WESTERN SYDNEY UNIVERSITY

# SYNTHETIC TURF IN PUBLIC SPACES

## SYSTEMATIC ASSESSMENT OF SURFACE TEMPERATURES AND ASSOCIATED ENVIRONMENTAL IMPACTS

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**AUTHORS**

**Sebastian Pfautsch and Agnieszka Wujeska-Klause**

Urban Planning and Management

School of Social Sciences

Western Sydney University

**PREPARED FOR**

Office of the NSW Chief Scientist and Engineer

**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.

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# 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.

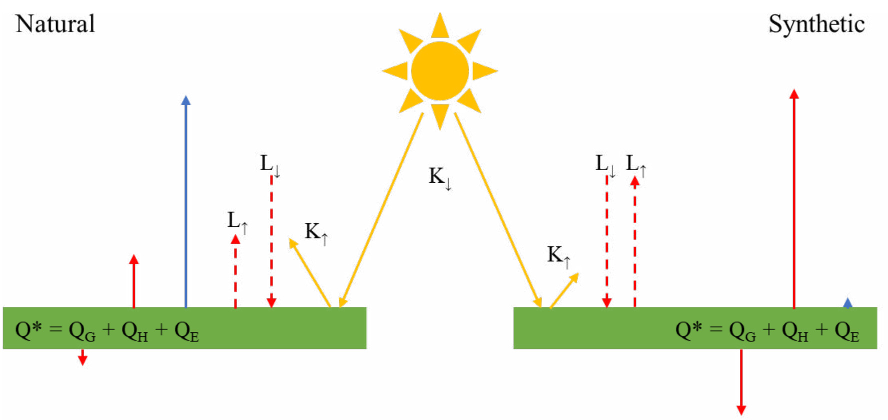


**FIGURE 2:** The daytime energy balance of well-watered natural (A) and dry synthetic turf (B). See text for explanation of symbols. The diagram was created using information from Carvalho et al. (2021), Devitt et al. (2007), and Jim (2017)

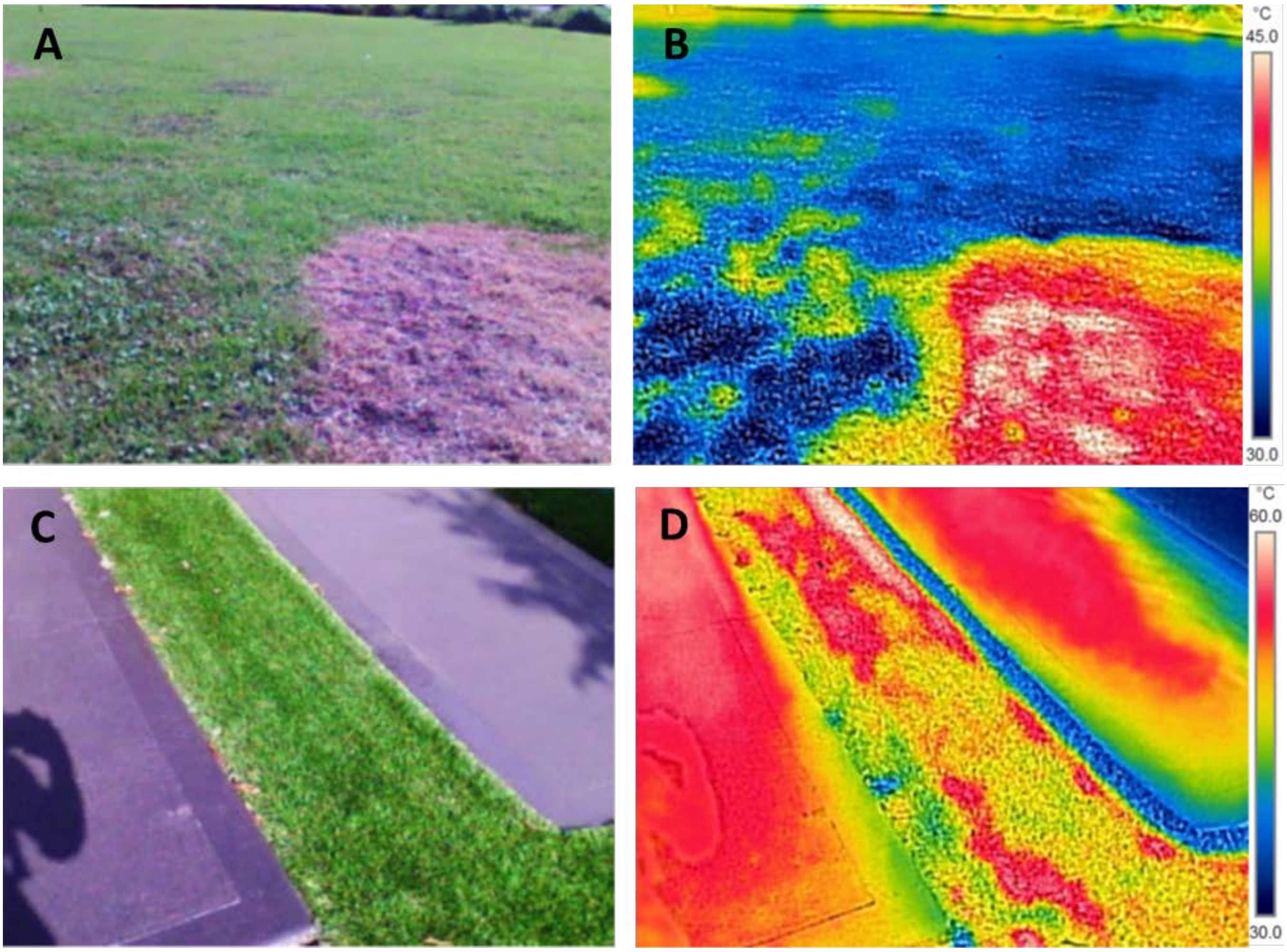


**FIGURE 3:** Normal (left) and infrared images (right) of green and dry grass surface temperatures at a public park (A, B) and a nearby house with synthetic turf and black painted concrete (C, D) in a western Sydney suburb. The images were taken at 16:40 (A, B) and 17:00 (C, D) on 1 March 2021. In full 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.

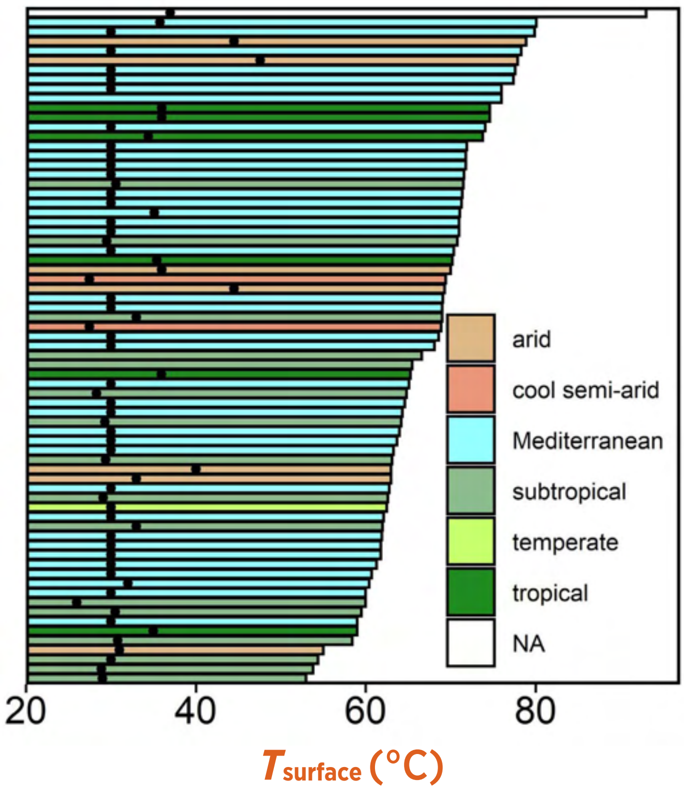


**FIGURE 4:** Surface temperatures (horizontal bars, $T_{surface}$) extracted from the literature in different climatic conditions. The data were collected in the laboratory, and in situ on the sports fields. The black dots refer to the air temperatures measured in these studies, either ambient or above 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.

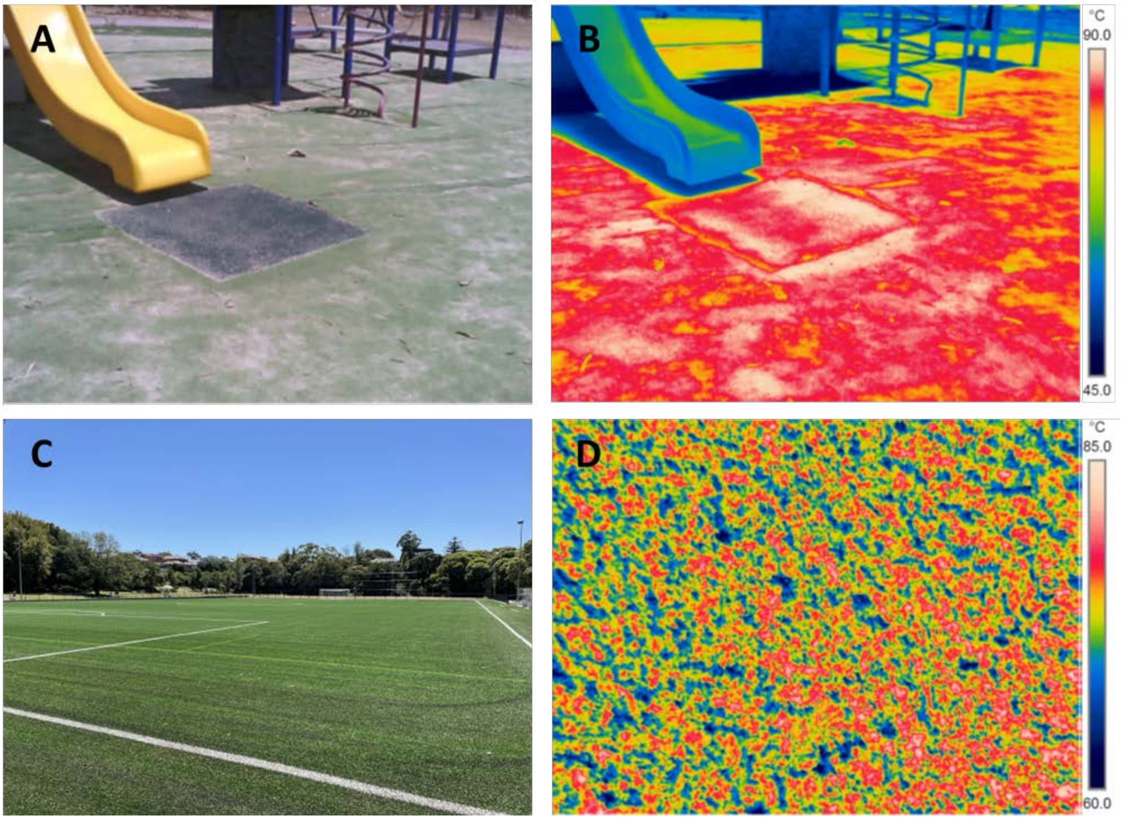


**FIGURE 5:** Normal and infrared images of synthetic turf surface temperatures at a public playground in western Sydney (panels A and B) and at the soccer field in eastern Sydney (panels C and D). The images were taken at 13:30 on 4 January 2020 (panels A and B) and at 11:00 on 10 February 2022 (panels 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 ($kWm^2$) |
|---|---|---|---|---|---|
| **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.

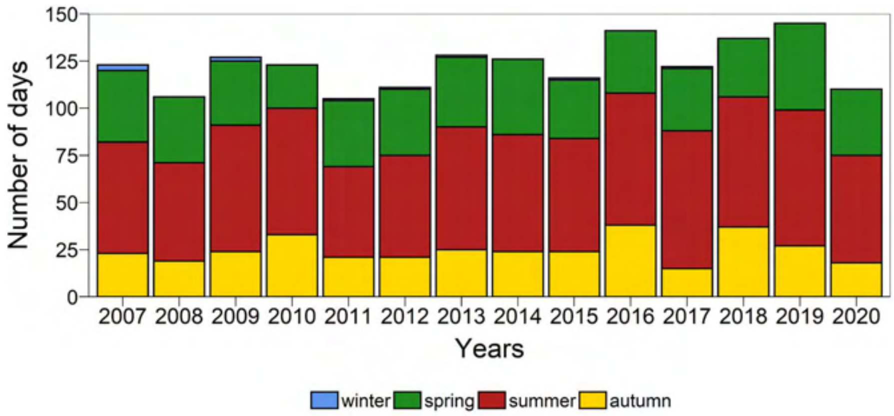


**FIGURE 6:** Number of days per year where daily maximum air temperature was above 27°C. Research at Western Sydney University has shown that at air temperatures below 30°C, surface temperatures of synthetic turf and associated black globe temperatures can be above 70°C and 40°C, respectively. Data 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.

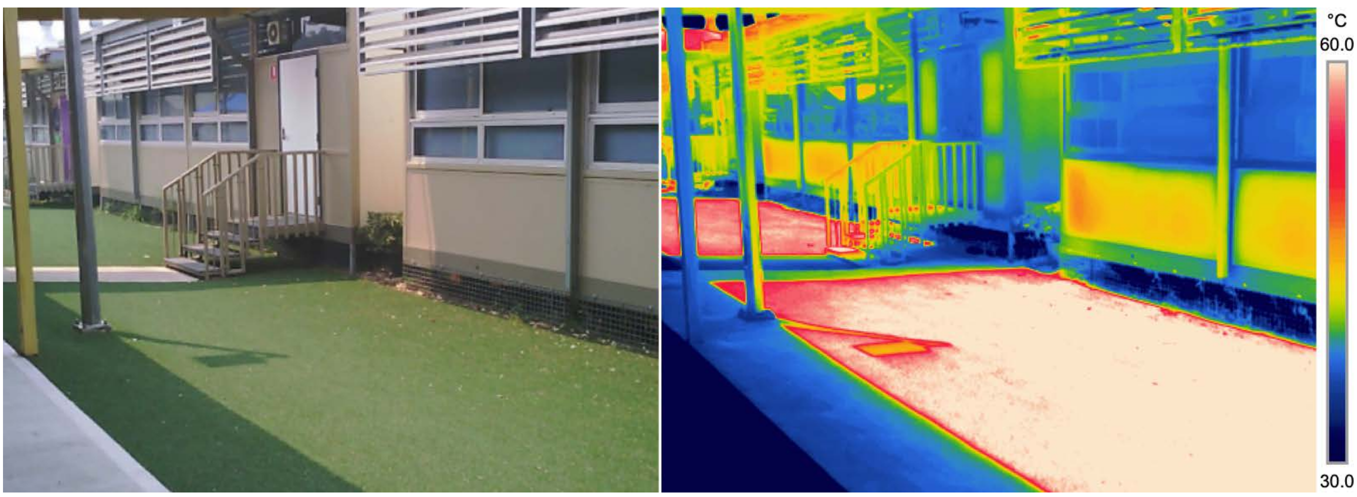


**FIGURE 7:** Normal and infrared images of synthetic turf in the sun and shade at a primary school in western Sydney (NSW). The images were taken at 12:03 on 19 December 2019. The sunlit synthetic turf reached on average 61°C and when shaded the surface temperature was 35°C. The colour scale on the 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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