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Measuring the instantaneous cooling effect of turf irrigation in Melbourne, Australia

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ABSTRACT

Private backyards are an important space for social and physical activities. Summer heat stress can reduce people's willingness to use their backyards. Long-term turf irrigation has been demonstrated to reduce daytime mean air temperature because it can maintain soil moisture content at or near field capacity for a longer period, thereby increasing evaporation from soil surface and turf transpiration. This cooling effect is likely to be stronger during and immediately after irrigation because of direct evaporation as the sprayed water streams pass through the air and from water intercepted by the turf grass canopy. This study aims to measure the magnitude and duration of this instantaneous cooling effect from turf irrigation. The field experiment consisted of two 6 m × 6 m plots (one irrigated and one unirrigated) fenced to mimic a backyard environment. Daily irrigation of 2 mm was applied at 13:00 local time. The experiment was conducted in summer 2021 in Melbourne, Australia and lasted for six weeks. The instantaneous cooling effect from irrigation lasted for approximately two hours (13:00–15:59, instantaneous cooling) before the air temperature and turf surface temperature returned to the levels measured before irrigation (10:00–12:59, baseline cooling). The instantaneous cooling effect for air temperature and turf surface temperature were –0.54°C and –1.01°C, respectively. The results suggest that the daytime cooling effect of irrigation may be strengthened by applying smaller amounts at multiple times throughout the warmest part of the day, thereby increasing the direction evaporation of water during and after irrigation.

Keywords: Irrigation, urban green space, cooling, turf.

Introduction

Global climate change is expected to increase human heat stress in summer in many parts of the world (Matzarakis and Amelung 2008). Increased heat stress can prevent people from using urban outdoor spaces because of thermal discomfort (Cheung and Jim 2018b). Various strategies have been proposed to reduce urban heat stress, such as urban greening, use of reflective surfaces and irrigation (Santamouris et al. 2017). Irrigation is an emerging and promising strategy to reduce heat stress in urban areas, including urban green spaces (Coutts et al. 2013; Livesley et al. 2021). Irrigating urban green spaces does not need to compromise

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potable water security if alterative water sources, such as recycled sewage water and stormwater, can be used.

Irrigation can reduce heat stress by changing the surface energy balance. Assuming that anthropogenic heat is negligible, the energy balance on a homogenous turf surface can be written as:

$$Q^{*} = Q_E + Q_H + \Delta Q_S [W\, m^{-2}] \quad (1)$$

where Q^* is the all-wave net radiation [W m^{-2}], Q_E the latent heat flux [W m^{-2}], Q_H the sensible heat flux [W m^{-2}] and ΔQ_S the net storage heat flux [W m^{-2}] (Oke 1988). Irrigation can increase latent heat flux by increasing evaporation from turf and soil surfaces and turf transpiration, thereby reducing sensible heat flux and air temperature. Irrigation can also promote the growth of vegetation and increase the leaf area index, causing a greater cooling effect from shading and transpiration (Liu and Wang 2023).

Modelling studies have quantified the mean cooling effect of irrigating pervious and vegetated surfaces in urban areas in summer or during heatwaves. Broadbent et al. (2018) predicted that irrigating all pervious surfaces (30 mm d^{-1}) during a heatwave could reduce daily mean air temperature by up to 2.3°C in a suburb in Adelaide, Australia. Gao et al. (2020) predicted that irrigating all vegetated surfaces (30 mm d^{-1}) during a heatwave could reduce daily mean air temperature by 0.5°C in Sydney metropolitan area, Australia. Wang et al. (2019) predicted that irrigating all vegetation surfaces (14 mm d^{-1}) in summer (June–August) could reduce daily mean air temperature by 1.9°C in the urban areas of contiguous US. However, few modelling studies focused on the instantaneous cooling effect of irrigation, i.e., the cooling effect during and immediately after irrigation. This is because observational data are lacking to validate the performance of the models at a fine temporal scale. Understanding the instantaneous cooling effect of irrigation is important because the cooling effect of irrigation is likely to be strongest during and immediately after irrigation. Measuring the magnitude and duration of the cooling effect immediately after irrigation can help schedule irrigation to maximise the cooling benefits for green space users.

Private green spaces can contribute to >30% of the total green spaces in certain cities (Mathieu, Freeman, and Aryal 2007). Backyards are an important private green space because they provide a truly secure and convenient place for physical and social activities. The aim of this study is to measure the instantaneous cooling effect of irrigating turf in a backyard environment in summer.

Methods and materials

This study was conducted in the Burnley Campus of the University of Melbourne in Victoria, Australia. Melbourne has a temperate oceanic climate (Köppen climate classification: Cfb). In summer (December–February), the mean daily maximum air temperature and total rainfall are 26.2°C and 155.3 mm, respectively. Droughts and heatwaves are common in Melbourne's summer. Irrigating turf can help maintain turf health and strengthen its cooling effect through evapotranspiration.

Figure 1. Ground photo (left) and birds eye view (right) of the experimental plots. The experiment consisted of two plots (6×6 m^2) at the Burnley Campus of the University of Melbourne, Australia. Each plot was enclosed by 1.8-m tall 70% shade cloth to mimic a backyard environment and reduce air mixing between the plots and the environs. One plot was unirrigated and the other was irrigated daily (2 mm d^{-1}) at 13:00 local time. Air temperature, relative humidity, wind speed, black globe temperature and soil moisture content were measured at the centre of each plot.

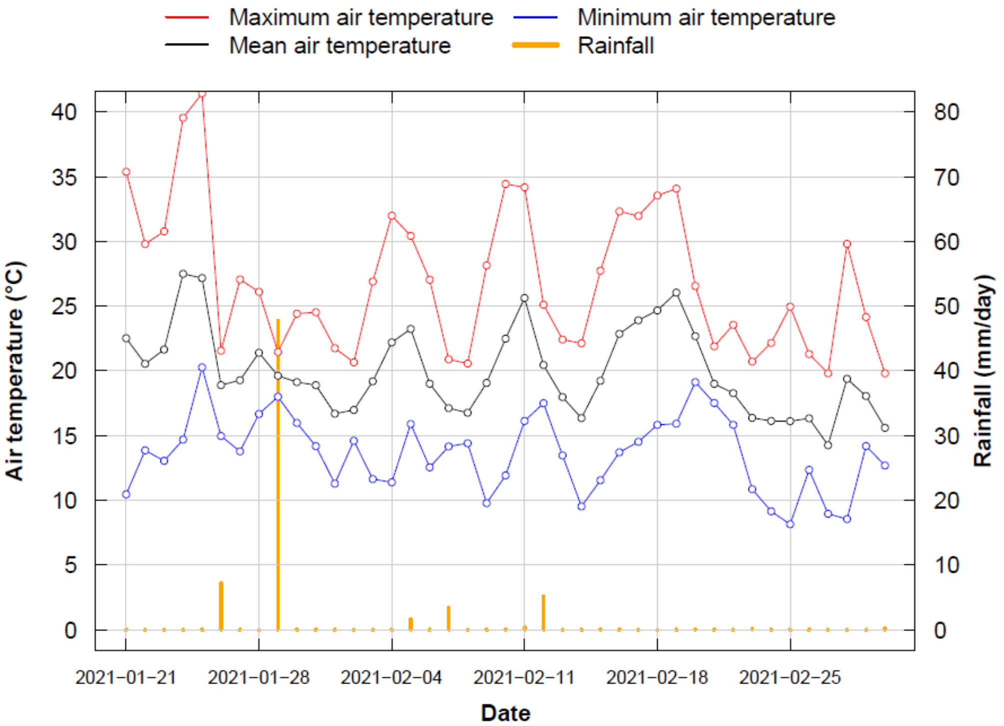

Figure 2. Daily mean, minimum and maximum air temperature, and daily total rainfall of the study period (2021-01-21 to 2021-03-02).

Two plots (6 × 6 m^2) were set up on a turf surface (kikuyu, *Pennisetum clandestinum*) to measure the instantaneous cooling effect of irrigation (Fig. 1). The turf was mowed every two weeks to approximately 50 mm tall. Each plot was surrounded by 1.8-m tall 70% shade cloth (SOLARSHADETM) to mimic a fenced backyard environment and to reduce air mixing between each plot and the surrounding air mass. One plot was unirrigated and the other was irrigated daily (2 mm d^{-1}) at 13:00 local time. One 360° Hunter Rotator nozzle (MP1000-360) was installed at the centre of each plot and four 90° Hunter Rotator nozzles (MP1000-90) were installed at the corners to irrigate the plot evenly. The nozzles were adjusted carefully to avoid wetting the climate station at the centre. At the climate station, air temperature, relative humidity, wind speed and black globe temperature were measured at 1.1 m above ground, and turf surface temperature was measured from 1.5 m above ground. Soil moisture content was measured at 0.04 m below ground. Air temperature and relative humidity were measured by ATMOS14, METER (accuracy: ±0.2°C for air temperature and ±1.5% @ 25°C for relative humidity). Wind speed was measured by 03101-L, Campbell Scientific (accuracy: ±0.5 m s^{-1}). Black globe temperature was measured by 44031, Omega (accuracy: 0.1°C @ 25°C). Turf surface temperature was measured by SI-111-SS, Apogee (accuracy: 0.2°C). Soil moisture content was measured by CS650, Campbell Scientific (accuracy: ±3%). All variables were measured every 10 seconds and the 1-min mean values were logged.

The experiment was conducted from 2021-01-21 to 2021-03-02 (study period). The average daily mean, minimum and maximum air temperatures in this period were 20.0°C, 13.6°C and 26.9°C, respectively (Fig. 2). The total rainfall was 66 mm. No heatwaves occurred in this period although there were two very hot days (maximum air temperature>39°C) in the first week of the experiment.

The microclimate data from 10:00 to 15:59 were averaged minutely over the whole study period for the data analysis. Air temperature, turf surface temperature and universal thermal climate index (UTCI) were used to quantify the baseline cooling effect (10:00–12:59) and the instantaneous cooling effect (13:00–14:59) of irrigating turf. The baseline cooling effect is attributed to the additional evaporation from soil surface and turf transpiration due to increased soil moisture content from long-term irrigation. The instantaneous cooling effect is attributed to the direct evaporation of sprayed water droplets during irrigation and the evaporation from canopy interception immediately after irrigation, and the additional evaporation from soil surface and turf transpiration due to increased soil moisture content from irrigation. UTCI is a thermal index that integrates the effects of air temperature, relative humidity, wind speed and mean radiant temperature on human thermal stress (Bröde et al. 2012). UTCI has ten thermal stress categories from extreme cold stress (<–40°C) to no thermal stress (9 to 26°C), and to extreme heat stress (>46°C). UTCI was calculated using the 'rBiometeo' package in R Studio 4.1.1.

Results

Figs. 3 and 4 show the average changes of four variables from 10:00 to 15:59 over the study period. From 10:00 to 12:59, the changes were attributed to the increase in soil moisture content due to long-term irrigation. From 13:00 to 14:59, the changes were attributed to the immediate impacts of the daily irrigation event that occurred from 13:00 to 13:11. The irrigated plot had a higher soil moisture content than the unirrigated plot from 10:00 to 15:59 (Fig. 3a). The air temperature of the irrigated plot was lower than that of the unirrigated plot throughout this period (Fig. 3b). A sharp reduction in air temperature was observed in the irrigated plot during and immediately after irrigation. The turf surface temperature of the irrigated plot was higher than that of the unirrigated plot from 10:00 to 12:00 (Fig. 3c). A sharp reduction in turf surface temperature was also observed in the irrigated plot during and immediately after irrigation. The UTCI of both plots was similar from 10:00 to 15:59 (Fig. 3d).

From 10:00 to 12:59, the mean difference in soil moisture content between the irrigated and unirrigated plots was 21.7% (Fig. 4a). The daily irrigation at 13:00 increased the difference to 22.4%. In terms of air temperature, the baseline (10:00 to 12:59) temperature difference between the irrigated and unirrigated plots was –0.30°C whereas the instantaneous cooling effect increased to –0.54°C (Fig. 4b). The strongest cooling effect was –0.79°C, which occurred at 13:16. After then, the cooling effect gradually weakened and returned to the baseline level at approximately 16:00. In terms of turf surface temperature, the baseline (10:00 to 12:59) cooling effect was 0.33°C, meaning that the irrigated plot was warmer than the unirrigated plot (Fig. 4c). The instantaneous cooling effect was very different at –1.01°C. The strongest cooling effect was –2.72°C, which occurred at 13:12. The difference in UTCI between the irrigated and unirrigated plots varied between 0°C and 1°C, and there was no obvious temporal trend and no obvious immediate impacts of irrigation (Fig. 4d).

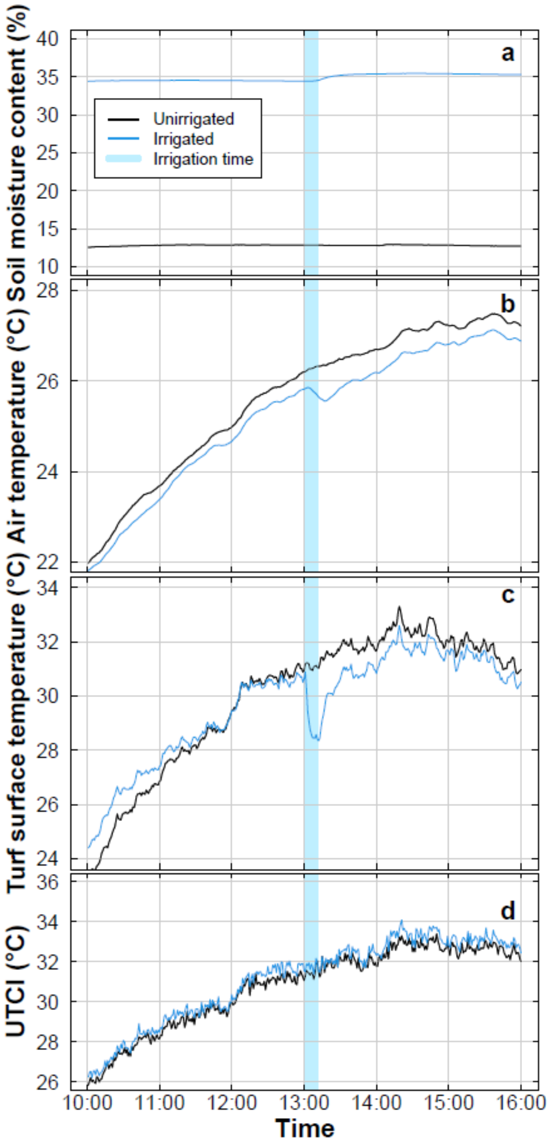

Figure 3. Changes in (a) soil moisture content, (b) air temperature, (c) soil temperature and (d) UTCI of the irrigated and the unirrigated plots between 10:00 and 15:59. Daily irrigation of 2 mm was applied from 13:00 to 13:11. The solid black lines are the minutely means of the unirrigated plot and the solid blue line the minutely means of the unirrigated plots over the study period (2021-01-21 to 2021-03-02).

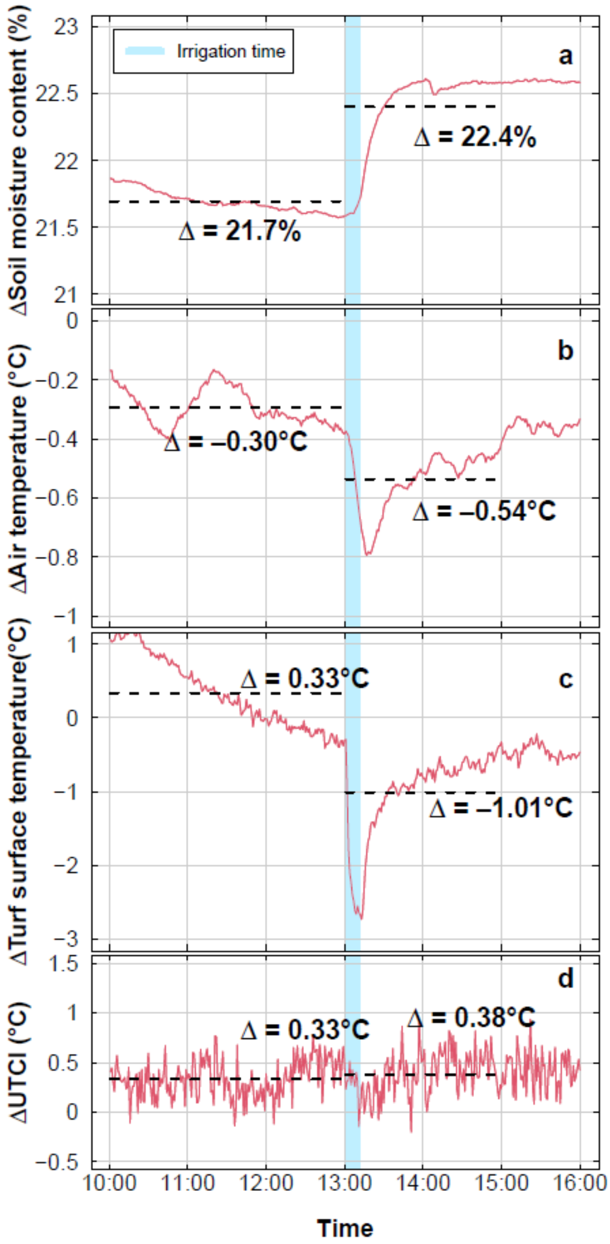

Figure 4. Daytime changes (10:00–16:59) in the differences in (a) soil moisture content, (b) air temperature, (c) soil temperature and (d) UTCI between the irrigated and the unirrigated plots (Δ = irrigated – unirrigated). The solid red lines are the minutely mean differences between the irrigated and the unirrigated plots over the study period (2021-01-21 to 2021-03-02). Daily irrigation of 2 mm was applied from 13:00 to 13:11. The horizontal long dashed lines are the mean difference before irrigation (10:00–12:59), i.e., the baseline cooling effect. The horizontal short dashed lines are the mean difference after irrigation (13:00–14:59), i.e. the instantaneous cooling effect.

Discussions

The baseline cooling effect from long-term irrigation and the instantaneous cooling effect of irrigation events were measured for turfed backyard environments in this study. The baseline cooling effect from long-term irrigation was attributed to the additional evaporation from soil surface and turf transpiration due to increased soil moisture content. The instantaneous cooling effect of irrigation events was attributed to the direct evaporation during irrigation and the evaporation from canopy interception immediately after irrigation, and the additional evaporation from soil surface and turf transpiration due to increased soil moisture content from irrigation. Irrigating turf at 13:00 could greatly reduce air temperature and turf surface temperature in the two hours following irrigation. The reduction in air temperature was comparable to that by tree shade (–1.52°C to –0.72°C) in Melbourne on hot days (maximum air temperature: 25.3°C to 43.9°C) (Sanusi et al. 2017). The strong instantaneous cooling effect of irrigating turf is likely attributed to the direct evaporation during irrigation and the evaporation from canopy interception immediately after irrigation. The water loss from direct evaporation and wind drift during daytime irrigation can account for 23% of the irrigation amount (Molle et al. 2012). This loss is beneficial to reducing human heat stress because the aim of using irrigation as a heat mitigation strategy is to maximise evapotranspiration and thereby maximising the cooling benefit. Irrigating in early afternoon is most beneficial to the users of urban green spaces because daytime heat stress is the strongest and people use urban green spaces most often during the day. The daytime mean cooling benefit of irrigation may be strengthened by irrigating multiple times throughout the warmest part of the day thereby increasing the direction evaporation of water during and immediately after irrigation. The interval between irrigation episodes and the amount of irrigation water for each episode depends on the weather conditions of the day.

Potable water is traditionally used to irrigate urban green spaces, but water sensitive urban design can provide alternative water sources for irrigating urban green spaces for cooling. Water sensitive urban designs are the approaches that keep water in the urban landscapes to achieve different objectives (Coutts et al. 2013). Stormwater harvesting and sewage treatment are two examples of water sensitive urban designs that can provide alternative water sources for irrigating urban green spaces. Recent housing development projects in Melbourne have started to incorporate water sensitive urban design into the building design to improve their capacity to retain non-potable water for different purposes. It is expected the stormwater harvesting designs in the new housing developments in Melbourne will increase the city's non-potable water supply by seven times by 2050, which is equivalent to 9.8% of the city's water consumption (Environment and Natural Resources Committee 2009). Irrigation for cooling has the potential to be used in larger public urban green spaces if the city is equipped with sufficient non-potable water collection and storage facilities.

Although irrigation can greatly reduce air temperature and turf surface temperature in the afternoon, it cannot reduce UTCI, i.e., heat stress. This is because the outdoor heat stress is primarily driven by incoming shortwave radiation (Cheung and Jim 2018a). Shading is still necessary to reduce incoming shortwave radiation and heat stress in urban green spaces in summer. Apart from reducing air temperature through increasing evapotranspiration, irrigating urban green spaces can potentially increase the leaf area index and growth of urban vegetation, thereby creating a synergistic cooling benefit. Liu and Wang (2023) predicted that irrigation would increase the leaf area index of crop by 0.4 m^2 m^{-2}, which accounts for 14% of the cooling effect of irrigation. This synergistic cooling benefit may be stronger for urban trees in the long term because the extra growth due to irrigation is accumulated over the years.

There are a number of practical considerations related to using irrigation to cool urban green spaces, such as identifying the cooling effectiveness for a particular background climate and finding the optimal irrigation amount (Cheung, Nice, and Livesley 2022). The cooling effectiveness of irrigating urban green spaces is highly dependent on the background climate of a city. The mean cooling effect of irrigating urban green space in summer is stronger in cities with higher air temperature or lower rainfall, while relative humidity, wind speed and incoming shortwave radiation had significant impact on the cooling effect (Cheung, Livesley, and Nice 2021). The meteorological variables that influence the instantaneous cooling effect of irrigation are likely the ones that influence wind drift and evaporation loss, i.e. air temperature, net radiation, vapour pressure deficit, and wind speed (Playán et al. 2005). The mean cooling effect of irrigating urban green spaces can strengthen with increasing daily irrigation amount, but the additional cooling effect will diminish when the daily irrigation amount exceeds certain levels (Broadbent et al. 2018). In practice, irrigation decisions are likely determined by the availability and cost of water. Current understanding about the cooling benefits of irrigating urban green spaces is mostly based on the mean benefits over a few days or a few months in summer. Since the cooling effect of irrigation is likely the strongest immediately after irrigation, further studies are required to understand the instantaneous impacts of irrigating urban green space on microclimate.

Acknowledgments

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