteristics of these elements will affect (and even sometimes dominate) the dispersion process. Of the many factors that can influence atmospheric dispersion of odorants from synthetic turf fields, some are most likely be relevant for most sites, including physical factors that are important for dispersion in general (wind speed, wind direction, wind meandering, aerodynamic roughness and atmospheric stability) and some of the potential complexities that could exist in many sites (fences and green belts, surrounding buildings and urban terrain downwind of the field). Chemical reactions are also presented as a potentially relevant phenomenon that can play a major role depending on the odorant.

4.3.1 *Wind speed*

Wind speed is one of the governing factors for dispersion in the atmosphere. In general terms, the stronger the wind, the faster the pollutant will dilute in the atmosphere, lowering its concentration. However, in cases where the emission itself is driven by the wind turbulence (which may be the case if emissions are originated via the desorption route), the increase in emission rate with wind speed may compensate the dilution effect to some extent; this possibility has not yet been well explored in the scientific literature (Brancher et al., 2021).

4.3.2 *Wind direction, meandering, and intermittency*

The direction of the wind will clearly determine where the emitted odours will travel and which areas will be affected. In cases with different types of land cover around the field, plumes may experience more or less aerodynamic roughness depending on the direction they are dispersing, meaning more or less turbulence and as a result, diffusion. If the wind direction oscillates within short intervals of time, plume meandering will occur. This will lead to an average lower concentration at points downwind, but large variations in the short-term concentration, which can contribute to odour impact.

4.3.3 *Aerodynamic roughness*

The presence of various roughness elements on the ground, such as grass, rocks, trees, and buildings, promote a loss of momentum from the wind flow to the ground boundary, which is characterised by the aerodynamic roughness length (z_0). For a same reference wind speed, the larger the z_0 along the path of the plume, the stronger the turbulent fluxes, which improves dispersion (Huang, 1979, Cimorelli et al., 2005).

4.3.4 *Atmospheric stability*

Atmospheric stability is the term used to refer to the influence of buoyancy of air parcels on the turbulence in the atmospheric boundary layer. When air parcels near the ground boundary are buoyant (smaller density due to sensible and latent heat being transferred from the ground to the air), they will tend to move upwards, thus enhancing the mechanical turbulence of the wind flow. This is denoted as unstable condition, and it promotes more dispersion of air pollutants. In contrast, if the air parcels near the ground are denser than the air layers above them (stable condition), they will resist vertical mixing, opposing the effects of mechanical turbulence and making dispersion more difficult. The development of unstable or stable conditions is controlled by the interplay of many factors, including air temperature and humidity, solar irradiance, wind speed, and terrain roughness.

4.3.5 *Fences and green belts*

The presence of fences and/or green belts upwind of the synthetic turf field can decrease the turbulent fluxes near the ground within the sheltered region downstream of the fence (Bradley and Mulhearn, 1983, Wu et al., 2015). This has the potential of decreasing emissions, if the emission of odorants is due to a desorption mechanism (thus susceptible to difference in the aerodynamic conductance). Nonetheless, this sheltering effect may increase the odour annoyance for people using the synthetic field, due to poorer dispersion over the field itself. It should also be noted that turbulent fluxes may not be significantly dampened at downwind distances farther from the fence/barrier (Bradley and Mulhearn, 1983) – in this specific case, if the size of the field is much larger than the height of the fence/barrier. **Figure 3** schematically illustrates some of the possible scenarios.

4.3.6 *Surrounding buildings*

If a building or group of buildings is upwind of the synthetic field, a sheltering effect may occur and, similarly to the presence of fences and green belts, decrease the emission of desorbed odorants. On the other hand, a few buildings downwind of the field have the potential to enhance dispersion, due to the formation of large eddies and increased turbulence.

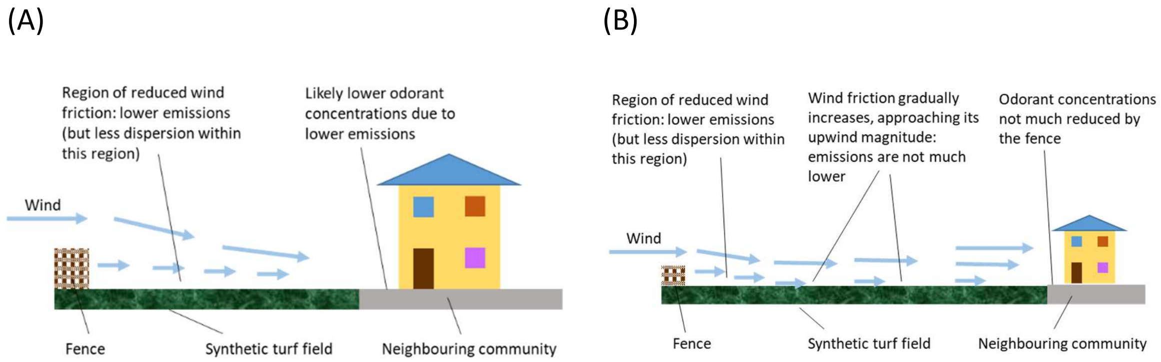

Figure 3. Conceptual representation of two possible scenarios for a fence sheltering a synthetic turf field upwind of a community: (A) a small field (compared to the size of the fence), most of which experiences a sheltering effect from the fence; (B) a large field, where the sheltered part is only a small fraction of the field.

4.3.7 *Urban terrain downwind*

Where the odorants emitted by synthetic turf fields disperse inside the urban canopy layer (that is, beneath the mean height of the buildings), several additional factors affect their transport and dispersion, including building wakes and urban canyons. One of the main aspects of these environments is that the spread of the pollutants is limited by the buildings, slowing the decrease of their concentration. Moreover, the plume may disperse in a direction that follows the street canyons (channelling), not exactly the direction of the wind (Hertwig et al., 2018); see left pane in **Figure 4** below, extracted from (Hertwig et al., 2018).

4.3.8 *Chemical reactions and odour perception*

As emitted compounds disperse in the air, they may be subjected to a variety of chemical and photochemical reactions. The occurrence and rate of these reactions will depend on the properties of each compound (some molecular forms are much more prone to react than others), the presence of other reactants, and physical factors such as temperature, humidity and solar radiation. Compounds that react in the atmosphere will most certainly have their odour characteristics altered. In that sense, some compounds may be converted to less odorous forms, while others become more odorous. Besides chemical transformations, the simple dilution of an odorant mix may change the perceived odour character, which has been dubbed the "Rolling Unmasking Effect" (Wright et al., 2021). In such cases, people at different distances downwind of the source may experience different odour impact, even identifying different odour characters/descriptors (Vitko et al., 2016).

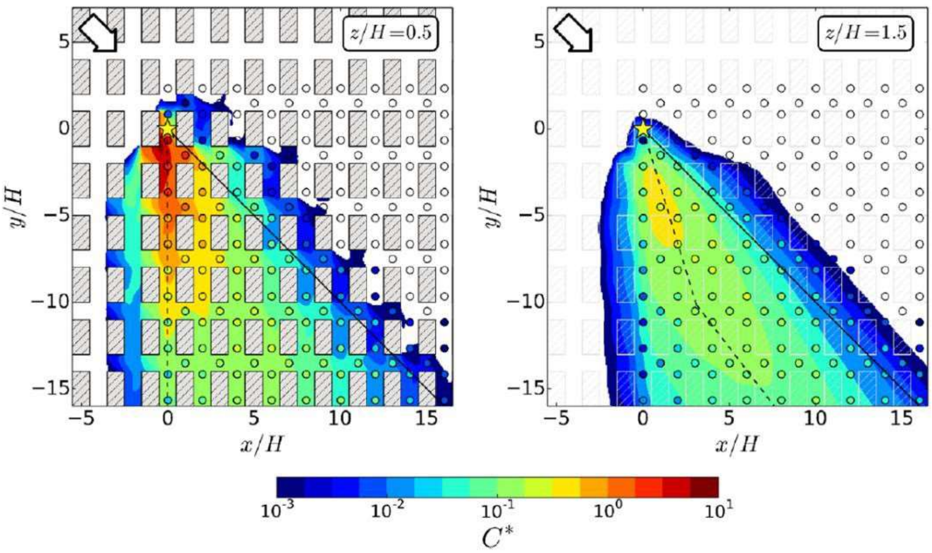

Figure 4. Example of channelling of a pollutant plume dispersing within a street network. Contours represent results of a Large Eddy Simulation (LES) and circles the experimental measurements in an aerodynamic wind-tunnel, at two different plane heights (left: half of the buildings' height; right: 1.5 times the buildings' height). Solid black lines indicate the wind direction (outside the canopy) and dashed black lines indicate the approximated plume direction based on the maximum mean concentration in the horizontal plane as calculated from the LES. The star indicates the source location. Reproduced from Hertwig et al. (2018).

5. Odour, community, and health

Odour plays a powerful, but nuanced role in an individual, and subsequently a community, and its structure and purpose require some consideration as to why it can cause significant impact.

5.1 *Neuropsychological basis of olfaction*

While an enormous topic, a small precis of how olfaction works can provide some insights into its capabilities. Briefly, the mechanism of olfaction involves odorants (predominantly VOCs) entering the nose and becoming lodged in olfactory mucosa before being detected by the olfactory epithelium (Greer, 1991, Vent et al., 2004). From here, the transduced information travels to various parts of the brain including the piriform cortex, amygdala, anterior olfactory nucleus, entorhinal cortex, parts of the thalamus, orbitofrontal and insular cortices as well as the hippocampus (Greer, 1991, Vent et al., 2004, Shipley, 1991). These are areas of the brain responsible for, among other things, emotion, memory, social behaviour regulation, navigation, and consciousness (Carter, 2019). In addition to its crucial role in emotion and memory processing, olfactory information has additional qualities including producing the most enduring and early memories available, acts as an early warning sign against hazards (in particular warnings against potential sources of illness), and promoting good hygiene (Doty and Mishra, 2001, Richardson and Zucco, 1989, Spackman, 2020). As a result of the olfaction's influence on our emotions and memories, community activism and dissatisfaction regarding malodourous emissions from various sources has resulted in numerous ramifications including installation of expensive odour amelioration technology (sometimes within the hundreds of millions of dollars), revised legislation and practice, calls for environmental justice, as well as site closures (Halpin, 2019, Sydney Water Corporation, 2019, Environmental Justice Australia, 2018, Lowman et al., 2013).

5.2 ***Odour's interaction with communities***

As a result of olfaction's importance and unique qualities, odour impact has potential to provoke emotional responses, changes in behaviour, modulation of memories, and shape the way in which the world is perceived (Richardson and Zucco, 1989, Press and Minta, 2000, Miwa et al., 2001, Doty and Mishra, 2001, Köster, 2002). Community dissatisfaction with odour can manifest in a variety of ways- typically these include becoming "activated" i.e., actively oppositional to an existence piece of infrastructure, register complaints to the company or EPA, engaging and alerting other community members, as well as attempts to bring media attention to the issue (Hayes et al., 2017a, Hayes et al., 2019, Robinson et al., 2012). There are some indicators as to predict the impact of any one specific odour; these include its intensity, quality, duration, and number of exposures (Sucker et al., 2008a, Sucker et al., 2008b). As Spackman (2020) points out, olfaction is used as an indicator of potential (or perceived) harm, particularly when unknowns are presented to a community. With that consideration, synthetic turf has several qualities that influence the way in which its odours are evaluated.

5.3 ***Factors of synthetic turf that modulate odour perception***

Because of the paucity of research based on synthetic turf, the qualities of synthetic turf and its influence on surrounding communities can only be speculated. With that in mind, there are some considerations that may influence odour perception- this includes pre-established opinions of synthetic turf as well as how synthetic turf is interacted with.

As discussed in Section 2, the predominant chemical research into synthetic turf has been based on an evaluation of its potential toxicity (Schneider et al., 2020a, Shalat, 2011). This investigation into synthetic turf potential toxicity has been driven by numerous government and public derived concerns, some of which have had intense media coverage, pitch closures, and other impacts (Claudio, 2008, Anderson and Falvey, 2016, Andrews, 2017, CDC/ATSDR, 2019). It should also be noted that the use of crumb rubber in synthetic turf has its detractors beyond potential toxicity concerns due to factors relating to rubber applications elsewhere, injury risk, processing complications, and CO2 emissions (Jones, 1994, Simon,2010, Smetsers et al., 2017, Fleming, 2011). More esoterically, ideas regarding the ”artificiality” of synthetic turf have been raised at a community level and as such should be considered when discussing community-related interactions; the smell of grass is a potent olfactory memory for many (Brooks and Francis, 2019, Bickerstaff and Walker, 2001). While none of these factors directly affect odour perception per se, odour is often considered a “lightning rod” for complaints when other issues may be more pertinent, or may bring more awareness to those concepts when the odour is experienced (Spackman, 2020, Hayes et al., 2019).

As a focal point for community dissatisfaction, synthetic turf has several unique factors to consider. Firstly, there are essentially two community groups that will likely be impacted by synthetic turf odour, namely the local community around the field, as well as the field users themselves. For local community, the fact that sufficient heat appears to intensify the odours emitted from synthetic fields is problematic as while odorants may be at a non-detectable or adapted level for the majority of the time, these heat events create multiple odour events. The numeracy of odour events is a very strong predictor of complaints (Hayes et al., 2014). For field users, in a similar vein to the “lightning rod” understanding of odours, William and Falvey (2016) note that the crumb rubber layer often disintegrates and must be washed off sports shoes and uniforms where it is noticed in a pellet form with unknown properties by community members. This sort of “unknown” may cause community members to rely on their olfactory abilities (Spackman, 2020). It is also possible, but speculative, that exertion on the fields may occasionally cause a “misattribution of arousal” wherein a person may subconsciously associate the feelings of breathlessness and exertion with the synthetic turf odour and not the fact they are exercising (White and Kight, 1984).

6. Recommendations

As the study of odour of synthetic turf is in its infancy, recommendations regarding new measurements techniques are broad but are thankfully well established. Recommendations can be divided into ways in which to measure the odorants themselves, or participate in community engagement. Chemical speciation and identification of crucial odorants represents an important goal in this research, as does ensuring the satisfaction of local communities.

Beyond this, based on pre-existing findings, there are some directions for future research. To begin with, while there is anecdotal reports of synthetic turf fields having a stronger odour with increases in temperature, and synthetic turf field heat up significantly greater compared to ambient air or natural turf, no studies have yet investigated the impact of temperature on VOC emissions (Bristol and McDermott, 2008, Smetsers et al., 2017).

Measuring the variability of VOCs with regards to temperature should be a key endeavour. Other considerations of note could include the impact of the local environment on synthetic turf fields- eucalyptus leaves and other detritus are certainly capable of interacting with odorants in unpredictable ways. Perhaps most importantly claims of sulfurs and some acids being present in detectable qualities demands further investigation, especially considering their overwhelming importance in most industrial odour control strategies and their requirement for specialised analysis (Hayes et al., 2020, Fisher et al., 2018, Fang and Qian, 2005, Choi et al., 2004).

6.1 ***Measuring odorants***

Measurement of odorants themselves can be established by either in situ techniques or laboratory analysis. In situ analyses typically involve dynamic flux chamber measurements and have had a number of pre-established settings to improve their findings (Lindberg et al., 2002). The advantages of in situ analysis include more ecologically valid measurements, but does come with drawbacks relating to experimental control, interference of ambient compounds, as well as the requirement to transport potentially heavy and delicate equipment. Similarly, laboratory analysis has international and national standards for testing VOC emissions that can be modified and will be essential to establishing odorant concentrations and qualities (International Organization of Standardisation, 2010). Laboratory based studies, such as an environmental chamber, provide more control- in instances where one variable (or several) should be focused on. Regardless of what method is established, the compound concentrations and fluxes detected by either method is affected by choices of sampling equipment, methodology, and flow rates (Lisha et al., 2022, Lindberg et al., 2002).

Regardless of the ways in which samples are prepared, the optimum route to determining pertinent odours is the use of Gas Chromatography-Mass Spectrometry/Olfactometry (GC-MS/O, **Figure 5**). GC-MS/O is a combined analytical and sensorial approach that take environmental odour samples, separates them via GC and then simultaneously detects abundance of specific compounds via MS while a panellist uses their sense of smell to detect which of these compounds elicits an odour (Hayes et al., 2014). From here, odorants of interest can be readily ascertained as well as their relative concentrations and descriptors. In this way, a trained panellist using a GC-MS/O can effectively categorise all pertinent odorants emanating from synthetic turf.

Figure 5. Example of a GC-MS/O setup. Samples are first placed in the left-hand side of the device where the GC separates the sample into its constituents, and then subsequently detected by MS. Note the olfactory detection port on the right-hand side for use by the

panellist.

Other olfactory methods could be used as well. As previously stated, sulfurs are poorly measured by GC-MS configurations and requires GC instruments with specialised detectors. GC-MS/O also does not account for antagonistic and/or synergistic effects between compounds, so a direct sampling of an air sample by a trained panellist could ensure that there are no discrepancies between the experienced odour event and GC-MS/O results (Hayes et al., 2014).

6.2 ***Community engagement policy regarding odour***

While community engagement typically does not involve sophisticated analytical instrumentation, the value of effectively engaging community members is difficult to overestimate. Surveys are a common and effective means of establishing a community's behaviour and attitudes towards odours- but they do require careful construction, so as to not "alert" participants as to odour incursions but also to investigate the core of the issue (Hayes et al., 2017b). Other tools such as town halls meetings, focus groups, and interviews are capable of providing rich qualitative information which is essential to encapsulating the factors involved in perceiving environmental odours (Hayes et al., 2014).

Engagement policies vary, but for synthetic turf complaints it can be speculated that odours are likely to affect a small proportion of the population given their commonplace presence without (as yet) significant attention drawn to their odorants. Characterising the community members impacted (as speculated to be users of synthetic turf and the local residents around it). With this in mind, care must be taken as to engage this small proportion so that the risk of an "activated" community is reduced (Robinson et al., 2012). This can be accomplished by direct, two-way communication with interested parties as opposed to more broad scope engagement of an entire community. In this way, by working with specific individuals the meaningful characteristics and qualities of the odours experienced can be well established (Hayes et al., 2017a).

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Appendix 15

Artificial turf and air quality in sporting fields: Review

Artificial turf and air quality in sporting fields: Review

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August 2022

Table of Contents

Executive Summary

	SUMMARY
Objectives of the research	The use of synthetic turf, cushioned with crumb rubber in sporting fields, has increased in recent years in Australia. However potential exposures and its risk on human health remain unclear. This review provides an overview of air quality related issues and potential benefits and risks associated with the use of synthetic turf surfaces used in outdoors sporting fields.
Scientific approach / Methodology	This review is based on scoping the scientific literature that investigated outdoor air quality and synthetic turf specifically cushioned with crumb rubber in sporting facilities and its possible health impacts on sports players as well as surrounding community. The search was conducted in *PubMed, ISI Web of Science, Scopus and Google advance* (for government reports).
New knowledge and/or added value	The literature in the current review showed that exposure to rubber crumb does not result in adverse health outcomes in sports people using synthetic turf. However, this outcome should be addressed cautiously due to the limitations observed in studies, reports and risk assessment.
Key messages	The evidence on the health and safety of synthetic turf use and air quality in sporting fields and its impact on sports people suggests being low risk. For future references: 1. There is evidence to show that certain gasses are released from artificial turf, and the main route of exposure is via inhalation. 2. The gases PAHs, VOCs, SVOCs, and other compounds in both infill and other turf components are released in air at higher temperatures, however, the possible health impacts and characteristics of these gasses within the Australian conditions needs to be further studied. 3. Epidemiological, biomonitoring and quasi experimental studies are required to understand measurements and health impacts of particles and gasses within Australian conditions and population in field conditions at the zone when compared between synthetic turf and natural turf as Australian data on this is lacking. 4. Personal air samplers (preferably equipped with a PM10 size-selective inlet) during a light sport activity like running would be a suitable procedure to estimate air quality around synthetic turf 5. Of particular concern are young children who may be at a higher risk of exposure (than adults) to gasses due to their small size and developing bodies. Further research is required to understand these exposures in children as evidence in this population is limited.

I. Introduction

The use of synthetic turf in sporting fields has increased in recent years and its impact on human health is still unclear. Synthetic turf remains a popular alternative to natural grass due to its relatively low maintenance costs, generally not requiring water or garden maintenance. Synthetic turf is artificially manufactured using a range of materials. Generally, there is a lower layer composed of padding, followed by sand and infill (rubber crumb or alternates such as cork), which holds the synthetic grass fibres which are often made of polypropylene or polyethylene (PE) (Peterson, Lemay, Pacheco Shubin, & Prueitt, 2018). Rubber crumb is usually derived from recycled tyres or rubber purposely manufactured for this role (Gomes, Rocha, Alves, & Ratola, 2021).

In recent years, there has been some public health concerns regarding artificial turf and the rubber crumb used and the potential exposure to contaminants via inhalation, dermal or absorption and ingestion (Armada et al., 2022; Claudio, 2008; Beata Grynkiewicz-Bylina, Bożena Rakwic, & Barbara Słomka-Słupik, 2022; Watterson, 2017). Critics of synthetic turf argue that the rubber crumb often contains carcinogens and organic compounds which sports players and surrounding community could be exposed to. Additionally, as sports players have higher respiratory rates, there is a danger to chemical exposure as the emitted contaminants from the rubber crumbs can be inhaled (Ginsberg et al., 2011). Due to lack of information on safety of synthetic turfs with rubber infills, a recent survey in the US found that people preferred to use natural lawns as compared to artificial turf (Barnes & Watkins, 2022)

In Australia, drought and stringent restrictions on water usage, led to the increase in the use of synthetic turf (Twomey, Otago & Saunders, 2011). This trend has continued in recent years due to easy maintenance Synthetic turf has become popular for sports including rugby and soccer in Australia, especially those with rubber infill (rubber crumb). Football NSW has produced a synthetic field guide for clubs and associations to assist in the overall use of synthetic turf (Football NSW and Northern NSWF, 2017).

The International Federation of Football Association (FIFA) is continuing to collect information on possible cancer risk due to synthetic turf use, although they report the risk to be negligible (Harrison, Bretscher, & Fletcher). Within the Australian context, it is necessary to understand the exposures to contaminants released from synthetic turf with rubber crumbs and its health impacts on potential users. This review is conducted with the aim of highlighting the literature, the gaps and further recommendations on this.

2. Methodology

The literature search was done in *PubMed, ISI Web of Science, Embase and Scopus* using the keywords in Table 1. Studies that examined human chemical exposures related to synthetic turf in sporting fields, and related exposures risks, were included. Grey literature was also searched. In determining whether to include a publication found during the literature search, a set of relevance criteria was developed. In addition, we reviewed reference lists related to recycled rubber or synthetic turf. We searched abstracts for relevance and obtained studies that evaluated either the chemical composition of recycled rubber, potential air emissions from recycled rubber, or health impacts of chemicals from recycled rubber. Injuries and accidents were not included in the report or indoor air quality. Settings other than sporting fields were not included but some overview is provided. Studies that were not in English were excluded.

Table 1: Search strategy

	Search Terms
Synthetic turf	“artificial turf” OR “Synthetic turf” OR “artificial grass” OR “rubber granulate infill” OR “synthetic pitches” OR “artificial pitch*” OR “synthetic grass” OR “synthetic playground surfaced” OR “hybrid turf” OR “astroturf”
Health implications	“Health” OR “safety” OR “risk” OR “air quality” OR pollutant OR “chemical off-gassing” OR “particulates” OR “particulate matter” OR “toxic*” OR “VOC” OR “volatile gas*” OR “semi volatile organic compounds” OR “Polycyclic aromatic hydrocarbon*” OR “benzothiazole and methyl isobutyl ketone” OR “air pollution” OR “hazard*”
Pubmed	("Health"[Title/Abstract] OR "safety"[Title/Abstract] OR "risk*"[Title/Abstract] OR "air quality"[Title/Abstract] OR "pollutant*"[Title/Abstract] OR "off-gassing"[Title/Abstract] OR "particulate*"[Title/Abstract] OR "toxic*"[Title/Abstract] OR "VOC"[Title/Abstract] OR "volatile gas*"[Title/Abstract] OR "semi volatile organic compound*"[Title/Abstract] OR "semi volatile organic compound*"[Title/Abstract] OR "volatile organic compound*"[Title/Abstract] OR "volatile organic compound*"[Title/Abstract] OR "polycyclic aromatic hydrocarbon*"[Title/Abstract] OR "benzothiazole"[Title/Abstract] OR "methyl isobutyl ketone"[Title/Abstract] OR "air pollution"[Title/Abstract] OR "Particle pollution"[Title/Abstract] OR "hazard*"[Title/Abstract] OR ("environmental exposure"[MeSH Terms] OR "hazardous substances"[MeSH Terms] OR "Health"[MeSH Terms] OR "toxic actions"[MeSH Terms] OR "Environmental Pollutants"[MeSH Terms] OR "Environmental Pollutants"[Pharmacological Action])) AND ("artificial turf"[All Fields] OR "Synthetic turf"[All Fields] OR "artificial grass"[All Fields] OR "rubber granulate infill"[All Fields] OR "synthetic pitch*"[All Fields] OR "artificial pitch*"[All Fields] OR "synthetic grass"[All Fields] OR "synthetic playground surfac*"[All Fields] OR "hybrid grass"[All Fields] OR "astroturf"[All Fields])
Scopus search	(TITLE-ABS-KEY ("artificial turf" OR "Synthetic turf" OR "artificial grass" OR "rubber granulate infill" OR "synthetic pitch*" OR "artificial pitch*" OR "synthetic grass" OR "synthetic playground surfac*" OR "hybrid turf" OR "hybrid grass" OR "astroturf") AND TITLE-ABS-KEY ("Health" OR "safety" OR "risk*" OR "air quality" OR pollutant* OR "off-gassing" OR "particulate*" OR "toxic*" OR "VOC" OR "volatile gas*" OR "semi volatile organic compound*" OR "semi-volatile organic compound*" OR "Volatile Organic Compound*" OR "Volatile-Organic Compound*" OR "Polycyclic aromatic hydrocarbon*" OR "benzothiazole" OR "methyl isobutyl ketone" OR "air pollution" OR "Particle pollution" OR "hazard*") AND NOT TITLE-ABS-KEY (injur*))
Embase search	('artificial turf'/exp OR 'artificial turf' OR 'synthetic turf' OR 'artificial grass' OR 'rubber granulate infill' OR 'synthetic pitch*' OR 'artificial pitch*' OR 'synthetic grass' OR 'synthetic playground surfac*' OR 'hybrid turf' OR 'hybrid grass' OR 'astroturf') AND ('health'/exp OR 'health' OR 'safety'/exp OR 'safety' OR 'risk*' OR 'air quality'/exp OR 'air quality' OR pollutant* OR 'off-gassing' OR 'particulate*' OR 'toxic*' OR 'voc' OR 'volatile gas*' OR 'semi volatile organic compound*' OR 'semi-volatile organic compound*' OR 'volatile organic compound*' OR 'volatile-organic compound*' OR 'polycyclic aromatic hydrocarbon*' OR 'benzothiazole'/exp OR 'benzothiazole' OR 'methyl isobutyl ketone'/exp OR 'methyl isobutyl ketone' OR 'air pollution'/exp OR 'air pollution' OR 'particle pollution' OR 'hazard*') NOT injur*

3. Results and Discussion

The popularity of artificial turf use in outdoor locations like sporting fields has increased in recent times. There has been a concern that artificial turf infill releases contaminants of health concern. However, it is unclear whether the exposure to these contaminants released have an adverse health outcome and if so to what extent. Some countries have developed guidelines and restrictions to reduce exposures to contaminants from rubber infills in synthetic turf. For example, recently the European Union approved a restriction on granules and mulches used in synthetic turf infill used in sporting fields and playgrounds to 20 µg g^{-1} for eight PAHs that are considered carcinogenic (European Chemical Agency., 2020). Further restrictions were placed by the Dutch authority to reduce the concentration of eight PAHs rubber infills in synthetic turf pitches to 17 mg/kg after further evaluating the health risks associated with synthetic turf infills (Rijksinstituut voor Volksgezondheid en Milieu (RIVM), 2017). No such restrictions have been created in Australia on the use of synthetic turf and turf materials.

3.1 Contaminant studies of synthetic turf using rubber crumb

Rubber crumb infill is used to provide cushioning and increases the life of the synthetic turf. Rubber tyres are known to contain contaminants such as volatile and semi volatile organic compounds (volatile organic chemicals (VOCs) and semi volatile organic chemicals (SVOCs) as additives that can be released in air during use, particularly the subgroup polycyclic aromatic hydrocarbons (PAHs) (CardnoChemRisk, 2013; Conesa, Fullana, & Font, 2000; Evans, 1997; Ginsberg et al., 2011; Skoczyńska, Leonards, Llompart, & De Boer, 2021). SVOCs are known to either have large ranges of vapour pressures (found in vapour phase in air) or low vapour pressures (as airborne particles) (EPA, 2022). The release of these compounds into the air is known to be largely affected by temperature (Nisar et al., 2020). An Australian study reported a mean surface temperature of synthetic turf to be higher than natural turf in both metropolitan and regional venues (by 12.46°C and 12.15 °C respectively) (Petrass, Twomey, Harvey, Otago, & LeRossignol, 2014), a potential factor in releasing airborne contaminants. A US EPA study of synthetic turf with rubber crumb identified increased emissions of VOCs and SVOCs at temperatures higher than 60°C (U.S. EPA & CDC/ATSDR, 2019). Higher temperatures recorded on outdoor synthetic turfs (up to 60°C or higher), can degrade the crumb rubber releasing chemicals such as SVOCs via air (Marsili et al., 2015).

Studies have shown that the types of contaminants released from synthetic turf rubber crumbs is dependent on the way it is being used (Perkins et al., 2019). Synthetic turfs that are new have also shown to have higher levels of PAHs and benzothiazole in crumb rubber samples than older synthetic turfs (Li, Berger, Musante, & Mattina, 2010; Junfeng Zhang, Han, Zhang, & Crain, 2008; J. Zhang et al., 2018). A laboratory study found high PAH levels from leachate from rubber compounds usually found in synthetic turf and other rubber products (National Toxicology, 2019). However, the type of rubber determines the leaching of types of chemicals (Lim & Walker, 2009; Lu, Su, Ji & Ji, 2021).

Human exposures to contaminants from synthetic turf with rubber crumb may occur via inhalation, ingestion or dermal contact. Dermal contact and inhalation are reported as a primary exposure route of PAHs and other chemicals released in synthetic turf (Diekmann, Giese, & Schaumann, 2019). However, the exposure route is highly dependent on the type and properties of chemicals released. For example, the exposure route for various PAHs (VOC, SVOCs) is through inhalation due to off-gassing, especially during higher temperatures (Perkins et al., 2019). In addition, individual characteristics (e.g. age), behaviour (e.g. use of use of gloves, mouthguards), sport played and player positions can influence exposure to the contaminants (Hibbert, Morgan, Morgan, Grissom Utile & Utile, 2017). Younger children, due to their hand to mouth habits may have higher exposures than other groups, and higher respiratory rates of players during games exposes them to higher inhalation rates of contaminants (Perkins et al., 2019).

An extensive review on health impacts of artificial turf found study results consistently showed no significant health risk to sports players on synthetic turfs, (Cheng, Hu, & Reinhard, 2014).The majority of the studies from the literature report that contaminants released from synthetic turf with rubber crumb are not high enough to not cause a health risk (Gomes et al., 2021; Pavilonis, Weisel, Buckley & Lioy, 2014). However, a few more recent studies have shown higher concentration levels that than standard concentrations (Celeiro et al., 2021; Pronk, Woutersen & Herremans, 2020; Schneider et al., 2020).

3.1.1 Study limitations

A key issue of studies reviewed is assessment of direct exposure to contaminants from synthetic turf were limited. Most of the studies reviewed extracted the chemicals from surfaces or materials in synthetic turfs using acid digestion processes and chemical analysis done at high temperatures to determine the contaminant levels. Whilst these extraction and analysis processes provide total amounts of contaminants in the material studied, a limitation is that they do not represent the number of contaminants found in the human body nor the toxicokinetic. Toxicokinetic is the absorption, distribution, and elimination of contaminates within a biological system. Furthermore, the half-lives of these chemicals in the body are not properly understood. Understanding half-lives of the chemicals from synthetic turf rubber crumb is important to understand the elimination process from the human biological system such as through the metabolic conversion or excretion through faeces. For example, chemicals such as mercury and lead have a half-life of 65 days and 30 days respectively (Brodkin et al., 2007).

3.1.2 Studies focusing on PAHs, SVOCs, or VOCs in synthetic turf

A detailed literature review was conducted to investigate more recent studies that specifically analysed PAHs, SVOCs, or VOCs in synthetic turf in sporting fields (Table 1).

There were eleven studies identified that assessed various composition of synthetic turf and infills in sporting fields in various countries. Many different compositions of PAHs were analysed, from which seven of those identified higher levels of exposures to PAHs as compared to the new EU limits of 20 $\mu g\ g^{-1}$ (European Chemical Agency, 2020). Differences in measurements and types of PAHs between studies reviewed were observed. The laboratory standards used in each of the different countries differed as well, making cross comparisons difficult.

The EU proposed limitation of eight PAHs to 20 µg g^{-1} (European Chemical Agency., 2020),was used as a comparison in this review. However, these levels are not used in other countries such as US, Netherland or not yet recognised in others like Australia. Different places have their own methodologies to calculate the threshold levels of chemicals. Standardised monitoring, sampling methods and calculating chemical threshold levels are required for better cross-comparison and assessment of risks for health purposes.

Considering the above, and in conjunction with research collaborations, Australian data needs to be generated so that it can directly inform regulatory development while remaining scientifically robust. This will lead to robust local regulation which can reduce any potential exposures from synthetic turf.

Table 1: Summary of studies that analysed PAHs, SVOCs, or VOCs in artificial turf in pitches or football fields

Reference	Country	Sample size	Samples tested	Laboratory chemical analysis	Chemical tested	Findings**
(Junfeng Zhang et al., 2008)	USA	8	Rubber granules, artificial grass fibre	HPLC & ICPMS	PAHs and other metals	Total PAHs (the sum of the 15 target PAHs) ranged from 4.40 p.p.m (i.e., mg/kg or ug/g) to 38.15 p.p.m above standards
(Nishi et al., 2022)	Japan	10	Rubber infills divided into various categories	GC–MS	46 PAHs	Lower concentrations - 14.7 µg/g for the discarded tyre samples, 11.4 µg/g for the industrial rubber samples, and 10.6 µg/g for the mixture/unknown samples.
(Celeiro, Dagnac, & Llompart, 2018)	Spain	15	Synthetic turf rubber infills and blades	GC–MS (non metals) and ICPMS (metals)	PAHs, adipates, phthalates, metals and others	16 of the PAHS detected with a total concentration of 50 µg/g- Higher concentrations
(Celeiro et al., 2021)	Portugal	50	Synthetic turf rubber infill	UAE-GC-MS/MS	40 PAHs, plasticizers and others	PAHs total concentrations up to 57 µg/g. Higher concentrations
(Schneider et al., 2020)	14 European Countries	96	Synthetic turf infills materials	GC–MS or HPLC	PAHs, metals, phthalates and heavy metals	PAHs were identified at average concentrations of <10 mg/kg-Lower concentrations
(Menichini et al., 2011)	Italy	13	Artificial turf infill	HRGC-LRMS, ICP-OES, ICP-MS	9 types of PAHS and 25 metals	High concentrations of PAH
(Marsili et al., 2015)	Italy	9	Synthetic turf and infills	HPLC/fluorescence system and atomic absorption spectrometers	PAHs, and metals	Higher concentrations of PAHs
(Pavilonis et al., 2014)	USA	25	Crumb infill and fibre products	SVOCs, PAHs, and 11 metals	Direct solid phase microextraction (DI-SPME) for SVOCs	Low concentrations of PAHs were observed
(Pronk et al., 2020)	The Netherlands	546	Synthetic turf pitches	PAHs, VOCs, phthalates and 16 metals	GCMS	High concentrations of PAHs were observed
(Sakai et al., 2022)	Japan	46	Synthetic rubber granules/products	VOCs	GCMS	28 VOCs were present – Lower levels
(B. Grynkiewicz-Bylina, B. Rakwic, & B. Słomka-Słupik, 2022)	Poland	84	Recycled rubber granules from artificial turf	8 PAHs	GCMS/MS	PAHs level reached up to 172 mg/kg
(Armada et al., 2022)	17 Countries and 4 continents*	91	Synthetic rubber infills	PAHs, phthalates	GCMS/MS	PAHs in most samples some which exceeded the standard limits

* Albania, Chile, Croatia, Finland, France, Germany, Greece, Italy, Netherlands, Poland, Portugal, Spain, Sweden, Thailand, Turkey, United Kingdom and United States;
**The EU proposed limitation of 20 µg g−1 was used as comparison (EU, 2001)

3.2 Studies examining synthetic turf exposures and specific health outcomes

A few studies have reviewed health outcomes including risk of cancer, endocrine disruptors, and allergies due to synthetic turf exposures to PAHs, VOCs, and SVOCs (Table 2).

Increased use of synthetic turf and rubber crumb infill for sports fields has led to concerns of cancer risk due to possible chemicals released (A. Bleyer, 2017). It has been suggested that chemicals like PAHs from rubber crumb may cause cancer, especially in young adults and children (Archie Bleyer & Keegan, 2018; Wiesman & Lofy, 2017). Mutagenic and/or carcinogenic effects have also been suggested due to the possible release of known or suspected chemicals from synthetic turf exposure (Dorsey et al., 2015; Leonard, Gerber, & Leonard, 1986; Luzer, 2016).The International Agency for research on cancer (IARC) identified certain type of PAHs as a group 1 carcinogenic substance. When exposure to nine PAHs via inhalation were examined in the air near artificial turf, the researchers suggested that people must be intensely using the synthetic turf for thirty years continuously to be at risk of cancer (Menichini et al., 2011). The highest risk of inhalation to synthetic turf exposure has been shown to be mostly in workers that install synthetic turf in poorly ventilated facilities and for a long period (Moretto, 2007). In a Tier 2 environmental–sanitary risk analysis, Ruffino, Fiore, and Zanetti (2013), found that the cumulative carcinogenic risk was lower than 10^{-6} and the cumulative non-carcinogenic risk lower than 1 when all the exposure routes were taken into account. The exposure routes included rainwater soaked mats, direct contact with rubber crumbs and inhalation (dusts and gasses) from artificial turf (Ruffino et al., 2013).

Concerns raised about cancer clusters in young female football players in the US, led to a review by the Washington State Department of Health, USA. The review found no causal association between playing in artificial turf and cancer risk (Washington State Department of Health., 2017). However, there study was not designed to detect causal relationship, nor was it representative of the population. Bladder cancer and leukaemia have also been linked to an organosulfur compound (a type of PAH) found in synthetic turf (Grosse et al., 2016) though we did not find any studies on this aspect in our review. An environmental analysis like those conducted by Schilirò et al. (2013) did not find any increased risk of cancer due to artificial turf use as compared to other kinds of sporting fields in relation to exposures to PM10 and PM2.5. Most of the studies have not identified whether any of the cancer causing chemicals from artificial turf are absorbed in humans (Luzer, 2016).

A biomonitoring study measured PAH levels in urine of players who were playing and training in synthetic turf fields for 2.5 hours. One of the participants out of four , excreted high 1-hydroxypyrene (proxy for PAH) (van Rooij, M., Jongeneelen, & J., 2009). However, they observed that concomitant dietary intake of PAH and not artificial turf field exposure seemed to be the cause of high PAH exposure (van Rooij et al., 2009). The sample size in this study was very small, however, was controlled for exposure through diet and other environmental exposures. Allergic sensitisation, which is the development and severity of allergic rhinitis and asthma, have shown to be associated with exposure to PAHs (Rosser, Han, Forno, & Celedón, 2018; Saxon & Diaz-Sanchez, 2005). However, no studies were identified that assessed synthetic turf use and allergic sensitisation.

There were no population-based studies identified. Most of the studies identified were risk assessment studies and only two epidemiological studies. Population studies are important to understand population variability due to dose-response relationship between contaminants and many other factors such as certain stressors, sex, age and genetics (Dornbos & LaPres, 2018). The genetic background of an individual will determine the toxicokinetic of contaminants (Dornbos & LaPres, 2018). These variabilities have not been considered in any of the studies reviewed. Longitudinal studies designs are useful in determining causality, and therefore following sports players who start using the synthetic turf fields to determine exposure to VOCs, SVOCs, PAH and health outcomes measured repeatedly over time is recommended. This would minimise in-person confounding factors leading to causal relationship between exposure and outcome.

3.2.1 Conclusions

None of the studies reviewed above have identified a causal risk due to exposures from synthetic turf and health outcomes. All the studies identified had a small sample size and none of the studies provided a sample size calculation. These results need to be interpreted with caution as small sample sizes can undermine the internal and external validity of the study. Most of the studies looked at indoor air quality rather than outdoors. Indoors studies have not been included as they were outside the scope of this review. Very limited epidemiological and biomonitoring studies were identified in the literature. In addition, studies of outdoor synthetic turf are mostly limited to adults and very few have included children. One laboratory study was identified, which determined biological and toxicological plausibility (National Toxicology Program (NTP), 2019). However, they were not able to determine vitro cytotoxic effects of volatile constituents of crumb rubber. Furthermore, they suggest there is very little evidence of systemic exposure to chemical constituents of crumb rubber(National Toxicology Program (NTP), 2019).

Table 2: Summary of synthetic turf exposure and health effects

Study	**Study sample**	**Population**	**Study design**	**Outcomes**
(Van Rooij, GM, Jongeneelen, & J, 2010)	7 (21 years)	Non-smoking football players	Toxicology study	The total PAH levels of the synthetic turf was 24 mg/kg measured for 3 days. However, the uptake of PAHs in urine of football players within the 2.5-hour timeframe was minimal.
(Archie Bleyer & Keegan, 2018)	58 counties	Young American soccer players with lymphomas (cancer)	Ecological study design	No association between individual levels exposures to artificial turfs and cancer incidence

(National Toxicology Program (NTP). 2019)	Rubber crumb cell type specific culture	Human cells	In vivo (lab study)	They suggest that "Cytotoxic effect of crumb rubber-conditioned medium in vitro might not be biologically relevant in vivo or to crumb rubber exposures in humans"

Children are known to be more vulnerable to chemical exposures than adults due to their size, physiology, and activities (Cohen Hubal et al., 2000). For example, and as noted by the World Health Organisation (WHO, 2018), children roll and crawl on the ground where contaminants reach peak concentrations, thereby exposing them to greater risk. Additionally they breathe more rapidly than adults and hence absorb more chemicals into their system (WHO, 2018). Their hand to mouth action also puts them at higher risk to exposures to contaminants. A study that looked at mouthing activities of children playing in synthetic turf playgrounds was higher in 1- to 6-year-old than older children putting them at risk of exposures to contaminants (Lopez-Galvez et al., 2022). However, this study did not assess exposures to PAHs, or VOCs. Therefore, further research is required within this population to understand how hand to mouth action may expose children to VOCs and PAHs while playing in synthetic turf.

3.3 Reports & Risk Assessments examining synthetic turf exposures and health outcomes

There have been various international agencies that have investigated and assessed the risks of using synthetic turf and rubber infill used in various settings such as sporting fields and playgrounds (Table 3).

Most of the reports identified the extent of contaminants (VOCs, SVOCs, PAHs etc.) that are released from rubber crumb and conducted health risk assessments, risk characterisation, hazard ratios, and simulations to understand the exposures. Of these reports, synthetic turf and rubber crumb infill samples were collected from various fields and the turf users were analysed which included children from 3 years up to adults.

The results and risk assessments did not identify concentrations of PAHs, VOCs, SVOCs to be of concern to human health. The reports used various risk assessment methods to determine the final outcomes of contaminants from synthetic turf with rubber crumb. Some reviews were criticised by epidemiologists like the synthetic turf and cancer study (Washington State Department of Health, 2017) due to incorrect use of interpretation of the data. It had several limitations that were noted, including flawed study design, incorrect interpretation and that their conclusion was not supported by their data (Watterson, 2017).

Table 3: Reports and key health risk assessments that addressed artificial turf with rubber crumb

Report	Country	Outcome of Interest	Findings
(Lim & Walker, 2009)	USA	Evaluating potential release of airborne particulate matter from synthetic turf fields	There was no concern for health effects from field use
(Toronto Public Health., 2015)	Canada	The health and social impacts of artificial turf on human health	There is no significant risk to health from using the fields, and the low level of risk is outweighed by the benefit of physical activity.
(BISE., 2009)	Canada	Toxicological risks from chemicals from artificial turf on outdoor sports fields.	Health risks from turf are not significant and it remains safe to play sports on artificial turf fields
(Rijksinstituut voor Volksgezondheid en Milieu (RIVM). 2017)	Netherlands	Assessed PAHs, phthalates, bisphenol A etc from rubber granulate from synthetic turf fields for health risks	Health risks are very low, in line with prior literature. An SVOC level was found to be 2.2 mg/kg dry weight.
(Norwegian Institute of Public Health and the Radium Hospital., 2006)	Norway	Risk characterisation was prepared using concentrations of PM10 and VOC where recycled rubber granulate was used	The concentrations of VOC do not increase health risk, however, knowledge on this area needs further assessment.
(National Collaborating Centre for Environmental Health., 2019)	Canada	Conducted health risk assessment of VOCs, phthalates etc from artificial turf and rubber crumb	The exposures to contaminants were not of public health concerns
(European Chemical Agency., 2020)	EU	Evaluated human health risks from PAHS, VOCs, phthalates, etc emitted from synthetic rubber crumb	The hazard estimates for excess lifetime of cancer and non-cancer for PAHs showed no thresholds of concern
(U.S. EPA & CDC/ATSDR., 2019)	US	Assessed VOCs and SVOCs, and metals in synthetic turf field with recycled tyre crumb	The concentrations of the contaminants released were below levels of harm.
(KemI, 2006)	Sweden	Comprehensive survey and assessment on current knowledge synthetic turf, with rubber granule contaminants (VOCs, PAHs)	PAH concentrations were high, however, this level could have been from other sources not assessed.
(TRC for NYC Dept of Health and Mental Hygiene., 2009)	NYC	Air sampling for a suite of SVOCs (PAHs and benzothiazole), VOCs, metals and particulate matter (PM2.5) at two outdoor crumb rubber athletic fields	No appreciable levels of SVOC and PAHs were observed.
(Wong et al., 2018)	California	Assesses various crumb rubber used in synthetic turf fields and measures PM2.5 and PM10	Ongoing
(Kawakami et al., 2022)			
(Ginsberg et al., 2011)	Connecticut	Air sampling (personal and stationary) from 4 outdoor and 1 indoor pitches.	No elevated health risks were associated with 27 chemicals of potential concerns in synthetic turfs. SVOCs were higher in indoor settings than outdoors. One of the pitches recorded 6.5 µg/m3 of one SVOC on surface.
(Washington State Department of Health., 2017)	Washington	They compared observed versus expected number of cancers in soccer players from ages 6 to 24 years	The number of cancer cases in soccer players was less than expected given rates in Washington DC.

4 Conclusion

Most of the literature reviewed has shown that rubber crumb found in synthetic turf release contaminants such as PAHs, VOCs, SVOCs, amongst other substances not included in this review. The literature in the current review showed that exposure to rubber crumb does not result in adverse health outcomes in sports people using synthetic turf. However, this outcome should be addressed cautiously due to the limitations observed in studies, reports and risk assessments.

No studies have been performed with large number of people, nor were there any longitudinal studies to understand long term effects of the air contaminants released. There was only one biomonitoring and one ecological study that have been conducted thus far. Future studies should consider epidemiological study designs, use of biological samples such as blood and urine to measure PAHs, VOCs and other contaminants in relation to health outcomes to understand body burdens. Other limitations include small sample sizes, where sample calculations have not been provided; studies that are not representative samples of populations, or methods that do not provide causality or temporality between synthetic turf use and health outcomes in various populations.

One of the risk assessment studies reviewed suggested personal air samplers (preferably equipped with a PM10 size-selective inlet) during a light sport activity like running to be a suitable procedure to estimate the actual concentrations of contaminants that athletes are exposed to (Menichini et al., 2011). Studies have shown that at higher temperatures, compounds such as VOCs, PAHs and SVOCs are released into the air exposing synthetic turf users., As Australia has a sunny and warm weather in summer, reaching high temperatures, it may be suitable to test the exposures of compounds in synthetic turf versus natural turf used in sporting fields in Australia.

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Appendix 16
Environmental lighting and heat impacts

Synthetic Turf in Public Spaces: effects of artificial light and heat on biodiversity

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Scope and brief from the NSW Chief Scientist

This document examines the potential for artificial light and heat associated with the use of synthetic turf on playing fields to affect biodiversity, in both terrestrial and marine environments. The scope required consideration of evidence specifically relating to playing fields and public spaces as well as the broader evidence for the impacts of artificial light and night and heat on biodiversity.

Light-related issues

Within the scope of the Review, provide advice on artificial light-related issues, including impacts on nocturnal (and possibly diurnal) terrestrial species, noting these issues would arise with both synthetic and grass surface sporting fields. The complexities are noted, including differences in species response, location, vegetation, colour and lux of lights. Impacts may be direct or indirect and include, but are not confined to, navigation, foraging behaviour, food sources, maturation and reproduction. The locations and scale of fields also vary e.g. dense residential areas, proximity to the coast, urban bushland or parks. It is recognised scale is relevant (e.g. impact from major stadia due to the number of lights etc.). Note that fields with lighting are typically used until 9pm-10pm on weeknights as well as on weekends.

Note that there are Australian guidelines on lighting as well as guidance from specific sports,– see for example Australian Standard AS2560 (updated in 2021 to AS5260.2), FIFA standards, Rugby, Hockey, Tennis. Sporting requirements vary in relation to lux levels, and encompass uniformity, colour temperature, glare and flicker.

Advice includes:

a. Current knowledge on environmental and ecological impacts associated with the use of lighting at sporting fields, including key issues and knowledge gaps
b. Key factors that are relevant to potential impacts, that may relate to the lighting, the species or the specific environment
c. Impacts of LED lights used for sporting fields and impacts of different coloured lights, including whether colour can mitigate adverse impacts
d. Knowledge of light spill behaviour and potential impacts on different species
e. Whether studies of non-Australian mammals and birds provide guidance on potential impacts, and/or the need for data specific to Australian conditions and species
f. Should information on sports field lighting be limited, comment on studies using non-sports field urban lighting (e.g. whether a useful proxy for potential impacts of sport fields lighting)
g. As possible, comment on national or international good practice frameworks for managing and mitigating adverse impacts of lights from sports fields
h. Critical issues for consideration by decision-makers
i. Advice on research and data collection priorities to address knowledge gaps
j. Comment on any other matters you deem relevant

Plain English Summary

Overall, there is a recognised need to limit artificial light at night (ALAN) to limit impacts on biodiversity. This seems to be universally accepted by ecologists; as solutions to these impacts rely heavily on absolute reductions on the use of light. The potential for new technologies (colour, intensity) coupled with innovative deployment (angles of lighting, filters using bands of trees) is still untested. Much of the evidence presented in this review supports the argument that these may reduce impacts on some groups depending on their relative sensitivities to different colours of light. These approaches may also reduce the extent of light spill impact on the surrounding environment, although concerns over sky glow would still persist.

At the coarsest scale the concerns are over sky glow and light spill, consensus being the less light the better, because of cumulative impacts beyond the specific site. There are potential effects on migratory species, marine protected areas, national parks, etc. by fragmenting the nocturnal habitat. There is a growing body of evidence demonstrating impacts across realms (terrestrial and marine), although some impacts are inferred from correlative studies or responses under controlled laboratory conditions.

At a finer grain, it is clear that there are good reasons to avoid a one size fits all approach for decision makers owing the idiosyncratic responses observed when assessing the impacts of ALAN. There are three key factors to take on board in the initial assessment of how light and heat;

Place based impacts: could be significant in some places (peri-urban areas with adjoining significant habitat). It is not possible to meaningfully predict impacts of ALAN without knowing what the constituent fauna are.

Temporal impacts: Light can influence breeding and nesting for some species. Therefore, while lights may have no impact at some times of year on some species, it can have significant impacts on specific times. For example, lights may be fine in Winter and catastrophic in Spring/Summer depending on the species around.

Taxonomic impacts: there is not a one size fits all for animals and different systems. Knowing what species live in areas impacted by ALAN is critical to predicting the impact, as is knowing if they are light sensitive or light tolerant.

Our understanding of biodiversity responses to ALAN and urban heat are informed by an emerging and rapidly growing knowledge base. While the key threats they pose is recognised, strategies for ameliorating their impact remain largely untested and opportunities for further research.

Current knowledge on environmental and ecological impacts associated with the use of lighting at sporting fields, including key issues and knowledge gaps

The environmental and ecological impacts of artificial lights at night (ALAN) have been widely documented (Gaston et al. 2015). These global impacts have been extensively demonstrated across multiple realms, affecting organisms in terrestrial, freshwater and marine ecosystems in multiple ways. The overwhelming evidence, is that ALAN has a dramatic effect on the physiology, ecology and behaviour of a range of animals, including;

- Extensive mortality events associated with animal navigation systems being disrupted by ALAN. These have been linked to alarming global declines in insects and migratory birds.
- Disrupted sleeping patterns as well as breeding and mating;
- Disruptions to key ecological services and interactions, such as pollination and predation; and
- Population declines and local extinctions caused by the introduction of ALAN to previously dark places, effectively fragmenting and reducing the quality of habitat for light-intolerant species

The potential groups impacted include virtually every animal with a nocturnal habit and particularly those who use light as cues for navigation and foraging activities. These include many groups of insects, including multiple key pollinator groups, bats, turtles, birds and numerous marine invertebrates and vertebrates. The research examining these impacts uses an array of experimental and survey-based approaches in field and laboratory to produce an overwhelming body of evidence that ALAN has an effect of the mortality, distribution, and behaviour across these groups. These all lend strong support to the contention that light pollution is seen as one of the leading hidden stressors in many discussions about human impacts on the environment.

The impacts of ALAN are not specific to the nature of playing surfaces, and are likely to apply to both synthetic and grass surface sporting fields. However, there is surprisingly little literature examining the specific effects of ALAN associated with sporting fields and, to our knowledge, nothing assessing how the interaction light and playing surface by impact the ecology of systems exposed to ALAN. Current knowledge is informed heavily by responses to light *per se* rather than light in sporting fields specifically. Broad general advice from the International Union for the Conservation of Nature (IUCN) on mitigating the biodiversity impacts of running sporting events and creating new sporting venues (Brownlie 2019, Brownlie et al. 2020) focuses on high level suggestions of limiting light and suggestions to explore emerging and untested technologies (Table 1).

The high level advice does not consider the importance of place-based impacts, which is critical in assessing potential impacts. Advice such as avoiding the use of lights at night where sporting fields are in close proximity to areas of high conservation significance, or attempting to position light in a way that will avoid it reaching the adjacent habitats, is central to reducing potential impacts. Areas likely to be of particularly importance are national parks, protected marine areas, habitats that supported threatened species listed under biodiversity conservation legislation, habitats that harbour species critical for ecosystem function (e.g. seagrasses) or areas that are used for nesting (e.g. beaches for sea turtles, seabird nesting grounds).

Table 1: Actions for providers of outdoor lighting to mitigate impacts on biodiversity from the IUCN report "Mitigating biodiversity impacts of sports events (Brownlie 2019). The column indicating the phase of the event in which the action should be taken highlights the ongoing nature of light impacts, as well as an emphasis on high level general impacts and actions rather than place-based approaches. (presented in Brownlie 2019 as "Table 2.2.5: Mitigating impacts of outdoor lighting on biodiversity")

Guidance	**Phase**
Habitat loss or modification	
Avoid parking heavy vehicles or placing heavy equipment under or close to mature trees where they can damage surface roots.	All phases
Disturbance or damage to wildlife	
Use essential lighting only, avoid lighting along known or likely wildlife corridors (e.g. along watercourses), especially at night	All phases
Use night lighting with a spectrum that does not disturb nocturnal wildlife. Avoid short wavelength 'blue' lights to minimise impacts on bats and insects.	All phases
Identify and implement ways to minimise light pollution within, and spreading from, the sports venue, e.g. through screening, or directional lighting.	All phases
Use shade or down lighting in areas known to be habitat for light-sensitive wild animals.	All phases
Use control systems, including timers to avoid using lights unnecessarily.	All phases
Remove all lighting as soon as possible after the sports event.	Taking down

Key factors that are relevant to potential impacts, that may relate to the lighting, the species or the specific environment

There is extensive evidence about the impacts of light on a range of fauna, in both terrestrial and marine environments. Much of what we know a diverse and growing literature identifying impacts of ALAN, at multiple spatial scales. Some of these described the impacts of ALAN at very coarse landscape scales, while others target very fine grain responses to light that are highly species and place specific. The impacts of ALAN across scales are summarised below.

At the coarsest scale, ALAN is seen as a global pollutant that operates at landscape scales and can potentially fragment the nocturnal habitat. Sky glow is the light that is scattered in the atmosphere and many cities produce a glow in the night sky that can be seen for 100 miles away (Gallaway et al 2010). Light pollution can spill into otherwise protected areas up to 15 km from urban centres and there is likely synergistic interactions between sky glow and direct illuminance (Dickerson et al., unpublished data). Management actions therefore need to consider, whenever possible, multiple spatial scales to mitigate light pollution and avoid impacts.

Light pollution affects a wide range of species, in terrestrial, marine and aquatic environment (Rodrigo-Comino et al. 2021). Below we summarise some of the work showing how a range of taxa are significantly disturbed by artificial lights (Kalinkat et al. 2021, Rodrigo-Comino et al. 2021), highlighting the widespread impacts of ALAN on biodiversity across these environments.

Impact of night light on terrestrial species

Vertebrates

Bats are one of the most diverse groups of mammals and their nocturnal habits make them especially vulnerable to the introduction of artificial light. Although responses by the group as a whole to artificial lights are inconsistent, there is a consistent global pattern that identifies strong species-specific responses driven by light-sensitive species responding negatively in a multiple ways.

Some species of bats are less effected by ALAN than others. The novel environments created by ALAN are a new niche for light-tolerant bat species, which are usually fast-flying and open-space foragers (Stone et al. 2015a, Haddock et al. 2019a), such as *Pipistrellus* spp., and *Nyctalus* spp., and their activity are related to the food abundance (Mathews et al. 2015, Bolliger et al. 2020, Villarroya-Villalba et al. 2021). Species who are slow-flying and foragers in more cluttered forest habitats, on the other hand, are actively avoiding the light areas (Haddock et al. 2019a, Villarroya-Villalba et al. 2021) and are particularly susceptible to the introduction of light into previously dark areas.

There is a strong consensus that ALAN has a negative effect on most bat species, even light-tolerant species (Jung and Threlfall 2018). Light-tolerant species in the lit areas alter their activities and behaviours, for example, *Eptesicus serotinus* delayed their emergence time (Mariton et al. 2022). *Rhinolophus pusillus* showed similar patterns when the LED light was set at their roost entrance, and they avoided departing from the roosts under the light (Luo et al. 2021). This may lead to a disrupting the cues they use to enhance their foraging activities, such as reducing their capacity to synchronise their emergence time from roosts with peak insect activity (Luo et al. 2021). Other studies show that light intensity was also the major factor affecting bat community composition, and that species richness negatively correlated to light intensity (Mena et al. 2022). However, the effects of light intensity on bat species are variable. For example, some of the fast-flying species, from the families Molossidae and Vespertilionida, do not be appear to be affected by light (Mena et al. 2022), whereas the activity of bats from other families, including open and edge foragers typically thought to light tolerant, are affected negatively by light intensity (Cory-Toussaint and Taylor 2022, Mena et al. 2022).

The behaviours and physiology of songbirds in artificially lit areas are altered as well. *Turdus migratorius*, *Fringilla coelebs*, *Cyanistes caeruleus*, *Parus major*, *Turdus merula*, and *Erithacus rubecula* sing earlier before dawn (Miller 2006, Kempenaers et al. 2010); *Turdus merula* shows earlier reproduction (Partecke et al. 2004, Dominoni et al. 2013); *Halobaena caerulea* and *Phalaenoptilus nuttallii* change their calling frequency (Mougeot and Bretagnolle 2000, Woods and Brigham 2008). ALAN disrupts the sleep cycles of diurnal birds, sleeping less and fragmented (Aulsebrook et al. 2018, Aulsebrook et al. 2020a) and affects their reproduction (Malek and Haim 2019, Malek et al. 2020).

If non-flying mammals do not evade or avoid the inappropriate habitats, those mammals may suffer from physiological disruptions under ALAN, e.g. suppressed immune activity in Siberian hamsters (Bedrosian et al. 2011) or metabolic disorders in Swiss-Webster mice (Fonken et al. 2010). These non-flying mammals may change their behaviours as well, for example, *Acomys cahirinus* decline the time of activity and foraging to avoid predation risk (Rotics et al. 2011).

Invertebrates

The effects of ALAN on arthropods have been examined from many perspectives, (e.g. Tierney et al. 2017, Owens and Lewis 2018, Owens et al. 2020), such as disturbing their circadian rhythms, behaviours, physiological processes, and so on. Insects under light areas may change behaviours, such delaying emergence time and affecting duration of feeding and courtship activity in *Drosophila melanogaster* (Tataroglu and Emery 2014). Female moths of *Mamestra brassicae*, have declined pheromones, which may affect their courtship (Van Geffen et al. 2015). ALAN also influences their orientation and navigation ability due to skyglow or disruptive polarisation (Owens and Lewis 2018). Even dim light has been shown to affect physiological processes, development rates, , immune activity, and movement (Durrant et al. 2015, Durrant et al. 2018, Thompson et al. 2019). At a global scale, concerns over the global decline of insects, sometimes referred to as "the global insect apocalypse" because of the impacts on critical ecosystems services, also implicates ALAN as a potential major stressor (Didham et al. 2020, Pennisi, 2021).

In addition to changing the distribution and abundance of animals, ALAN may also potentially affect the trophic interactions from local to a whole ecosystem (Desouhant et al. 2019, Grubisic and Grunsven 2021).The responses of invertebrates to ALAN can affect behaviours of their predators too, with some bats pursuing aggregations of insects attracted to ALAN (Rydell 1992), with bat activity positively related to insect abundance under lights (Bolliger et al. 2020, Villarroya-Villalba et al. 2021). Some spiders such as *Eriophora biapicata*, change their web building behaviour, preferring to forage under lights that have attracted potential prey items (Willmott et al. 2019).

Impact of night light on marine species

A recent high-resolution global atlas of ALAN under the sea revealed that, at 1 m depth, 1.9 million km^2 of the world's coastal seas (which is approximately the equivalent of 3.1% of the global exclusive economic zones) are exposed to biologically important ALAN (Marangoni et al 2022). This area decreases to 1.6 million km^2 at a depth of 10 m, and to 840,000 km^2 at 20 m. ALAN from both land-based sources (particularly highly urbanised coastal areas) and offshore structure/activities are driving the major impacts in the marine environment ALAN can also penetrate to significant depths within the water column (>40 m) depending on the clarity of the water.

Vertebrates

Artificial light at night has demonstrated adverse effects on a wide range of marine vertebrates, such as fish (Bolton et al 2017, Fobert et al 2019), turtles and seabirds (e.g. Rodriguez et al 2017).

Observed impacts of ALAN on fish, for example include decreases in the reproductive success (Fobert et al 2019) and changes in their predatory behaviour. Artificial light at night also causes high mortality of seabirds, one of the most endangered groups of birds globally (Rodriguez et al 2017). A recent global review showed that fledglings of burrow-nesting seabirds, and to a lesser extent adults, are attracted to and then grounded (i.e., forced to land) by lights when they fly at night. Light-induced grounding can be fatal due to collisions with human-made structures (e.g. buildings, fences, or posts) or the ground. The authors found that at least 56 species of shearwaters (Procellariiformes), of which more than 1/3 are endangered, are subject to grounding by lights.

Artificial lights can also change the abundance of prey of some seabirds. For example, on coastal, marine and terrestrial areas, light has shown to increase the foraging opportunities of several species of seagulls (Marangoni et al 2022).

Artificial light pollution has several known impacts on marine turtles, including nest site selection of adult females and orientation and dispersal of hatchlings (e.g. Witherington & Bjorndal, 1991). The degree to which species, or populations are exposed to light pollution varies across the world with populations nesting at sites closer to areas of urban or industrial development being more exposed. Therefore, if the sporting field is close to a nesting site, the light from the field can affect sea turtles.

Invertebrates and microbes

Light pollution has been shown to affect microbial assemblages, changing the composition of biofilms on rocky shores (Maggi et al. 2020), and impacting the abundance of invertebrates such as amphipods (e.g. Navarro-Barranco & Hughes, 2015). As well as affecting fouling assemblages (Bolton et al 2017, Davies et al 2014), both inhibiting and encouraging the colonization of taxa analysed, including sessile and mobile species (Davies e al 2014). Artificial light at night has also changed predatory behaviour of a gastropod (Underwood et al 2017) and caused alterations in the physiology and biochemistry of reef building corals (Levy et al 2020).

Impacts of LED lights used for sporting fields and impacts of different coloured lights, including whether colour can mitigate adverse impacts

Emerging technologies exploring the use of different colours of light are also seen as possible ways to ameliorate the impacts of ALAN (Stone et al. 2015a). However, these do not offer a one size fits all solution. There is some evidence that red lights have reduced impacts for bats and insects, but have a significant impact on migrating birds. Similarly, work in in the USA suggests that yellow light has little effect on turtles and insects, but affects some amphibians (salamanders) dramatically. There is a strong consensus that lights with blue and white wavelengths have the largest impacts, as they interfere with circadian rhythms (body clocks) and are major attractors of insects. This is of particular concern given that white LEDs (often proposed as energy efficient) contain significant amounts of blue light, and scatter more easily, increasing the footprint of light pollution. Additionally, blue light penetrates further in the water, potentially increasing the number of marine taxa that will be affected by light pollution. As such, the shift from the sodium and mercury vapour lights owing to emission concerns may increase the extent of global light pollution and impacts on biodiversity.

The effects of different light types on local bat diversity varies on among species, being strongly influenced by the spectral composition (i.e. different colours of light, Stone et al. 2015a). Bats showed a variety of responses under different light colours and types. For example, *Rhinolophus hipposideros* and *Myotis* spp. avoided areas with high-pressure sodium (HPS) and LED streetlights (Stone et al. 2009, 2012). In the contrast, some bat species, *Nyctalus*/*Eptesicus* spp. foraged extensively under the LED streetlights (Stone et al. 2012, Kerbiriou et al. 2020), but they avoided passing under the low-pressure sodium (LPS) (Stone et al. 2015b). In some cases, inconsistent results were reported. For example, some studies reported that *Pipistrellus* spp. foraging more under the LED streetlight than LPS streetlight (Stone et al. 2012), but other studies found the opposite (Kerbiriou et al. 2020). This highlights the idiosyncratic and context-dependent nature of some responses to ALAN, and how predictions of responses needs to consider species identity, location of study, and time of year.

The effect of light types and colours on arthropods have not been studied as thoroughly and a variety of responses among taxa to manipulations of these have been observed (Tierney et al. 2017). While some studies suggested that light colours do not affect the insect groups, but suggest a more binary responses of insects to any type of light (Pawson and Bader 2014, Bolliger et al. 2020), while although most detailed studies demonstrate the effects of light types and colours on insects. Metal halide (MH) attracts the most compared to LED and HPS, which tend not to differ, except for beetles (Coleoptera) which is significantly more likely to be attracted to HPS light (Wakefield et al. 2018).

However, the broad-spectrum in 'white' lights such LED and MH can attract a great diversity of insects (Pawson and Bader 2014, Wakefield et al. 2018). Reviews of work in agricultural systems suggest a substantial effect of light colour on insects (Park and Lee 2017), with the shorter wavelength LED lights being most attractive to insects, while relatively long wavelength LED lights such as red can reducing the attractiveness to insects. This is a consistent pattern among many studies show similar results, revealing that Diptera, Lepidoptera and Hemiptera in general are the most attractive by compact fluorescent lamps (CFLs) compared LED. Lower temperature colour and longer wavelength in LED can reduce phototactic behaviours of insects (Longcore et al. 2015, Davies and Smyth 2018), so a slightly adjusting the wavelength of LED lamps may reduce the negative effect of light for this group.

It is posited that LED will have greater impacts on the marine environment, due to the greater amount of blue wavelengths, which can not only penetrate further in the water column, but also have a wide range of impacts on more taxa. It is expected that the broad range of wavelengths emitted by white LEDs might allow organisms to perform colour-guided behaviours at night that were previously only possible during the day (Davies et al., 2013). Davies and Smyth (2018) highlighted that the short wavelength peak emitted by white LEDs coincides with the wavelengths to which many biological responses are known to be sensitive. These affected many invertebrate behaviours (van Langevelde et al 2011) and the melatonin response in humans (West et al., 2011), which are sensitive to short wavelengths of light (between 350 and 500 nm). Further studies have demonstrated that white LED lighting has a greater impact on short wavelength sensitive responses compared to alternative lighting technologies (Pawson & Bader, 2014). Thirdly, because LEDs illuminate a broad range of wavelengths, they have the potential to affect a greater variety of biological responses that are sensitive to specific wavelengths of light. However, there is still a big gap in knowledge on the efficacy of these strategies. more research is needed on the spectrum of light in the perception of seabirds and other marine organisms.

Knowledge of light spill behaviour and potential impacts on different species

The ecological footprint of light pollution is driven mainly by light spill, where the effects of light may manifest beyond the areas being illuminated. The degree to which these affect biodiversity are poorly known (Haddock et al. 2019a, 2019b). Most assessments of light spill are driven by human concerns over the 'trespass' of lighting into unlit areas, including the night sky. Changing the spectral composition of lighting, and possibly changing the intensity of lighting, are potential management options for sporting fields where it is impractical to prevent areas from being artificially lit or limiting the duration of lighting to outside activity periods of animals known to have activity peaks around dusk.

Despite the lack of evidence on the extent of light spill on biodiversity ,there is compelling evidence that the effects of light pollution can occur even in extremely low light levels. For example, a study looking at impacts of light pollution on the species of amphipod *Talitrus saltator* found that levels as low as 0.2 lux white lighting, which is lower in brightness than a full moon, (equivalent to artificial sky glow) reduced its locomotor activity and disorientated the migration behaviour (Torres et al., 2020). As such, understanding how these low levels of light may affect biodiversity is a key part to assessing impacts beyond the sites being lit.

Studies of ALAN on Australian fauna

The studies of ALAN on Australian animals are still limited and incomplete. In Table 2 we list ten examples for terrestrial arthropods, one for reptiles, four for birds, and six for mammals in terrestrial systems, as well as a smattering in the marine system. Although this list is not exhaustive, it reflects most of the work that has been undertaken, the taxa that have been studied and the responses that have been measured. Some studies focus on the physiological function under ALAN, such as the immune responses in Australian black field cricket (Durrant et al. 2015, Durrant et al. 2020) and Australian budgerigars (Malek and Haim 2019, Malek et al. 2020); sleep cycling in Domestic pigeons and Australian magpies (Aulsebrook et al. 2018, Aulsebrook et al. 2020a); juvenile development in Australian garden orb-web spiders (Willmott et al. 2018) and Australian black field cricket (Durrant et al. 2018). Others focus on animal movement and mating behaviours, such as Australian black field cricket (Thompson et al. 2019), Australian garden orb-web spiders (Willmott et al. 2019), and Australian native house geckos (Nordberg and Schwarzkopf 2022). Several studies focus on species composition in regional areas, such as bats (Scanlon and Petit 2008, Straka et al. 2016, Haddock et al. 2019a, b), non-flying mammals (Borchard and Eldridge 2013), and insects (Lockett et al. 2021).

Many of these studies focus on identifying the response to light, but most also speculate on the potential ways to limit the impacts of ALAN. For example Aulsebrook et al. (2020a) suggest that switching light from white to amber may decline the disruptive effect on sleep in bird species caused by white light, while increasing the tree cover in the vicinity of habitats may benefit light-sensitive bat species around urban wetlands (Straka et al. 2016). An experimental study manipulating light types indicates that bat activity reduced when switching light from mercury light to LED light, (Haddock et al. 2019b). This is an example of the field experiments that are necessary to understand how animals interact with ALAN in different habitats and their strategies to persist in anthropogenically impacted environments (Willmott et al. 2019).

Table 2. Studies of the effect of artificial light at night on biodiversity in Australia in terrestrial and marine systems

Taxa and Species	Light types	Effect	Reference
Invertebrates			
Australian black field cricket *Teleogryllus commodus*	1) 24 h constant light: white light florescent tubes (4000 lux) vs. 12 h light and 12 dark (0 lux)	Reducing body size and melatonin concentration. Negative impact on haemocyte concentrations and lytic activity (immune function)	(Durrant et al. 2015)
	2) 12 h daylight (500 lux) with 12 h darkness (0 lux) or 12 h dim (1, 10, 100 lux) environments	The high level (100 lux) of light impact on mating behaviours	(Botha et al. 2017)
	3) 12 h daylight (2600 lux, 6800 K) with 12 h darkness (0 lux) or dim (1, 10, 100 lux, 5900 K) environments	Longer juvenile development time and larger femurs	(Durrant et al. 2018)
	4) Light on or off LED (6700 K, λp = 450 nm, central zone: 14.57, lux; dimmer lighting: 1.37 lux; relative darkness: 0.20 lux)	Taking longer time for initial movement. Male spent more time in lit area during broadcasting	(Thompson et al. 2019)
	5) 12 h daylight (2500 lux) with 12 h darkness (0 lux) or dim (1, 10, 100 lux) environments	Negative impact on heamocyte concentration, lytic activity, and phenoloxidase activity	(Durrant et al. 2020)
Australian garden orb-web spiders *Eriophora biapicata*	Cool white LED light with 0 and 20 lux at night time	Maturing earlier and fewer moults but shorter lifespan, smaller body size and fewer spiderlings in lit area	(Willmott et al. 2018)

	Cool white LED light (2000 lux) at daytime; 20 lux at night time or illuminated treatments	Constructed their web in the lit areas with higher prey availability (laboratory and field experiment)	(Willmott et al. 2019)
General insects	Mercury vapour streetlights (light and dark edge); ambient darkness;	Higher biomass and lower Lepidoptera numbers in the lit areas	(Haddock et al. 2019a)
	LED (12-17 lux) mercury vapour lights (7.9-12 lux) darkness (0.29-0.66 lux) changeover from mercury vapour lights to LED	Unaffected by light treatment but moon illuminated Biomass decreasing after changeover	(Haddock et al. 2019b)
Airborne and ground-dwelling invertebrate	LED Illuminance Correlated colour temperature (CCT) Photon flux (UV/blue/yellow/red)	Aerial insect composition: interaction with trap location (under light or between the two lights) and CCT and photon flux Ground dwelling insect composition: affected by illuminance and photon flux	(Lockett et al. 2021)
Marine invertebrate			
Amphipod assemblage	LED (330 Lux) and Halogen lamps (11 lux)	Higher abundance of amphipods' individuals for all species in both ALAN treatments compared to control (dark). Greater effects observed on LED treatments, with LED attracting more individuals and differing composition.	(Navarro-Barranco & Hughes 2015)
Vertebrates			
Marine Fish			
Common clownfish *Amphiprion ocellaris*	White LEDs: 12 hours at day time (~ 2400 lux) and 12 hours at night (26.5 lux)	Eggs incubated in the presence of ALAN did not hatch; no effects on frequency of spawning or fertilization success.	(Fobert et al 2019)
Fish assemblages	LED spotlights (~159 lux)	Predatory behaviour was greatest during the day and under ALAN than at night. Fish abundance	(Bolton et al 2017)

		decreased in ALAN treatments compared to dark nights.	
Reptilia			
Australian native house geckos *Gehyra dubia*	Simulating the moon phase: full moon (0.023 lux), new moon (0.0019 lux)	Earlier emergence times and higher activity in the lit areas	(Nordberg and Schwarzkopf 2022)
Green turtle *Chelonia mydas*	400 W metal-halide light, deployed on an 8.25 m boat moored at the edge of the array, creating a light loom on the water	88% of individual hatchlings trajectories oriented towards the light	(Thums et al 2016)
Flatback turtle *Natator depressus*	Simulating impacts of coastal and industrial light glow: High-pressure sodium vapour (500, 1000 and 1300 W), metal halide (500, 1000 and 1300 W), and fluorescent white (504, 1008, and 1296 W) at different elevations	Degree of disruption that artificial light glow poses to hatchling sea-finding is highly dependent upon beach topography and horizon elevation	(Pendoley and Kamrowski 2015)
Birds			
Domestic pigeons *Columba livia* and Australian magpies *Cracticus tibicen tyrannica*	LED White (18.08 lux, 4190 K) and amber light (17.83 lux; 2,140 K)	Sleep less and fragmented sleep	(Aulsebrook et al. 2020a)
the black swan *Cygnus atratus*	blue-rich (white, 10 lux, 3,700 K) and blue-reduced (amber, 13 lux, 2,100 K) LED streetlights	Sleep less	(Aulsebrook et al. 2020b)

Australian budgerigars *Melopsittacus undulatus*	Fluorescent (200 lux, 4000K, λ = 460 nm)	Increasing body mass, suppressed melatonin levels, decreasing egg production, reducing hatchability, and increasing the disease severity	(Malek and Haim 2019, Malek et al. 2020)
Little penguin *Eudyptula minor*	natural night skylight (0.215 lux) and artificial lights (orange halogen light around 3 lux) for tourism turned on from sunset 1.5h	No obvious effect	(Rodriguez et al. 2016)
Mammals			
General bats	Artificial light at night mercury vapour street lights (3–4 lux); unlit area (0.5 lux)	A negative impact on overall bat activity and species richness for species scale, no effect on *C. gouldii, C. morio, Vespadelus vulturnus, Austronomous australis, Miniopterus schreibersii oceanensis*	(Linley 2017)
	mercury vapour streetlights (light and dark edge); ambient darkness;	Lower bat activity in the lit areas. Species-specific responses, supporting more light-sensitive species in the non-lit areas	(Haddock et al. 2019a)
	LED (12-17 lux) mercury vapour lights (7.9-12 lux) darkness (0.29-0.66 lux) changeover from mercury vapour lights to LED	Species specific responses	(Haddock et al. 2019b)
	Artificial light at night	A positive effect on Gould's wattled bat (*Chalinolobus gouldii*) and Mormopterus species	(Scanlon and Petit 2008)
General bats and White-striped free-tailed bat	Artificial light at night	Reducing bat species richness but a positive effect on White-striped free-tailed bat	(Straka et al. 2016)

Austronomus australis			
Wombats and other vertebrate animals	General floodlight on/off	No effect on wombats More kangaroos in daytime but less individuals in night time during light on. More birds in daytime during light on	(Borchard and Eldridge 2013)

Good practice frameworks for managing and mitigating adverse impacts of lights from sports fields

While there is a great deal of advice available on how to manage ALAN, much of this is highly specific to certain pressures (e.g. changes to amenity for people, or species in specific places), and some suggestions for good practice rely heavily on predicted rather than demonstrated effectiveness.

Nevertheless, documents like the Australian National Light Pollution Guidelines for Wildlife: Including marine turtles, seabirds and migratory shorebirds (2020), offer considerable insights into good practice for limiting impacts on those groups. While human-focussed documents like the Guidance Note produced by the Institution of Lighting Professionals (2021) UK , "The Reduction of Obtrusive Light" may also offer a roadmap for better ways to manage light. There are a range of studies that make up a body of work that could be built into frameworks for good practice, although many highlight the need to further work as part of their conclusions. Some of the findings from this body of work include;

- Exploring the potential to ameliorate the negative impact on bats is to turn off the light when people do not exercise. For example, turning off a swimming pool light when people do not use it (Bennett and Agpalo 2022).
- Tree cover contributes to mitigating the light effect, which can also reduce the insect vacuum effects of the light. Bats may benefit from this action as well (Straka et al. 2019, Cory-Toussaint and Taylor 2022).
- Changing the light intensity and spectral composition of lighting can decrease the effect range, and that short wavelength lighting (i.e. blue light) should be avoided (Stone et al. 2015a, Tavares et al. 2021).
- Considering the installation position of lights, such as angle and height, can be more efficient and minimise the effect of spill light in dark areas (Institution of Lighting Professionals, Guidance Note 1 for the reduction of obtrusive light 2021).
- Red lights, emerging as a popular mitigation strategy for urban night lighting, may be more likely to disrupt migratory species of birds and bats than non-migratory species (Voigt et al. 2018).
- Part-night lighting (PNL, turning off street lights during times of low human activity) have little benefit for crepuscular and nocturnal species, as their activity typically peaks around the same time as high human activity and demand for lighting, and is probably not possible at sporting fields. For some fishing species of bat, overall activity is not affected by PNL along rivers but feeding activity is reduced (Hooker et al. 2022). This is also seen in single-species studies showing the fishing bat *M. dasycneme* reduced feeding activity in response to ALAN while overall activity remained unaffected and insect prey abundance increased (Russo et al. 2019).
- Horizontal and near-horizontal lighting, such as illuminated advertisements, architectural lighting and vehicle lights, increase light trespass into areas outside the target area into adjacent unlit areas, produce more skyglow (even compared to light emitted upwards and certainly much more than light emitted downward), and are more likely to disrupt animal navigation (Gaston et al. 2012) – prioritise downward-facing lighting
- Gaston et al. (2012) suggests reducing upward and horizontally directed lighting, construction of walls and other structures and planting of vegetation to shield sensitive areas against light, replacing reflective surfaces with light absorbent ones, and greater use of light-focussing reflectors would be good options to reduce light trespass and ecological light

pollution, as well as save money as “more focussed lighting means a lower luminous flux is necessary to illuminate a given area to a required intensity”.

- More efficient design of light-focussing reflectors to help direct light where it is required (Gaston et al. 2012) may also limit light spill.
- Develop coatings for LED lights that create white light with good colour rendition, maximising human vision while minimising wavelengths emitted, allowing critical regions of the spectrum to be avoided (Gaston et al. 2012); retain older style lighting in ecologically sensitive areas, or use white lights that minimise impact on organism ecology, eg metal halide lamps emit more UV than LEDs do, potentially having a greater impact on insects and birds that use this region of the colour spectrum (Gaston et al. 2012)
- In places where sporting fields are close to the coastline, recreational events should, whenever possible be held during the day (rather than at night) and if not possible, artificial lights should be shielded to avoid attracting seabirds. In Hawaii, the number of grounded Newell’s Shearwaters decreased by 40% when the main lights of a tourist resort were shielded (Rodriguez et al 2017).
- Although some countries, such as Chile, Spain and France are trying to regulate light pollution, most documents to date have no legal basis for enforcement of recommendations (Marangoni et al 2022). Furthermore, many documents are targeted at lighting engineers or designers and provide little detail regarding ALAN management and mitigation for the protection of sensitive receptors (Marangoni et al 2022).
- Turning off streetlights along the 600 m-long bridge connecting Phillip Island to the Australian mainland reduced the number of grounded Short-tailed Shearwaters (*Ardenna tenebrosities*) (Rodrıguez et al. 2014).
- Changing the spectral composition of lights might also minimise the number of grounded birds (Rodriguez et al 2017), as fewer Short-tailed Shearwaters were grounded when LED and high pressure sodium lights were on compared to metal halide lights (Rodriguez et al 2017)

An upshot of the exploration of this early work looking at the effectiveness of managing light differently is that there are multiple approaches being advocated to address the widespread concerns over the impacts of ALAN on biodiversity, with many showing great potential. However, much of this work is recent and these findings have not been integrated into a set of best practice guidelines. These guidelines would most likely require considerable assessment of local conditions and contexts, as the work examining effects reveals multiple taxon-specific and place-based responses to ALAN.

Critical issues for consideration by decision-makers

The review of evidence of the impacts of ALAN on biodiversity highlights the challenges of using general rules to infer the potential impact of the introduction of lights to a previously dark location, or increase the use of existing lights. While there are significant concerns over the landscape and global level impacts of light through increasing sky glow with increasing the use of ALAN, the ALAN associated with playing fields depends heavily on the location of these fields, and the existing biodiversity in those areas. As such, the key questions relating to the introduction of lights to new places, or extending the use of lights in areas where they were used infrequently, and the possibility of minimising these impacts using new technologies require explicit, place-based assessments considering the fauna likely to be affected, the existing impacts of ALAN, and the cumulative impacts of increased light usage. There is a need for place-based approaches that identify the particular conservation significance of local biodiversity and surrounding landscapes, particularly of light sensitive groups taxa , in areas where ALAN is introduced

The four key issues to be considered when lights are being introduced or light regimes are being changed are;

1. Local biodiversity surveys are necessary because of the species-specific nature of responses to ALAN. It should include wider-ranging taxa and target those with known susceptibility to ALAN, especially if those are considered as being of high conservation significance. This may require both desktop surveys as well as field surveys.
2. Before and after studies are needed to understand the local species composition and potential effects after light installation. These are essentially all experiments in waiting, and an opportunity to test the effectiveness of different approaches to manage ALAN.
3. Consider the light spectra and intensity to be used in the context of the animals likely to be affected, given different animal taxa show different responses (Park and Lee 2017, Desouhant et al. 2019). While the evidence for using these to manage impacts is still relatively sparse, the putative evidence is that some emerging technologies may reduce impacts on biodiversity is promising.
4. The installation position of lights, such as angle and height, can be more efficient and minimise the effect of spill light in dark areas (Institution of Lighting Professionals, Guidance Note 1 for the reduction of obtrusive light 2021).

Effects of different light types, colours, and light spill generally on biodiversity

The emerging evidence outlining the effects of differently light types on biodiversity tells a complex story and highlights the urgent need for research testing the effectiveness of emerging technologies, especially on the assemblages of animals that may be affected by ALAN (Table 3).

- Red lights, emerging as a popular mitigation strategy for urban night lighting, may be more likely to disrupt migratory species of birds and bats than non-migratory species (Voigt et al. 2018).
- Reducing the 'trespass' of lighting into unlit areas (including the night sky), changing the spectral composition of lighting, and possibly changing the intensity of lighting may be potential management options for sporting fields where it is impractical to prevent areas from being artificially lit or limiting the duration of lighting to outside activity periods of animals known to have activity peaks around dusk (e.g. Haddock et al. 2019b).
- Part-night lighting (turning off street lights during times of low human activity) have little benefit for crepuscular and nocturnal species, as their activity typically peaks around the same time as high human activity and demand for lighting, and is probably not possible at sporting fields. For some fishing species of bat, overall activity is not affected by part-night lighting along rivers but feeding activity is reduced (Hooker et al. 2022). This is also seen in single-species studies showing the fishing bat *M. dasycneme* reduced feeding activity in response to ALAN while overall activity remained unaffected and insect prey abundance increased (Russo et al. 2019).
- Horizontal and near-horizontal lighting, such as illuminated advertisements, architectural lighting and vehicle lights, increase light trespass into areas outside the target area into adjacent unlit areas, produce more skyglow (even compared to light emitted upwards and certainly much more than light emitted downward), and are more likely to disrupt animal

navigation (Gaston et al. 2012). The potential to employ downward-facing lighting may alleviate this.

- Reducing upward and horizontally directed lighting, construction of walls and other structures and planting of vegetation to shield sensitive areas against light, replacing reflective surfaces with light absorbent ones, and greater use of light-focussing reflectors would be good options to reduce light trespass and ecological light pollution, as well as save money as "more focussed lighting means a lower luminous flux is necessary to illuminate a given area to a required intensity" (Gaston et al. 2012).

Table 3. Previous studies assessing the effects of different light types on animals

Light types	**Effects**	**Location**	**reference**
Sodium vapour			
Low-pressure sodium (LPS)	*P. pipistrellus* was lower activity	Ireland	(Mathews et al 2015)
	Nyctalus/*Eptesicus* spp. avoid passing / reduced activity	England	(Stone et al 2015b)
High-pressure sodium (HPS)	Negative impact lesser horseshoe bats	North Somerset, southwest Britain	(Stone et al 2009)
	P. pipistrellus - lower activity	Ireland	(Mathews et al 2015)
	showed lower percentages of attraction of short-tailed shearwaters	Phillip Island, Victoria, Australia	(Rodriguez et al 2017)
Metal halide (MH)	multiplied the mortality risk of short-tailed shearwaters by a factor of 1.6 and 1.9 respectively in comparison with light emitting diode and high pressure sodium lights	Phillip Island, Victoria, Australia	(Rodriguez et al 2017)
White LED	Less influence on insects than Metal Halide	southern England	(Wakefield et al 2018)
	Attracted more flying invertebrate than HPS lamps	New Zealand	(Pawson and Bader 2014)
	Attract orb-web spiders	Melbourne, Australia	(Willmott et al 2019)
	Potentially affect moth abundance and distribution	Review paper	(Davies and Smyth 2018)
	Negative impact on slow-flying species (*Rhinolophus hipposideros* and *Myotis* spp.)	southwest England and Wales	(Stone et al 2012)
	No impact on fast-flying species (*Pipistrellus* spp. and *Nyctalus*/*Eptesicus* spp.)	southwest England and Wales	(Stone et al 2012)
	showed lower percentages of attraction of short-tailed shearwaters	Phillip Island, Victoria, Australia	(Rodriguez et al 2017)
Mercury vapour			

General light (unspecified in studies)	Shift in reproductive behaviours (American robins)	Vienna, Austria	(Kempenaers et al 2010)
	Species from the bat families Molossidae and Vespertilionida not affected by light	Peru	(Mena et al 2022)

Advice on research and data collection priorities to address knowledge gaps

As mentioned, there is little work specifically on sports lighting's specific impacts on biodiversity so many of our insights rely on extrapolating from work on ALAN generally. While there is a growing body of work examining the impacts of ALAN in Australia, particularly for terrestrial systems, the largest bodies of work come from work in North America and Europe. These offer considerable insights into how Australian fauna may respond to ALAN, although we are wary of generalising from them owing to the unique nature of Australia's biodiversity. However, this work does provide a very useful roadmap for what work needs to be undertaken and a starting point for developing good practice frameworks. Current guidelines such as the Australian National Light Pollution Guidelines for Wildlife are vital first steps but focus heavily on a limited suite of fauna (Marine Turtles, Seabirds and Migratory Shorebirds). Guidelines for sporting organisations tend to focus unsurprisingly on the capacity of light to provide safe and high quality environments to play sport, and, outside of light intensity, do not offer significant guidance for options to limit the impacts of light pollution.

The evidence base we have is limited. Some of the significant limits to our understanding include;

- Impacts beyond single species: many studies look at individual species or small groups of species within a genera, and cannot ascertain cascading impacts or ecological responses – e.g. aphids seem unaffected by ALAN, however parasitoids become less efficient allowing aphids to proliferate, showing a strong impact of ALAN on daytime species interactions (Sanders et al. 2022)
- Most studies on ALAN are well- designed laboratory studies and interpretation without practical applications. The empirical and practical evidence helps ecologists understand the mechanisms causing responses to light, as well as insights into the potential to adapt to light (Desouhant et al. 2019, Willmott et al. 2019), but does not necessarily predict how ALAN affects distribution and abundance of light-sensitive animals.
- Interdisciplinary research, e.g. research integrating biology and engineering, is still lacking.
- The effect of ALAN broadly on Australian animals is still incomplete, and more research, particularly examining the temporal scale of impacts (short to long) on a wider range of species is essential to develop a general understanding. Much of the research we have focuses on a limited number of groups studied for a very short period.
- Trophic interactions under ALAN have been less described such as potential disruptions to predator-prey interactions.
- Lack of knowledge on how ALAN interacts with other stressors, such as warming and pollution.

There are numerous research and data collection priorities that could address significant knowledge gaps. Critical issues and actions for consideration by decision-makers as light is deployed around sporting fields should consider;

- Local surveys. These are necessary because species-specific responses under ALAN is varied. It is not possible to predict the impacts of the introduction of new lighting associated with sporting fields, or increased usage, without identifying the community of animals that may be affected. These surveys should include a wide range of taxa, given the extensive evidence showing the effects of ALAN on ecological communities . These surveys should also include species targeted with respect to State and Commonwealth threatened species legislation, to identify species protected under relevant acts.
- Before and after studies are needed to understand the local species composition and potential effects after light installation. There is an urgent need to undertake experimental approaches at new developments to test the predictions from previous work
- The light spectra and intensity being recommended, given how different animal taxa show different responses (Park and Lee 2017, Desouhant et al. 2019).
- The effects of installation position of lights, such as angle and height, to be more efficient and minimise the effect of spill light in dark areas. These are suggested by the Institution of Lighting Professionals (Guidance Note 1 for the reduction of obtrusive light 2021) although the effects relate primarily to human perception of light. There is little evidence demonstrating how these actions would impact biodiversity.
- How light pollution will interact with other local and global stressors such as pollution and warming. Australia is particularly vulnerable to ocean warming, with temperate SE Australia – a hotspot of biodiversity – experiencing well-above global average rates of ocean warming (Ridgway 2007). Predicted increases of ALAN on urbanised coastal areas means that effects of artificial light at night will occur in areas affected by climatic changes and urban stressors. ALAN impacts are thus likely to have synergistic effects with these stressors.

Advice on research and data collection priorities (TOR) to address knowledge gaps

In the longer term, there are opportunities to examine a suite of more complex questions addressing not only the impacts of ALAN on biodiversity but the mechanisms driving these changes and the ecosystem level responses. Some of these opportunities include assessing;

- Ecological Impacts beyond single species responses: many studies look at individual species or small groups of species within a genera, and cannot ascertain cascading impacts or ecological responses – e.g. aphids seem unaffected by ALAN, however parasitoids become less efficient allowing aphids to proliferate, showing a strong impact of ALAN on daytime species interactions (Sanders et al. 2022).
- Translation of laboratory studies to field responses. Most studies of mechanisms for the impacts of ALAN are well controlled laboratory studies. The empirical and practical evidence may help ecologists understand the animal plasticity and evolutionary ecology in light areas (Desouhant et al. 2019, Willmott et al. 2019), but also generate hypotheses to be tested in the field.

- The ALAN effect on a wider range of Australian animals. The cases explored in this review point to an incomplete knowledge, and more research on a wider range of taxa is urgently needed. need.
- Species between trophic levels interaction under ALAN have been less described such as prey-predator interactions. This interaction may amplify on whole populations, communities and ecosystems.
- The potential to identify solutions through Interdisciplinary research. e.g. studies integrating biology and engineering, are still rare, and the potential to codesign research to generate innovative solutions is largely unexplored. These include options like designing more efficient light-focussing reflectors to help direct light where it is required (Gaston et al. 2012), or developing coatings for LED lights that create white light with good colour rendition, maximising human vision while minimising wavelengths emitted, allowing critical regions of the spectrum to be avoided (Gaston et al. 2012).
- It may also be that we need to retain older style lighting in ecologically sensitive areas, or use white lights that minimise impacts on the ecology of organisms, e.g. metal halide lamps emit more UV than LEDs do, potentially having a greater impact on insects and birds that use this region of the colour spectrum (Gaston et al. 2012)

Increasing heat impacts on terrestrial species

Current knowledge on the impacts of climate change, especially heat, and extreme weather on Australian animals and birdlife, including direct and indirect impacts

There is overwhelming evidence showing that the flora and fauna of Australia is particularly susceptible to increased heat and increased exposure to extreme events (Australia State of the Environment Report 2021). The evidence for this comes primarily from studies examining the impacts of climate change, with the evidence base including everything from distribution modelling of spaces through to lab experiments and mesocosm experiments manipulating temperature. The 2021 Commonwealth State of the Environment report is the best and most recent summary of the impacts of heat on the continent's fauna and flora, noting:

"Climate change and extreme weather events are becoming increasingly important as direct drivers of changes in biodiversity. Australian ecosystems and associated species are expected to continue to change substantially in response. Following the 2019–20 bushfire season, many species and ecosystems require rapid recovery interventions, mitigation of ongoing threats, and reassessment of their status"

The sorts of impacts listed include lifecycle shifts, changing abundances, range expansions and contractions driven by long term temperature shifts, existing with the increased in extreme events such as fires, droughts and other causes of mass mortality of biodiversity (Prober et al. 2019).

While there is no doubt that anthropogenically mediated climate change will affect biodiversity, the scale at which elevated heat associated with synthetic turf (e.g. Yaghoobian et al. (2010) impacts biodiversity may be much finer than the global reach of climate change. This provides the opportunity to draw upon an emerging body of evidence from work examining how flora and fauna respond to urban heat islands. Urban heat islands are created as cities modify their surface energy balance and generally exhibit higher air and surface temperatures than surrounding rural areas

(Manoli et al 2019), and is likely to be operating at the same scale as the likely impacts of synthetic turf on local environments.

There is absolutely no doubt that increasing the temperatures on and around days playing fields will have effect on anything exposed to elevated temperatures, but it is likely that these will be relatively localised. The footprint of any impact of elevated temperatures associated with synthetic turf is likely to be limited to the playing areas itself. For example, converting playing fields from natural to synthetic turf at a university campus in Saudi Arabia created significant new urban hotspots, although the heat island effect was limited mainly to the areas immediately around the playing field (Addas et al. 2020)

Key knowledge gaps for synthetic turf and associated heat increases

Our understanding of biotic responses to urban heat islands provides the best road map for understanding the impacts of heat increases associated with synthetic turf. Urban heat island effects, a dramatic difference between temperatures in urban areas and suburban and rural areas, are caused by the increased proportion of impervious surfaces in cities and subsequent impacts on albedo and geometry (Manoli et al. 2019). These have been shown to have significant effects on a range of factors that affect liveability in cities, including biodiversity, net primary production, and air quality (Imhoff et al 2004, Li et al. 2021). As such, many of the questions being asked of the impacts of urban heat islands are directly applicable to the impacts of heat caused by synthetic turf.

Perhaps the key knowledge gap with respect to this is not what the impacts are likely to be, but how they might be ameliorated. One "silver bullet strategy" that might help ameliorate these impacts is the possibility of strategic planting (often described as nature based solutions) to reduce the impact of elevated heat on the surrounding environment (e.g. Ahern et al. 2014). This strategy has been widely promoted as a solution that brings multiple benefits to urban communities (McPherson et al. 2014) and offers a valuable opportunity to address multiple concerns about the impacts of synthetic turf replacing natural turf, and aligns with some of the concerns raised about light spill associated with ALAN. Ultimately, the knowledge gaps around the relatively local heat impacts of synthetic turf need to be considered in the context of global climate change and urban heat islands at coarser landscape scales (Manoli et al. 2019), as they do not occur independently of these pressures.

Advice on research and data collection priorities, and national or international good practice frameworks for managing and mitigating adverse impacts of heat from sports fields adopting synthetic turf

Acknowledging the likely impacts of increasing local temperatures and building this into the potential future monitoring is critical, as the evidence that increasing temperatures will have an impact on local biodiversity is clear. However, identifying the spatial scale that any impact will occur at and how that will contribute to other concerns over escalating temperatures driven by climate change and urban heat island effects requires a bigger picture perspective. While it is likely that there may be a significant impact on some components of biodiversity, particularly if there are any locally significant or heat sensitive species adjoining the playing fields, the most effective tool requires a big picture integrative approach, particularly for playing fields in urban areas (Nilon et al. 2017).

Frameworks for assessing heat impacts of artificial turf relate primarily to concerns over the welfare of players using them, although even these are not completely clear (Wardenaar, et al. 2022). In terms of mitigating elevated temperatures around playing areas, the most substantial advice relates to the opportunity to look at nature based solutions (essentially tree planting) to manage some of the potential impacts Ahern et al. 2014). It is likely that the effects of increased ALAN and the replacement of natural grass with synthetic turf will have a bigger impact on biodiversity than temperature alone. However, it is likely that strategies to try and mitigate for some of these impacts by managing surrounding environments through strategic planting creates an opportunity for an experimental approach to address the key knowledge gaps (McPherson et al. 2014).

Synthetic turf beyond light and heat – Other relevant matters

While the focus of this report was on the artificial light and heat associated with synthetic turf, no discussion of the impacts of synthetic turf on biodiversity should exclude the fundamental shift in habitat. There is compelling evidence that the shift from natural to artificial grass leads to a loss of habitat for animals foraging on and around grassed areas. Recent research from Spain has highlighted that the trend of replacing natural by artificial grass in urban parks has harmful effects on urban bird communities, and that increasing artificial turf in public spaces may be a significant new threat to bird conservation (Sánchez-Sotomayor et al. 2022). Similarly, plastic pollutants and synthetic material fibres are likely to have significant potential harmful effects on wildlife health, both in marine systems (Gall and Thompson 2015) and soil ecosystems (Pochron et al. 2017).

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Appendix 17
Soil Health

Soil Health

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1.0 What is soil health and why is it important

Soil is not an inert growing medium but contains a large number of both visible (macroinvertebrates) and microscopic organisms. The soil microbiome teams with billions of bacteria, archaea and fungi (The Australian Microbiome initiative). These communities underpin the existence of all other life.

Healthy soil is the basis of all terrestrial ecosystems on Earth (Doran and Zeiss, 2000; Thakur et al., 2019). Soil health is the continued capacity of soil to function as a living ecosystem that sustains terrestrial life, provides clean air and water, mitigates global climate change by storing large amounts of organic carbon, mitigates flooding, provides abundant crops, bushland, and grazing lands, and supports diverse wildlife. Considering these functions and services, soil is Australia's most valuable natural asset and the value of soil greatly exceeds the value of land itself (Soil Science Australia, 2019).

Earthworms comprise the dominant biomass in temperate soils (Curry 1993; Hoeffner 2018; Lee, 1985; Zhang et al., 2000), and prodigious amounts of soil pass through them (Bonkowski et al., 2000; Tiwari, 1993; Zhang et al., 2000): 1 m^2 of soil could contain about 1 litre of earthworm gut volume (Drake and Horn, 2007). Earthworms are constantly ingesting soil (Bonkowski et al., 2000; Gómez-Brandón et al., 2011), and *Eisenia fetida* passes food from mouth to anus in 2.5 hours (Hartenstein, 1981). Earthworms pedogenesis, development of soil structure

The contribution of earthworms to soil quality is widely documented in the literature (Edwards and Bohlen, 1996; Brown et al., 2004). They play a critical role in soil formation and nutrient cycling (van Groenigen et al., 2014), decomposition (Schimel and Schaeffer 2012; Creamer et al. 2015), the recovery of soil carbon pools after natural and anthropogenic disturbance (Angst et al. 2019), maintaining soil microbial diversity (Liu et al. 2019; Liu et al. 2020), controlling plant pathogens (Euteneuer et al. 2019; Li et al. 2019; Plaas et al. 2019), and maintaining soil porosity (Edwards and Bohlen, 1996; Brown et al., 2004). Earthworms improve net carbon storage and increase drainage, thereby decreasing flood risks and increasing land value (Schon and Dominati, 2020). The role of earthworms in remediating pollution and protecting sub-soil archaeological remains has also been highlighted (Blouin et al. 2013).

2.0 What is required for a healthy soil microbiome

Some areas of eastern Australia have fertile soils, however in general surface layers have low levels of organic matter and may be poorly structured. Soil can degrade rapidly and is difficult to remediate as it is formed slowly and is essentially therefore a non-renewable resource (Commonwealth of Australia, 2017). One of the biggest threats to soil biological activity is the physical degradation of soil (Greenwood and McKenzie, 2001; Schon and Dominati, 2020).

Soil health is influenced by a range of physical factors including drainage, soil moisture, pH, composition of minerals, nutrients and organic matter, physical structure of particles and layers, the surrounding air and oxygen between soil particles. Health of the soil and the biome is influenced by the types of invertebrates present, their abundance and their diversity (Kumar and Karthika 2020); and diversity within the soil microbiome. The soil microbiome includes pathogens, beneficial microorganisms; comprising of including bacteria, archaea, fungi, protista (Banerjee and van der Heijden, 2022). Diversity is important in terms of biological diversity at phyla to species levels and in the range of ecological roles and variety of body structures (functional diversity, trophic diversity, structural diversity). Enhanced soil biodiversity enables proper ecosystem functioning (Bender et al., 2016) and also promotes heterogeneity in the soil structural environment, providing a variety of micro habitats containing unique assemblages of life (Fierer, 2017). Generally the greater the complexity and diversity in the soil microbiome, the more resilient the environment is, enabling it to limit disease development, reduce the level of soil pollution, and support plants and animals (Wang and Li, 2019).

Among the complex interactions necessary to maintain soil health (Chaparro et al., 2012; Marsden et al., 2019), there is a strong body of research from northern hemisphere environments showing that many key functions can be traced to the close and recursive relationship between earthworms and microbes, whereby the worm microbiome and the soil microbial community undergo constant exchange. Functions traceable to this worm/soil loop include: decomposing organic material (Creamer et al., 2015; Schimel and Schaeffer, 2012), the recovery of soil carbon pools after natural and anthropogenic disturbance (Angst et al. 2019), maintaining soil microbial diversity (Liu et al., 2020; Liu et al., 2019), but see Ferlian et al. (2020), and controlling plant pathogens (Euteneuer et al., 2019; Li et al., 2019; Plaas et al., 2019). Thus, interacting microbial communities, whose composition and diversity depend on the continuous material cycling via earthworms, mediate both soil condition and ecological function (Liu et al., 2019). In many Australian environments the limited rainfall does not provide suitable conditions to support sufficient earthworm populations to make significant contribution to ecosystem functions (pers comm. Dr Vadakattu). Other members of the soil food web play an important role in such functions with the same result: healthy invertebrates beget healthy microbiomes and soils, and healthy soils beget healthy invertebrates.

3.0 The uniqueness of the soil microbiome in urban environments

Large-scale transect surveys in NSW have found that microbial diversity is predominately shaped by soil composition, but there are a range of influential factors (Pino et al., 2019). Urbanisation and agriculture reduce the variation of microbial communities (Xue et al., 2018; Delgado-Baquerizo et al., 2021). A study of urban greenspaces across six continents found that compared to natural ecosystems, urban greenspaces had a greater proportion of fast-growing bacteria, algae, amoebae, and fungal pathogens. Urban soils from greenspaces also had a lower proportion of Ectomycorrhiza, the fungi that form a symbiotic relationship with the roots of various plant species and assist the uptake of nutrients and were found to have more globally homogenised microbial communities (Delgado-Baquerizo et al., 2021). Although revegetating urban areas might alter diversity, as research in South Australia found soil microbiota in revegetated urban green spaces were similar to remnant woodland microbiotas and differed greatly from lawns and vacant lots (Mills et al. 2020).

4.0 Potential impacts of installing synthetic turf

Lacking complete studies on the changes to soil and biota before and after installation of synthetic turf in the Australian environment, the main impacts would likely be compaction and contamination.

Compaction and sealing of the soil surface would include some physical compaction and loss of soil pore structure resulting in death or restricting movement of invertebrates and reducing the air-filled pore space contributing to anerobic environment. Where soil has been covered by impermeable surfaces such as tarmac, the anerobic environment means that only certain microorganisms are able to survive and there may be an increase in pathogens harmful to human health (Swartjes et al., 2011). While compaction is an immediate impact occurring directly where the synthetic turf is installed, if it results in a significant loss of soil biota and diversity and a dominance of harmful pathogens there will be two effects: (1) rehabilitation of soils and a healthy environment once synthetic turf is removed may not be feasible, or be a long-term perspective and (2) these changes in the soil community may adversely impact surrounding environments including terrestrial vegetation, waterways leading up to human health (Banerjee and van der Heijden, 2022). Research on the impact of synthetic turf installation to environmental and human health should therefore concentrate on the surrounding areas.

Contamination from crumb rubber and other materials and additives used in synthetic turf have potential to adversely impact surrounding environments as particles and leachate travel from the soil to the water, and through the food chain, potentially containing hundreds of chemicals and metals, many unstudied. Not all rubber crumbs contain the same chemical constituents. While the impact of crumb rubber and its leachate is poorly studied in terrestrial systems, and only moderately better studied in aquatic systems, it has been found to have a negative impact on plants, algae, earthworms and crustacea (see sections below).

It is also important to understand the mechanism of these impacts and how this may change with time and the influence of other factors. Toxicity of crumb rubber changes over time, Li et al. (2010) found that under natural conditions, crumb rubber material outgassed volatile and semi-volatile organic compounds at the highest rates during the first 14 days after field application and that the material outgassed consistently after that, for up to 70 days. Also, Li et al. (2010) and Rhodes et al. (2012) independently report that zinc leaching increases with longer exposure time, and Rhodes et al. (2012) report an initial pulse of zinc leaching with new crumb rubber. Lu et al. (2021) report that UV radiation induced crumb rubber to release more Zn and PAHs than was found in unexposed crumb rubber.

4.1 Invertebrates as indicators of soil health and toxicity

An indicator species is an organism whose presence, absence or abundance reflects a specific environmental condition. Indicator species can signal a change in the biological condition of a particular ecosystem, and thus may be used as a proxy to diagnose the health of an ecosystem.

There are an estimated 1,000 species of earthworms native to Australia from three families, and approximately 80 introduced species from eight families. Of the three Australian native earthworm families, Megascolecids are more commonly found in southern states. Earthworms are found in soils, leaf litter and sometimes in vegetation of both terrestrial, freshwater and marine environments. One particular family, the Lumbricidae is found all over the world but are native to

Britain, North America and Asia. Lumbricidae includes *Eisenia fetida*, commonly found in compost heaps (Blakemore, 2019).

Earthworms play a critical role in soil ecology (reviewed in Edwards, 2004). Indeed, the earthworm's role in soil health is such that the European Union (EU), the Organization for Economic Co-operation and Development (OECD), the International Organization for Standards (ISO) and the Food and Agriculture Organization of the United Nations (FAO) all use earthworms (*Eisenia fetida*) as one of five key indicator organisms for ecotoxicological testing (Piola et al., 2013; Santadino et al., 2014).

Worm casts (earth consumed by worms and deposited) contain stable communities of microorganisms (Aira et al., 2019) that get released into the soil as the worm moves through it (Moody et al., 1996; Schlatter et al., 2019). While the mere physical presence of worms influences soil environments, the worm gut in particular acts as a strong filter on the soil microbial community, contributing to soil resilience (Aira et al., 2008) where some microorganisms are digested and others flourish (Aira and Domínguez, 2011; Thakur et al., 2019; Drake and Horn, 2007; Furlong et al., 2002). In contrast to the generally aerobic, nutrient-poor and spatiotemporally heterogeneous soil environment, the worm gut acts as a mobile, anaerobic, stable and nutrient-rich bioreactor (Aira et al., 2015; Drake and Horn 2007; Horn, 2005; Karsten and Drake, 1995). Thus, worm guts select for specific groups of microorganisms (Aira et al., 2015; Thakur et al., 2019; Clapperton et al., 2001; Drake and Horn, 2007; Gómez-Brandón et al., 2011; Gong et al. ,2018; Rudi et al., 2009; Schlatter et al., 2019; Wüst et al., 2011), generally promoting soil Proteobacteria, Actinobacteria, Firmicutes, Acidobacteria, Planctomycetes, Bacteroidetes, Nitrospirae, and Chloroflexi (Medina-Sauza et al., 2019).

In the Mediterranean and semi-arid regions of Australia, nematodes have been shown to be good indicators of ecosystem health both in terms of the soil system health and contaminant effects (Gupta and Yeates, 1997; Yeates and Stirling, 2008; Stirling et al., 2016; Hodda et al., 2009; Stirling, 2008). Nematodes are considered one of the key components of soil food web and with over 10,000 described species they occupy a central position linking microbial communities with soil fauna (Bongers and Bongers, 1998). A number of nematode communities and metabolic and ecological indices have been reported as indicators of soil health and ecosystem functioning including processes related to decomposition of organic matter and nutrient mineralization. The commonly distributed soil-dwelling nematode species *Caenorhabditis elegans* is a well-established model organism for ecotoxicological tests of different pollutants including for biosafety assessments of nanoparticles (Wu et al., 2019).

4.2 Impacts of crumb rubber in the gut of soil invertebrates

Earthworms experience constant dermal contact with soil and therefore contaminate such as crumb rubber and its leachates, and they may consume the leachates and particles of rubber. If soil contaminated with crumb rubber harms earthworms, the soil cannot be assumed healthy. The impact of crumb rubber on soil-dwelling invertebrates, including earthworms, is very poorly understood. A Web of Science search returned only four papers on the topic: Pochron et al., 2017, 2018, Dolar et al., 2021, and Fort et al., 2022.

Contaminants can alter microbial communities in both the soil and in the gut of earthworms, causing pathology in both. Earthworm health depends in part on the health of the microbial community living in its gut. Despite its apparent strength, disturbances such as microplastics (Wang et al., 2019b), arsenic and sulfamethoxazole (Wang et al., 2019a), and chromium (Tang et al., 2019) can affect the worm gut microbial community. Unsurprisingly, the soil microbial community also influences the worm gut microbiome, with diet modulating the gut microbiome of anecic (vertical burrowing) and endogeic (lateral burrowing) worm species (Egert et al. 2004;

Knapp et al., 2009; Nechitaylo et al., 2010; Thakuria et al., 2010; Tiunov and Scheu, 2000). In contrast, diet has less influence on the gut microbiome of the epigeic (surface dwelling) *Eisenia andrei* (Gómez-Brandón et al., 2011), implying a stronger ecological filter in this species.

Coping with environmental contaminants is energetically expensive for invertebrates, and under stress, invertebrates mobilize proteins and lipids as an energy source (Salvio et al., 2016). Internal proteins and lipid concentrations can decrease, indicating high energetic demands under contaminant exposure (Givaudan et al., 2014; Salvio et al. ,2016), potentially leading to loss in body mass (Piola et al., 2013). However, earthworms that find themselves needing to pay metabolic costs to cope with contamination can respond via indicators other than body mass. For instance, one earthworm species (*Allolobophora chlorotica*) increased the activities of enzymes associated with oxidative stress as pesticide concentration increased, while a second (*Aporrectodea caliginosa*) responded by losing mass (Givaudan et al., 2014). When exposed to crumb-rubber contaminated soil, compost worms (*Eisenia fetida*) sometimes maintain growth rates at the cost to resilience as measured by stress-test survival time (Pochron et al., 2017) and sometimes forgo body mass maintenance and invest instead in resilience (Pochron et al., 2018).

In the human gut microbial ecosystem, xenobiotics and infections can cause compositional shifts in the microbial community, a process known as dysbiosis when it exerts a pathophysiological effect on the host (Illiano et al., 2020; Shaler et al., 2019). Despite its biomedical origin, ecologists have recently applied this concept to describe disturbances causing compositional shifts in environmental microbial communities, allowing the emergence of disease (Egan and Gardiner 2016; Pochron et al. 2020). Many diseases caused by changes in microbial communities have been described in the literature, even if not always labelled dysbiotic. Dysbiosis in the soil can drive dysbiosis in the worm gut, and the opposite may also be true. To best understand the impact of any contaminant on a soil ecosystem, researchers should consider studying not only macroinvertebrates but also their associated gut microbes and the microbes in the soil on which they rely (Stirling 2008).

4.3 Impacts of plastics on terrestrial environments

Plastic particles and crumb rubber comes in sizes that earthworms and other soil-dwelling invertebrates consume and move it, facilitating migration. Adding plastics of various sizes to soil alters the function of the microbial communities and the makeup of the communities, sometimes to the detriment of the earthworms and plants.

Qi et al. (2018) showed that microplastic residues affected both above-ground and below-ground parts of the wheat plant during both vegetative and reproductive growth. The presence of earthworms had an overall positive effect on the wheat growth and chiefly alleviated the impairments made by plastic residues.

Ding et al. (2021) examined the impact of a variety of plastics on earthworms. They showed that microplastic concentration rather than plastic type was more important in regulating earthworm responses to soil contamination. Earthworms (*Eisenia fetida*) exhibit microplastic avoidance behaviour at a critical threshold of 40 g kg^{-1} soil, and earthworms significantly reduce number of cocoons and juveniles at 53 g kg-1and 97 g kg^{-1}, respectively. Earthworm mortality was impacted at 500 g kg^{-1}. Plastic contamination in soil exists at levels up to 67 g kg^{-1}, indicating that microplastics are now starting to pose a threat to earthworm populations.

Microplastics have been found to affect reproduction and body length of the soil-dwelling Nematode Caenorhabditis elegans (Schopfer et al., 2020). Research has also found evidence of plastic type and particle size-based effects on survival and behaviour of indicator nematodes (Lei et al., 2018).

Pathan et al. (2020) state that the number of soil-inhabiting, plastic-eating bacteria, fungi and insects is increasing. Nanoplastics (< than 50 nm) can pass through the membrane of both prokaryotic and eukaryotic cells. Soil biota, particularly earthworms and collembola, can carry both micro- and nanoplastics through soil profiles, changing the composition and activities of the microbial communities inhabiting the soil and the guts of soil plastic-ingesting fauna.

Maity and Pramanick (2020) provide a review of the toxicity of micro- and nanoplastics to plants and the organisms associated with them (e.g. microbes and earthworms). Terrestrial systems have higher concentrations of plastics than aquatic systems. Plastics can alter soil enzymatic systems, soil properties, and soil-borne microorganisms and earthworms. Micro- and nanoplastics inhibit plant growth, seed germination and gene expression; and they also induce cytogenotoxicity by aggravating reactive oxygen species generation. Micro- and nanoplastics can alter the soil–microbe–plant interaction.

Lwanga et al. (2017) show that micro- and macro- plastics can enter the terrestrial food web, providing evidence that plastics can transfer from soil to chickens in traditional Mayan home gardens. They measured micro-and macro-plastics in soil, earthworm casts, chicken faeces, and the chicken crops and gizzards used for human consumption. Microplastic concentrations increased from soil (0.87 +/- 1.9 particles g^{-1}), to earthworm casts (14.8 +/- 28.8 particles g^{-1}), to chicken faeces (129.8 +/- 82.3 particles g^{-1}). Chicken gizzards contained 10.2 +/- 13.8 microplastic particles, while no microplastic was found in crops.

4.4 Impacts of crumb rubber leachate on terrestrial indicators

Xu et al. (2019) report that crumb rubber leachate injected into the yolk of a chicken egg caused mild to severe developmental malformations, reduced growth, and specifically impaired the development of the brain and cardiovascular system, which were associated with gene dysregulation in aryl hydrocarbon receptor, stress-response, and thyroid hormone pathways.

Dolar et al. (2021) investigated how the exposure to two types of microplastics (polyester fibres and crumb rubber) induced changes in immune parameters of a wood louse (*Porcellio scaber*). They also asked if the co-exposure of microplastics affected the response induced by chlorpyrifos, organophosphate pesticide. Both types of microplastic at environmentally relevant concentrations caused only slight changes in immune parameters, which were not dependent on the type of microplastic, although the two types differed significantly in terms of the chemical complexity of the additives. Mixtures of chlorpyrifos and microplastics induced changes that differed from individual exposures.

Fort et al. (2022) exposed two terrestrial plants, lettuce (*Lactuca sativa*) and white mustard (*Sinapis alba*) to crumb rubber leachate and report a significant decrease in root elongation. In their study, exposed compost worms (*Eisenia fetida*) demonstrated 100% mortality after exposure. Leachate from crumb rubber promoted the survival and growth of *Salmonella*, making it more resistant to zinc exposure (Crampton et al., 2014).

4.5 Impact of synthetic particles and leachate in freshwater and marine ecosystems

Proximity and rainfall events mean that rubber crumb and synthetic material wash into freshwater and marine environments (Reef Clean, 2021). There is a growing body of evidence relating to the transport of micro and nano plastics, and associated contaminants into the marine environment and resulting interactions as they are carried through the water column and complex food webs. In marine environments it has been found that the surface of microplastics from synthetic fibres and other sources facilitates sorption of chemicals to the particle surface, increasing bioaccumulation of contaminants (Bhagwat et al., 2021, Carbery et al., 2018).

Studies of freshwater and marine invertebrate indicator species exposed to crumb rubber have found a range of negative impacts. Halsband et al. (2020) analysed new and aged crumb rubber and detected benzothiazole, *N*-1,3-dimethylbutyl-*N*′-phenyl-*p*-phenylenediamine and a range of polycyclic aromatic hydrocarbons (PAHs) and phenolic compounds (e.g., bisphenols) in both types. They also found Zb, Fe, Mn, Cu, Co, Cr, Pb, and Ni. Benzothiazole, Zn, Fe, Co, PAHs and phenolic compounds readily leached from the crumb rubber into sea water, where it increased mortality rates in two species of marine copepods. Tallec et al. (2022) report that crumb rubber negatively impacted early life stages of the Pacific oyster (*Crassostra gigas*), inducing embryotoxicity with newer crumb rubber being more toxic than older samples.

Fort et al. (2022) exposed a suite of freshwater organisms, including duckweed (*Lemna minor*), green algae (*Desmodesmus subspicatus*), and daphnia (*Daphnia magus*) to crumb rubber and report decreased growth rate and decreased biomass for the duckweed and the algae. Lu et al., (2021) report that UV radiation induced crumb rubber to release more Zn and PAHs than was unexposed crumb rubber, and that the exposed crumb rubber was more toxic to freshwater *Daphnia magna* than was unexposed crumb rubber. Research from the Pochron Earthworm Ecotoxicology lab (manuscript in preparation) shows that leachate made from crumb rubber slows the speed of regeneration in a planaria (*Dugesia tigrina*) and negatively impacts its locomotion.

5. 0 Knowledge gaps and research agenda

We expect that the degradation and transport of materials from synthetic turf under Australian soil and environmental conditions will be quite different to other places in the world. This review also highlights knowledge gaps on multiple fronts: from the chemical composition of the materials to be used, potential ecotoxic effects on biota in connected water and soil systems and ultimately on human health:

1. **Soil and associated environmental health impacts**: A large knowledge gap is the soil health underneath the synthetic turf. It is unknown whether areas that have been covered by synthetic turf and associated layers can be reclaimed due to significant likely changes in the biotic and abiotic components and contamination. While the impact in the layers under synthetic turf may be more relevant as part of potential reclamation efforts after synthetic turf is removed, understanding the impacts on the surrounding environments when the synthetic turf is in place are more critical. Therefore, the study of environments surrounding synthetic turf fields should be the primary focus.
   The proposed in-situ research would examine the spatial relationship of environmental health and surface type, with a grid or randomised stratified design of soil samples and other measurements taken at specific distances out from synthetic turf surfaces. This research might be applied to the management of greenspaces in urban areas and regional planning, with indicators for soil health being taken up in planning and approvals processes. Planning approaches could adopt a prioritisation of refugia and sacrifice zones based on soil and environmental health in urban areas.

   The in-situ study could be complemented with targeted controlled studies to gather eco-toxicity information for indicator organisms, specifically for materials for which no information is available in the literature, including:
    a. Total microbial communities and/or key functional groups relevant to the region of NSW using BASE project protocol (Bissett et al., 2016; The Australian Microbiome initiative). Experimentation using local earthworms common to NSW may be appropriate to understand aspects of the worm/soil loop, how contamination may alter soil microbial communities, potential changes to worm gut and whether worms with healthy guts be brought in to repair damaged soil. Since nematode communities are key members of soil food webs in Australian environments, nematode community

composition could be examined in-situ or through experiments on survival and reproduction responses with indicator nematode species.

b. With only a handful of papers reporting the impact of crumb rubber on terrestrial organisms, we have very little knowledge of how soil ecosystems will be impacted as crumb rubber and its leachate inevitably moves through the environment. A study of the potential impacts on soil microorganisms should examine a combination of (i) composition and abundance of key members of soil food web, including earthworms, nematodes, arthropods and soil dwelling insects and the prokaryotes and protists of the soil microbiome; (ii) functional properties and (iii) ecotoxicological measures (including the functional capacity of soil biota, enzymatic activity, genotoxicity, mutagenicity, reproductive impacts, and behavioural changes) should be considered when investigating the impacts of crumb rubber and its leachates.
c. Given that microplastics can travel up the food chain from the soil on up, the impact of crumb rubber contamination on the gut microbes of birds, bees, and other pollinators should be addressed. Indicator and keystone species should also be studied. Including the pathway of leachate into groundwater and drinking water, freshwater and marine environments. Standard methods used to evaluate ecotoxicological effects of agrochemicals could be applied to study the effects of leachates or nano particles on aquatic organisms.

2. **Chemical constituents of crumb rubber**: Few comprehensive lists of ingredients appear to exist for crumb rubber (Perkins et al., 2019). This is essential information as without it, predicting risks to environmental and human health is very challenging. One approach might include obtaining crumb rubber from several sources and having an environmental science lab dissect their materials, as per Schneider et al. (2020a,b) and Armada et al. (2022). Once the composition of the materials proposed for use then the ecotoxicological risks for environmental and human health could be evaluated or at least derived from existing information on individual components of the crumb rubber and other material, as per Ginsberg et al. (2011). Examinations should include aging and weathering patterns under Australian / NSW conditions i.e. rainfall and temperatures. This would involve a desktop study combined with some laboratory analyses to generate a database for use in NSW and throughout Australia.

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Appendix 18

Natural turf sporting surfaces

The following section summarises soil, species selection, drainage, water and maintenance considerations that feature in best practice natural turf guidance resources and expert information. Some misconceptions impacting current practices are highlighted in Table 1. The impact of extreme weather, such as recent significant rainfall and flooding and the earlier drought is addressed, with some best practice recommendations for immediate flood damage assessment is listed in Table 2. During the course of this Review individuals contributed a range of expert advice; these are listed in Appendix 1. Many of these individuals and organisations have also written best practice natural turf guidance resources, which are referenced here, with details about organisations and research groups listed in Table 3.

Soil

As sands are often used to construct playing surfaces at elite stadiums, there is a broad perception that sand is the best soil type for community facilities. However, very few community facilities are constructed this way as there is not the construction or maintenance budgets to support them. In a sample of over 840 fields, it was found the vast proportion of community facilities (~98%) are constructed from soil.[1] Therefore, the discussion of the performance, construction and management of community fields needs to reflect the vast proportion of fields that are constructed from soil, rather than the sand used for elite stadiums.[2]

Turf sporting fields at community facilities can perform well on a range of soils. Furthermore, soil characteristics vary,[3] and soil behaviour is not solely related to the texture classification as soil structure is also critical.[4] Soil characteristics affect watering requirements, turf health and growth, drought resilience, site drainage and the incidence of weeds, pests and diseases. In 2011 Sydney Water published best practice guidelines for holistic open space turf management in Sydney, focusing on the importance of soil care, turfgrass species selection and irrigation to improve surface resilience and minimise water requirements.[5] Similar initiatives have been adopted in other jurisdictions.[6]

Poor turf performance can often be directly attributed to problems in the soil profile, with examples including nutrient deficiency, hardness and compaction, water repellency, lack of topsoil depth and soil layering. Underlying soil issues can also present as symptoms, for example waterlogging or extensive weed cover. Poor drainage may be a consequence of impermeable soil within the profile (e.g. the soil imported with turf rolls during construction or patching).

Regardless of soil quality, topsoil is a critical component to supporting natural turf. Deep topsoils (at least 250 mm) hold more water than shallow soils (<170 mm) and require more frequent watering. Risks include waterlogging, susceptibility to compaction and increased vulnerability to weed infestation. Shallow topsoil will also struggle to maintain coverage even if the site receives little or no traffic. Despite this, turf is often laid directly on top of the soil base (such as shale, clay, loam or sand) and struggles to provide the support grass needs to allow root penetration.[3]

A healthy soil is critical for supporting turf growth. The key characteristics of a healthy soil profile include:

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[1] Battam M and Lamble P (2019) Planning for Park and Sport Field Carrying Capacity, https://www.parksleisure.com.au/includes/download.ashx?ID=155497

[2] Elite stadiums generally have sand topsoil with specific characteristics with an underlying gravel layer (perched water table design), automatic irrigation and drainage.

[3] Martin, P and Battam, M (eds) (2011). Best practice guidelines for holistic open space turf management in Sydney. Sydney Water.

[4] Soil structure describes the way soil particles (organic matter, sand, silt clay) group together. Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter. Book 2: Soils and Turf, p12-13.

[5] Martin, P and Battam, M (eds) (2011). Best practice guidelines for holistic open space turf management in Sydney. Sydney Water.

[6] See for example, G & M Connellan Consultants (2015) Best Practice Guideline for Functional Open Space in Victoria https://www.clearwatervic.com.au/user-data/research-projects/swf-files/bpg-final.pdf

- adequate soil depth (>200mm topsoil, deeper required on some sites)
- soil is moderately friable and does not set hard (i.e. is well structured)
- soil has acceptable nutrient balance and holding capacity
- topsoil and subsoil have appropriately matched characteristics
- soil is appropriately amended so it does not limit the performance of the field or increase the irrigation requirements.[7]

There is no single recipe for amending soils to achieve a healthy profile. Instead, the soil at each site should be assessed and appropriate amenders used to address the issues that limit turf performance at that site. Annual independent soil testing is recommended to determine soil fertility and nutrient requirements.[8]

Compared to soil chemistry, which is relatively widely understood, there is far less understanding of the role of soil structure in turf health. Soil structure is a critical physical element in soil profiles. Soil texture class is not a reliable indicator of soil behaviour as soils in the same texture class (e.g. sandy loam) can display vast differences in behaviour (e.g. ability to drain, grow healthy turf), depending on their structure (e.g. well-structured or poorly structured).[9] Furthermore, well-structured clay soils can have superior characteristics compared to poorly structured sandy loams.

Soil compaction is one of the most common soil problems and occurs when soil particles are pushed together due to foot and vehicular traffic, especially in wet weather.[10] Compaction leads to less water storage, reduced drainage, harder playing surfaces and limited root growth. Regular aeration, supported by dethatching, may be required as part of routine maintenance schedules, to reduce soil density and thereby support movement of air, water and nutrients into the soil.

Turf cultivars

The level of wear that the field will receive is the first critical consideration in selecting the appropriate turf cultivar. Turf varieties and cultivars vary significantly in their capacity to handle wear.[11,12] The wear tolerance will depend greatly on local climate conditions, including microclimate. Once the required wear levels are factored in, other elements can be considered, such as tolerance to drought and/or poor water quality, soil type, susceptibility to pests and diseases and management practices.

Different species of grass have different growth patterns, rates of recovery, tolerance levels (wear, drought and water) and pest and disease susceptibility. Optimal use may therefore be dependent on the use of the field as well as the surrounding microclimate of the region. For example, temperature can affect the recovery potential of species in different ways and management therefore is often species-specific or sub-species specific. Species selection should reflect seasonal variation (warm and cool turfgrasses) and location. Successful turfgrass should provide sufficient coverage for safety, and adequately cover the soil so that moisture can be retained.

Recovery time, such as the time taken to achieve full turf cover after winter sport depends on many elements. These include the amount of wear from winter sport, the turf cultivar,

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[7] Lamble, P., Askew, S. and Battam, M. (2022). Best practice guidelines and benchmarks for turf open space in the lower hunter. OzWater22.
[8] Department of Agriculture, Fisheries and Forestry (2022). National Soil Package. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils
[9] Soil structure describes the way soil particles (organic matter, sand, silt clay) group together. Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter. Book 2: Soils and Turf, p12-13.
[10] DAFF (2014). The National Soil Research, Development and Extension Strategy, Securing Australia's Soil, For profitable industries and healthy landscapes, Canberra. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils/national_soil_rd_and_e_strategy
[11] Roche, M (2012). Traffic Tolerance of Warm-Season Grasses under Community Sportsfield Conditions
[12] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter. Book 2: Soils and Turf, p12-13.

the health of the soils, turf management practices and how field users concrete or spread the wear from sport across the site.

While there is marketing material that promotes the benefits of particular cultivars, what is lacking in Australia is an industry-backed set of grass trials which are independently conducted in a properly designed format and conducted over an extended period.[13]

Water management and drainage

According to Football NSW in 2015, 38 percent of existing grounds in NSW have drainage issues.[14] Effectively managing excess water, or having a field that "drains well", means the field can return to play in reasonable timeframes after rain. Preventing waterlogging supports healthy turf growth and prevents additional damage that is caused when the field is used while it is wet. Often industry publications will promote high rates of water infiltration into the soil as the key to preventing waterlogging[15,16]. However, this is heavily dependent on-site conditions, as it relies on the infiltrated water having somewhere to go when reaches the base of the topsoil.

Waterlogging on community fields is usually caused by a combination of factors, not just one element. Common causes of waterlogging include but are not limited to: surface water running onto the field from surrounding areas (run-on), an uneven surface, lack of crossfall and layering (particularly impermeable layers) within the soil profile. Best practice involves addressing the underlying causes in preference to treating symptoms.

Once the underlying causes are addressed, slit drainage systems can be used to further reduce the risks of waterlogging and shorten the time a field can return to play after significant rainfall. Not all fields require slit drainage, and both the slit drainage design and the installation need to be carefully planned to suit site conditions. Best practice is to design the slit drainage system in conjunction with the irrigation and field design and then to install slit drainage after soil amendment and turf works are completed. There are many elements to good drainage design. Including consideration of hydraulic conductivity, depth of sand, lateral pipe spacing, and sand slit width. [17]

For community facilities based on soil profiles, effectively managing surface water to achieve acceptable timeframes for a return to play typically requires:

- no surface water runs onto the field from upslope areas
- excess water that falls on the surface is removed as run-off by ensuring field has sufficient crossfall (1 in 70 to 1 in 100) and slope lengths less than 70 m. Alternatively, a slit drainage system can remove this water at a rate of at least 8 mm/hr over the entire field area
- downward movement of water in the rootzone is not impeded by soil layers
- excess water reaching the base of the rootzone is removed at a rate of at least 2 mm/hr by the subsoil and/or a subsoil drainage system.[18]

Meeting water requirements for turf growth

In a sports turf situation, automatic irrigation systems perform two key functions. First, they enable supplementary water to be applied when there is insufficient rainfall to support turf growth. Second, they assist in optimising turf management practices, particularly

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[13] McMaugh, P (2022). Australian Turfgrass Management 24.3 Page 52-53. May-June 2022
[14] Football NSW Limited (2015). Drainage and Irrigation. A guide to the essentials for a first-class football field.
[15] Neylan, J. (2022). Australian Turfgrass Management 24.1 Page 42. January-February 2022.
[16] Leake, S (2019). Presentation: Classifying sports fields and construction methods in Australia. https://www.parksleisure.com.au/includes/download.ashx?ID=155496
[17] Bruce Macphee (2021). Australian Turfgrass Management 23.6 Page 26-29. November-December 2021
[18] Source: Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter; Lamble, P., Askew, S. and Battam, M. (2022). Best practice guidelines and benchmarks for turf open space in the lower hunter. OzWater22.

herbicides for weed control and fertilisers, and some chemicals require watering into the soil.

Several best practice documents have outlined the critical design, installation, maintenance and management practices that underpin efficient irrigation and the effective use of water.[19,20,21,22] The amount of water that is required to sustain a turf surface depends on many elements, such as soil type and depth, geographical location and climate, microclimate, turf cultivar, irrigation system efficiency and how much damage occurs from sporting use (wear).[22] Variable rainfall as a response to drought and climate change can complicate irrigation needs. The quality and reliability of water supplies is a critical consideration, especially for construction types that have little or no resilience to reduced water availability (e.g. sand-based profiles).

If the field has healthy soil and an appropriate turf cultivar then usually rainfall and water stored within the soil profile are adequate to meet turf needs. As a result, minimal supplementary irrigation is required, particularly for fields that receive low levels of wear and reasonable levels of summer rainfall (e.g. coastal NSW). The resilience of many soil-based natural turf sporting fields to low water availability has been demonstrated during previous droughts and water restrictions. In Sydney between 2003 and 2009, numerous recreational areas and sports fields survived without supplementary irrigation. During a dry spell in February 2009, when little rain fell for 20-30 days, some sports fields performed well despite limited irrigation. Sites with deep loamy soils performed best, with the turf able to draw on water reserves stored within the soil. In the Lower Hunter, during the 2019-20 drought, many unirrigated sporting fields survived with no irrigation and minimal rainfall for over 60 days during summer. These experiences suggest that well-constructed and maintained turf grass may have less irrigation needs than previously thought.[19,21,22] Therefore baseline water requirements of turf surfaces may be less than previously understood.

Turf maintenance

Implementing regular maintenance practices is an essential part of turf management. Best practice involves tailored maintenance activities to address the issues that are limiting sporting field performance at each specific site. At many sites frequent aeration is crucial to relieve compaction arising from poor soil structure, but it is rarely required on some fields on dune sands in coastal areas (these dune sands have other issues and specific maintenance requirements). Adequate nutrition and effective control of weeds are essential to support turf growth. Regular independent soil testing is required to ensure nutrition requirements are being met.[23]

[19] Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter;
[20] G & M Connellan Consultants (2015) Best Practice Guideline for Functional Open Space in Victoria
[21] Martin, P and Battam, M (eds) (2011). Best practice guidelines for holistic open space turf management in Sydney. Sydney Water.
[22] Lamble, P., Askew, S. and Battam, M. (2022). Best practice guidelines and benchmarks for turf open space in the lower hunter. OzWater22.
[23] Department of Agriculture, Fisheries and Forestry (2022). National Soil Package. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils

Table 1: Common misconceptions impacting natural turf field management practices

Common misconception	Comment from best practice guidance
The best soil for turf is sand or 80:20 mix	It is unsuitable because it is too sandy for community fields
Using new turfgrass variety will give the best performance	Needs to be verified using small scale trials in high wear areas.
All fields require drainage	For drainage at an acceptable rate, waterlogging issues can be overcome using techniques that do not require slit drainage.
All fields require automatic irrigation, and the sprinklers need to throw "head-to-head" coverage	May not be efficient or effective if not installed properly

Source: Hunter Water (in press). Best Practice Sporting Fields: A guide for turf surfaces in the Lower Hunter; Lamble, P., Askew, S. and Battam, M. (2022). Best practice guidelines and benchmarks for turf open space in the lower hunter. OzWater22.

Weather extremes

Weather extremes such as the significant rainfall and flash flooding experienced in 2021-22; and earlier droughts, pose short and long terms risks to turf health. Guidance is available on undertaking damage assessments and subsequent recovery programs to minimise impacts (Table 2).[24] Immediate action recommended post-flood is to remove the water and silt layer as much as possible to allow turf recovery. This can take 4-6 weeks and is recommended to be undertaken with the following actions:

- Improving water infiltration through coring, verticutting and sanding to stimulate growth and to break up layers
- Increasing cutting heights during recovery by keeping the heights greater than 6 mm
- Applying slow-release fertiliser with moderate nitrogen, high potassium and phosphorus.
- Using liquid organics for root health
- Managing disease and weed by applying the appropriate fungicide and herbicide.
- Testing the soil and checking the condition of the rhizomes and stolons.[24]

The impact of flooding on the field and turf and therefore the measures required for post flood recovery are site and event specific.[25] Factors such as field construction type, turf cultivar, depth and duration of inundation, depth of material deposition and the timing of the flood are all relevant considerations. Extreme climates with prolonged rainy days and drought will require more maintenance and affect the playability of the field. However, the impact of a changing climate and rainfall regime is not yet fully understood. Work being undertaken more broadly to manage weather extremes, including adapting to changes to water resources and embedding drought resilience in urban areas, is also relevant to informing future practices.[26] Relevant resources to inform best practice are listed in Table 3.

[24] SPORTENG (2021). What are the consequences of flooding on sportfield natural turf? https://blog.sporteng.com.au/what-are-the-consequences-of-flooding-on-sportfield-natural-turf
[25] McPhee, B. (2022). Australian Turfgrass Management 24.2 Page 26-28. March-April 2022.
[26] See for example, Adapt NSW Climate Change impacts on our water resources, retrieved from https://www.climatechange.environment.nsw.gov.au/water-resources ; Greater Cities Commission, exposure to natural and urban hazards, retrieved from https://greatercities.au/metropolis-of-three-cities/sustainability/resilient-city/exposure-natural-and-urban-hazards-reduced; Sydney Water (2022) Innovative water management for the Aerotropolis Precinct https://www.sydneywater.com.au/content/dam/sydneywater/documents/iwcm-summary-report-2022.pdf

Table 2: Factors to consider for damage assessments from extreme weather: significant rainfall and floods

Factor	Effect
Silt deposits	Silt deposits can stay within the soil profile and restrict water infiltration and root growth
Depth of water	Increasing depth results in oxygen depletion in the rootzone, rotting of roots and less light available for the leaf.
Length of time turf is inundated	Prolonged flooding has similar effects as increasing water depth. Greatest damage is observed for flooding longer than 6 weeks.
Turfgrass species	Species have different flood tolerance. Most submersion-resistant for warm-season grass: Couch or Bermudagrass hybrid (*Cynodon dactylon* x *Cynodon transvaalensis*)
The age of the turf	Older turf contains higher organic matter and experiences more damage
Surface topography	Lower areas are usually points for surface drainage and subjected to longer periods of saturated soils and scorching due to increasing water temperatures

Source: SPORTENG (2021). What are the consequences of flooding on sportfield natural turf? https://blog.sporteng.com.au/what-are-the-consequences-of-flooding-on-sportfield-natural-turf

Table 3: Resources for natural turf management

a) Industry bodies

Resource	Description	Website
Turf Australia	Representative body of the turf industry in Australia comprising levy-paying turf producers and individual members that provides advocacy, works with Hort Innovation on research and development, and markets the benefits of the turf industry. Information about turf industry is available to members through monthly newsletter, quarterly magazines and local and international research reports	turfaustralia.com.au
Australian Sports Turf Managers Association	A peak industry body for sports turf management in Australia that provides support to members through education, industry awards facilitation, advocacy and research and development into professional and environmentally sustainable turf management. Resources available to members include: Australian Turfgrass Management Journal Sports turf managers certification program Turfgrass management resources, including turf management practices, environmental management, education & research, and HR & management Analytical, diagnostic and consultancy services for the public	agcsa.com.au
Irrigation Australia (IAL)	Australia's peak national organisation representing the Australian irrigation industry in all sectors from water users, consultants, designers and installers through to educational institutions, government, manufacturers and retailers. It is also a Registered Training Organisation delivering a wide range of nationally accredited irrigation qualifications, workshops and short courses	Irrigationaustralia.com.au
Sports Turf Association(s) (STA)	The National and state-based STAs are dedicated to the development and professionalism of turf management. They are managed by a voluntary team of Committee Members. Various resources are available on each of the websites (e.g. NSW, QLD, VIC, WA, SA)	
Australian Sports Turf Consultants	A private company providing independent turf consultancy services to sporting organisations and companies, government and industry bodies. It also conducts research and development on warm-season turf grasses for Australian and international turf related industries.	astcs.com.au

b) Government and research organisations

Resource	Description	Website
NSW Department of Primary Industries (DPI)-Soils	A government agency that provides information to the public on soil management, research & development to improve soil productivity and quality, publications through a free quarterly e-newsletter and monthly webinar series, and soil testing and analysis.	DPI Soils

University of New England	Publications on weed science research	UNE Weed Science
Charles Sturt University	Research in plant systems that include soil science and weed science and management and technology.	CSU Graham Centre

c) Research resources beyond those held by industry bodies

Resource	Description	Website
TurfFinder	An independent website that provides information on comparing, selecting, purchasing and maintaining turfgrasses for domestic lawns and sports turfs.	turfinder.com
PACE Turf	A website that provides research-based information on turf management guidelines on pests, soils, water and plant analysis	www.paceturf.org
Michigan State University Turfgrass Information File (TGIF)	A collection of published and unpublished materials related to turfgrass science, culture and the management of turfgrass-based facilities in the US, Australia, United Kingdom and Canada.	TGIF
National Turfgrass Evaluation Program (NTEP)	A US-based program that evaluates turfgrass varieties to provide information to turfgrass producers to choose the varieties that will perform best in their specific growing area and under their management programs.	ntep.org
Asian Turfgrass Center	A website which provides turfgrass information for the golf and sports turf industry in Asia	Micah Woods; Asianturfgrass.com

Appendix 19

Environmental Plastics

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EPIC identified research priorities to improve our understanding of synthetic turf and its potential issues- Submitted to the Office of the Chief Scientist, NSW

On the request of the Office of the NSW Chief Scientist and Engineer, the Environmental Plastics Innovation Cluster (EPIC) at the University of Newcastle has identified research priorities to fully understand the potential risks associated with microplastics and chemical exposure from synthetic turf, including *in-situ* and *ex-situ* experiments in parallel:

- Immediate measures to capture 99% of the microplastics: Stormwater and surface water drain more than 10kgs per annum of fine microplastics <10um (from the confidential study completed by EPIC in 2022), therefore, by targeting these known sources, at least 99% of the potential spread of microplastics can be prevented immediately.
- Microplastics could also originate from other sources, such as road wear and abrasion of tyres. We must set up a standard protocol for extracting microplastics from stormwater that could accurately differentiate turf plastics from the other suspended materials.
- Treatment solutions for micro and nano plastics in waste and grey water- using advanced treatment technologies that extract more than filtration can.
- Transportation of the samples from the field to a laboratory can also increase the uncertainties of the result. EPIC has been receiving samples within the state and interstate in non-plastic containers; biofouling and rust formation occurred in a short period, affecting the analysis of fine-size microplastics (Bhagwat et al., 2021). and we have developed site-specific protocols to maintain quality assurance and quality control. EPIC developed a site-specific quality control protocol and an apid on-site analysis method quantifying microplastics in laundry water samples from NSW health linen facilities. This method is currently susceptible to high concentrations, and work is in progress for low engagement and various sample matrices.
- *In-situ* long-term weathering studies incorporating chemical mixtures and microbial interactions. Besides the consequences of microplastics and associated chemicals, the association of microbes with plastics has more significant environmental implications as microplastics may select for unique microbiome participating in environmentally essential functions; despite this, the functional potential of the microbiome associated with different types of plastics is understudied. We demonstrated that microplastic surfaces exhibit unique microbial profiles and niche partitioning among the substrates through whole-genome sequencing. In particular, the abundance of *Vibrio alginolyticus* and *Vibrio campbellii* suggested that microplastic pollution may pose a potential risk to the food chain(Bhagwat et al., 2021). We have also demonstrated that weathering underpins the sorption and desorption of chemicals in microplastics; mixed contaminants such as PAHs and metals may be released from some of the synthetic turf components, have higher toxicity and are highly bioavailable than those in isolation (Carbery et al., 2018; Idowu et al., 2019, Carbery et al., 2022-under review, Thavamani et al., 2012a&b).
- Seasonal and climate effects on the microplastics and chemical release. Unravelling exposures and uptake over different seasons may prove helpful in understanding the release patterns fully. Extreme climatic conditions in Australia and proven heat generation make it a solid case to develop a

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quantitative measure of the *in-situ* and *ex-situ* flux of microplastics and chemical mixtures due to the ageing and weathering of turf materials.

- Relative environmental and human health risk assessment studies to contextualise the potential risks from synthetic turf on sports players and nearby residents.
- Transparent consideration of potential alternatives. Based on overseas progress and trend, other manufactured granular infill materials include elastomer, polymer, or organic substances such as coconut fibre, cork, and ground walnut shells. These alternative materials may be used more commonly in the future.

Background context

Synthetic turf has changed considerably since its inception. Playing surface is a critical component of the athletic environment, playing a role in performance and athlete safety. Many synthetic turf fields consist of not only synthetic grass but also rubber granules that are used as infill. The material's environmental and human health effects in third-generation synthetic turf components have been the subject of much debate. Still, they are based on the minimal information available to date. The main concerns are the release of microplastics and any associated toxic chemicals.

Plastics contain multiple chemicals –intentionally or unintentionally inserted into plastic – including those used to convey specific properties such as colour, flexibility, strength, fire resistance and water repellency. These chemicals can be released into the environment and available to organisms (Menichini, 2011; Negev et al., 2022). Based on limited overseas studies, synthetic turf pitches may be one of the substantial sources of microplastics in the environment (European Chemical Agency Report, 2018; Reef Clean AUSMAP Rubber Crumb Report, 2021). Some of these chemicals may be degraded by microorganisms (Bhagwat et al., 2021), and qualitative and quantitative evidence on the risks are still unknown.

Weathering of plastic material and potential risks associated with synthetic and hybrid turf use

Weathering underpins the fate and behaviour of plastics in the environment. Much of the existing academic research on this topic is based on virgin characteristics of plastics, based on limited samples, which do not consider the ageing and weathering influence on microplastics and chemical release (Carbery et al., 2018).

Third-generation infill systems have been reported to have surface temperatures as high as 93°C (Jastifer et al., 2019). This is possible because the infill material has been shown to have very low heat flux, and most of the energy from the sun goes into heating the exposed pile fibres, which have low specific heat. Thus, the surface temperature is driven by the total amount of solar radiation. Such a high-temperature forms cracks and generates nano plastics (Carbery et al.,2022, Under review), and also, under extreme conditions, chemicals are transformed into toxic metabolites, which are highly bioavailable.

Existing studies do not incorporate fields with a range of ages, adjacent contaminant sources, geographic location, synthetic turf manufacturers, use patterns, etc. With the small sample size, we cannot distinguish the effects of field age or indoor/ outdoor facility on the microplastic emission and associated chemical flux.

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Turf architecture encourages more aeration and sunlight and water penetration, which could accelerate weathering; synthetic turf could act as an initial sink with the gradual release over time. From our involvement with two confidential studies on the safety of synthetic turf, synthetic turfs generally consist of different layers of filaments; rubber granulates and crushed; the top layer of artificial turf (monofilament and slit form) is made of straws with a mixture of material of polypropylene (PP), polyamide polyolefin, and polyurethane. Straws with a length of 3-6 cm are typically filled with sands and rubber granulates to make the straws stand up. Rubber granulates' materials depend on the surface's design, and the granulates' size varies from 0.8 mm to 3 mm. The fibres of modern systems have a pile height of 40 to 70 mm and have been made of polyethylene, nylon, or polypropylene. However, polyethylene fibres are the most popular currently. Some of these materials are not fully characterised, and these unknown components remain uncertainties in risk evaluations. Non-specific sampling and analytical methods are still needed to describe synthetic turf fields fully.

Capabilities of EPIC

The Environmental Plastics Innovation Cluster (EPIC) at the University of Newcastle has set up research programs that underscore the many unknowns and uncertainties surrounding current knowledge of plastic's health effects and pioneered plastic weathering research in 2015. We investigated the long-term weathering of plastics in various environments that may influence microplastics' transport, fate and toxicity. Using an advanced analytical approach, we demonstrate that ageing and weathering processes alter the surface morphology, surface chemistry, crystallinity, thermal stability, particle size and adsorption of chemical compounds to plastic surfaces over time, releasing plastic degradation products (Carbery et al., 2022, Nat Mat Deg, under review).

Determining the hazards posed by microplastics requires understanding their transformation due to weathering processes. Despite their perceived risks, limited information exists on synthetic turfs' weathering and associated risks. From the extrapolation of our *in-situ* weathering experiments, the plastic types used in synthetic turf could lose between 0.25 and 0.37 kg of rubber/m^2/year on average (more loss will be from the infill materials). Apart from stormwater and runoff, people's shoes and clothes could transport microplastics from the field.

EPIC has also set up an inventory of weathered plastics of all polymer types, aged at different time scales showing that plastic weathering influences its interactions with chemical and biological hazards such as pathogens (Bhagwat et al., 2021; Raju et al., 2018).

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