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Research Paper

Impacts of irrigation scheduling on urban green space cooling

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ABSTRACT

The increasing heat stress in cities due to climate change and urbanisation can prevent people from using urban green spaces. Irrigating vegetation is a promising strategy to cool urban green spaces in summer. Irrigation scheduling, such as daytime vs night-time irrigation and the frequency of irrigation in a day, can influence the cooling benefit of irrigation. This study aimed to investigate whether irrigation scheduling can be optimised to increase the cooling benefit and determine how the cooling benefit changes with weather conditions. A field experiment with twelve identical turfgrass plots (three replicates × four irrigation treatments) was set up to measure the afternoon cooling benefits of irrigation. The four treatments included: no irrigation, single night-time irrigation (4 mm d^{-1}), single daytime irrigation (4 mm d^{-1}) and multiple daytime irrigation (total = 4 mm d^{-1}). The cooling benefit was defined as the air temperature difference measured at 1.1 m above the turfgrass between the irrigated and unirrigated treatments (air temperature sensor accuracy ± 0.2 °C). The afternoon (12:00–15:59) mean cooling benefit of multiple daytime irrigation (–0.9 °C) which was significantly stronger than that of single night-time irrigation (–0.6 °C) and single daytime irrigation (–0.5 °C). Regardless of irrigation scheduling, the afternoon mean cooling benefits of irrigation were greater for days when background air temperature, vapour pressure deficit and incoming shortwave radiation were greater. The findings suggested that irrigation scheduling can be optimised to increase the cooling benefit of urban green space irrigation without increasing overall water use.

1. Introduction

Urban green spaces are an important part of a city because they offer a number of ecosystem services to urban dwellers such as noise pollution reduction (Koprowska et al., 2018), air purification (Wu & Chen, 2023) and human health benefits (Lee & Maheswaran, 2011). The perceived general health (Maas et al., 2006) and mental health (van den Berg et al., 2015) of urban residents are positively associated with the proximity of urban green spaces to their homes. Good proximity of urban green spaces encourages people to engage in physical and social activities and these activities are related to better physiological health and well-being (Markevych et al., 2017). Providing a safe space for physical and social activities is increasingly being recognised as one of the most important roles of urban green spaces (Lachowycz & Jones, 2013).

Nevertheless, the presence and good proximity of urban green spaces does not necessarily equate to the use of those urban green spaces by local residents. The use of urban green space is highly dependent on the quality of the space (Giles-Corti et al., 2005). Thermal comfort is an important aspect of urban green space quality. Urban green spaces with dry soil (Spronken-Smith & Oke, 1998) or sparse and unhealthy vegetation (Shashua-Bar & Hoffman, 2000; Speak et al., 2013) can have a high air temperature. High air temperature can reduce people's willingness to use urban green spaces (Cheung & Jim, 2018b), thereby undermining the health benefits that urban green spaces can deliver. As summer air temperature is expected to increase in many parts of the world due to climate change (Matzarakis & Amelung, 2008), cooling strategies are needed for urban green spaces to maintain their functionality and high use by local residents.

Irrigating vegetation has been proposed as a sustainable and effective cooling strategy to reduce air temperatures in urban green spaces and other parts of a city (Coutts et al., 2013; Livesley et al., 2021). Irrigation can be a sustainable cooling strategy when non-potable water is used for irrigating urban vegetation. Non-potable water can be collected and retained in the city through stormwater harvesting and wastewater treatment (Wong, 2006). The effectiveness of irrigating

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vegetation as an urban cooling strategy has been investigated in some modelling studies (Gao et al., 2020; Wang et al., 2019). Gao et al. (2020) used the Weather Research and Foresting model to predict that irrigating all ground surfaces in Metropolitan Sydney, Australia during a heatwave would reduce daily mean air temperature by approximately 0.5 °C. Wang et al. (2019) used the Weather Research and Forecasting model to predict that irrigating all vegetated surfaces in the urban areas of the contiguous US in summer would reduce daily mean air temperature by 1.8 °C. There is also some empirical evidence that the irrigating vegetation in urban green spaces can reduce air temperature (Cheung, Jim, et al., 2022; Lam et al., 2020). Such cooling effects of irrigating vegetation are induced by an increase in latent heat flux from increased evapotranspiration (Chen et al., 2018).

Since urban green spaces may be frequently used in the afternoon, it is important to investigate whether optimising irrigation scheduling can increase evapotranspiration and strengthen the cooling effect in the afternoon. Daytime and night-time are two contrasting irrigation schedules that can be considered. When irrigation is used solely to maintain plant health, daytime irrigation is avoided because evaporation occurs more quickly during the day (Burt et al., 2005) and this does not directly improve plant growth. However, if irrigation was to be used primarily to cool urban green spaces, then daytime irrigation may be desirable because evaporation occurs more quickly during the day, which can potentially strengthen the cooling effect during and immediately after irrigation (Chen et al., 2018). Broadbent et al. (2018) suggested that irrigation scheduling could be optimised to potentially strengthen the cooling effects but using the same amount of irrigation water.

Weather conditions can have a strong influence on the cooling effects that result from irrigating urban green spaces. Studies have reported a stronger cooling effect of irrigation during a heatwave than during non-heatwave conditions, again due to the higher rates of evapotranspiration (Gao et al., 2020; Lam et al., 2020). When soil water availability is not limiting, the rate of evapotranspiration from a turfed soil surface is dependent on the background air temperature, vapour pressure deficit, wind speed and solar radiation (Allen et al., 1998). High air temperature and solar radiation provide more energy for water to be evaporated while high vapour pressure deficit and wind speed reduce the resistance for that water vapour to diffuse from the evaporating surface (Burt et al., 2005). Although it is clear that the cooling effect from irrigation is stronger in warmer seasons (Wang et al., 2019; Yang & Wang, 2015), little is known about the impacts of different weather conditions on the cooling effects from irrigation within a summer season. It is important to understand how different weather conditions can make irrigating urban green spaces a more effective, or less effective, cooling strategy to inform irrigation management.

In this study, we used a replicated field experiment to measure the impacts of irrigation scheduling and weather conditions on the afternoon (12:00–15:59) mean cooling effect of irrigating a small turfed green space. The experiment consisted of four treatments: unirrigated (U0), 4 mm irrigated at 01:00 am (N1), 4 mm irrigated at 13:00 pm (D1), and 1 mm irrigated at 12:00, 13:48, 14:00 and 15:00 pm (D4). The three irrigated treatments were irrigated at different times of the day, but they received the same daily total irrigation amount. We defined the cooling effects of irrigation as the difference between the irrigated and unirrigated treatments (Δ = irrigated − unirrigated). We used air temperature, turf surface temperature, mean radiant temperature and universal thermal climate index (UTCI) to quantify the cooling effects. We tested the following three hypotheses:

(1) all three irrigated treatments would induce significant afternoon (12:00–15:59) mean cooling effects;

(2) the strongest afternoon (12:00–15:59) mean cooling effect would be irrigating four times in the afternoon (D4), and the least significant would be irrigating once at night (N1);

(3) the afternoon (12:00–15:59) mean cooling effects of irrigating turf would be significantly and positively associated with background air temperature, vapour pressure deficit, wind speed and incoming shortwave radiation.

This is study is unique because it directly measures the cooling effect of irrigating turfgrass in a replicated experiment, which provides empirical evidence to help optimise irrigation scheduling as a strategy to cool urban green spaces and the urban landscape more broadly.

2. Methods and materials

2.1. Study area and climate

This study was conducted in Melbourne, Australia. The elevation of the study area was 13 m above mean sea level. This area is classified as Local Climate Zone B (scattered trees) (Demuzere et al., 2022) under the local climate zone classification system (Stewart & Oke, 2012). Melbourne (−37.8, 145.0 / 37°50′S 145°01′E) has a temperate oceanic climate (Köppen climate classification: Cfb). The summer of Melbourne is dry. The mean monthly total rainfall of summer (December–February) is only 51.8 mm. The dry summer climate of Melbourne is conducive to a strong cooling effect of irrigating urban green spaces (Cheung, Nice, et al., 2022). The summer of Melbourne is also characterised by a large difference between daytime and night-time air temperatures. The mean daily maximum air temperature of summer (December–February) is 26.2 °C and the minimum is 15.6 °C (Bureau of Meteorology, 2023a). A large difference between daytime and night-time air temperatures provides an opportunity to strengthen the cooling effect of irrigation by optimising the irrigation schedule.

2.2. Experimental design

The field experiment consisted of twelve identical plots (four treatments × three replicates). Each plot had a footprint of 36 m^2 (6 m × 6 m) and was enclosed by a 1.8-m 70 % shade cloth (SOLARSHADE™) to reduce air mixing between the plots and the surrounding (Fig. 1). The wind speed inside the shade cloth was approximately half of that outside the shade cloth (Fig. S1). The main purpose of installing the shade cloth was to reduce the mixing, not to shade the plots. Since the shade cloth was only 1.8 m, it did not shade the centre of the plot where the climate station was located. The surface of the plot was turfgrass and the dominant species was Kikuyu (*Pennisetum clandestinum*). The turfgrass was mowed every two weeks to approximately 0.05 m tall. The top soil (5–10 cm) of the site was sandy loam and the subsoil (50–55 cm) was sandy clay. The pore volume of the top soil and subsoil was 61 % and 40 %, respectively. The bulk density of the top soil and subsoil was 1.02 g/cm^3 and 1.58 g/cm^3, respectively. The soil was well-drained with an infiltration rate of approximately 650 mm/h. A climate station was installed at the centre of each plot to continuously measure air temperature, vapour pressure, black globe temperature, wind speed and soil moisture. Incoming and outgoing shortwave and longwave radiation and turf surface temperature were measured in one of the three replicates. A reference climate station was installed within 50 m of the plots to provide background air temperature, relative humidity, wind speed and rainfall. Each air temperature sensor was enclosed in an ATMOS14 plastic weather shield (METER Group). The specifications of the instruments and their installation height/depth are provided in Table 1. All climate and soil variables were measured every 10 s and the 1-minute average was logged. The results will be rounded to 1 decimal place because the accuracy of the sensors is in the same order of magnitude.

The three irrigated treatments were irrigated at different times of the day but their daily total irrigation amount was the same, i.e., 2 mm. The daily total irrigation amount was increased to 4 mm in the last 26 days of the study period. When the daily total irrigation amount was 2 mm, the four treatments of the experiment and their irrigated times were: unirrigated (U0), irrigated from 01:00–01:11 (N1), irrigated from

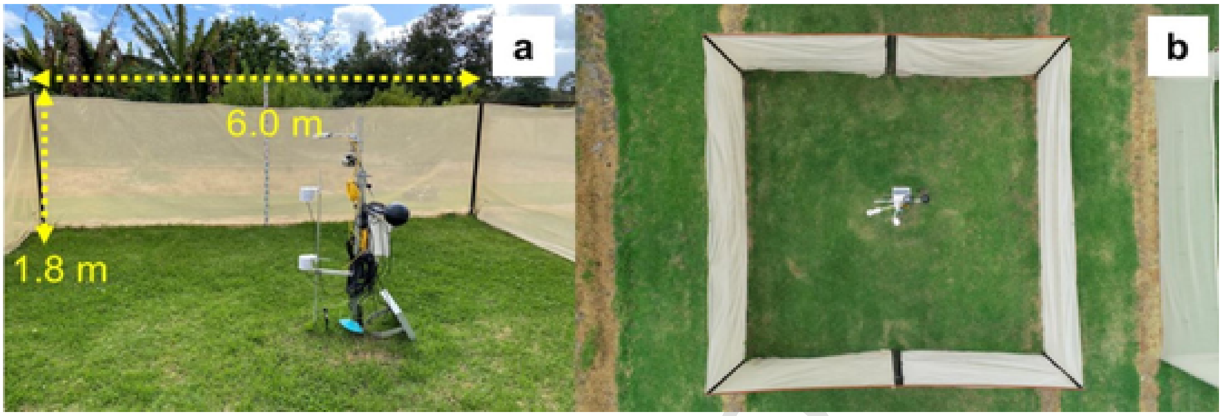

Fig. 1. (a) Ground view and (b) bird-eye view of a plot. The experiment consisted of twelve identical plots (four treatments × three replicates). The four treatments were: unirrigated (U0), irrigated at 01:00 (N1), irrigated at 13:00 (D1), irrigated at 12:00, 13:48, 14:00 and 15:00 (D4). The daily total irrigation amount of the three irrigated plots was the same except that they were irrigated at different times of the day. Each plot was 6 m × 6 m and was enclosed by 1.8-m tall 70 % shade cloth (SOLARSHADE™). A climate station was installed at the centre of each plot, measuring soil temperature (–0.05 m), soil moisture content (–0.05 m), air temperature (1.1 m), vapour pressure (1.1 m), turf surface temperature (1.5 m), and incoming and outgoing shortwave and longwave radiation (1.5 m). A reference climate station was installed at the centre of the experimental site, measuring air temperature (1.1 m), vapour pressure (1.1 m), rainfall (2.0 m) and wind speed (2.0 m).

Table 1
Specifications of the microclimate and soil instruments used in this study and their installation height/depth.

Location	Model and brand	Variable	Accuracy	Height/depth (m)
Plot	03101-L, Campbell Scientific	Wind speed	±0.5 m/s	1.1
	44031, Omega	Black globe temperature	±0.1 °C @ 25 °C	1.1
	ATMOS14, METER	Air temperature	±0.2 °C	1.1
		Vapour pressure of water	±0.05 kPa @ 25 °C	1.1
	CNR4, Kipp & Zonen	Incoming longwave radiation (4.5–42 μm)	<10 % (daily total)	1.5
		Incoming shortwave radiation (300–2800 nm)	<5% (daily total)	
		Outgoing longwave radiation (4.5–42 μm)	<10 % (daily total)	
		Outgoing shortwave radiation (300–2800 nm)	<5% (daily total)	
	CS650, Campbell Scientific	Soil moisture	±3%	–0.05
	SI-111, Apogee	Turf surface temperature	±0.2 °C (–10 °C to + 65 °C)	1.5
Reference	S-RGB-M002, Onset HOBO	Rainfall	±1%	2
	S-THB-M002, Onset HOBO	Air temperature	±0.2 °C at 25 °C	1.1
		Relative humidity	±2.5 % (10–90 %)	1.1
	S-WCA-M003, Onset HOBO	Wind speed	±0.5 m/s (< 17 m/s)	2

13:00–13:11 (D1), and irrigated from 12:00–12:03, 13:24–13:27, 14:00–14:03 and 15:00–15:03 (D4). When the daily total irrigation amount was 4 mm, the four treatments of the experiment and their irrigated times were: unirrigated (U0), irrigated from 01:00–01:23 (N1), irrigated from 13:00–13:23 (D1), and irrigated from 12:00–12:07, 13:48–13:55, 14:00–14:07 and 15:00–15:07 (D4). For simplicity, we will report the irrigation times of the 4 mm hereafter unless specified otherwise. All the times reported in this paper are local time (UTC + 11 h). The mean reference crop evapotranspiration rate between January and March in Melbourne is approximately 4 mm d^{-1} (Bureau of Meteorology, 2023b). Four Hunter MP1000–90 Rotator nozzles and one Hunter MP1000–360 Rotator nozzle were installed at the four corners and the centre of each plot, respectively. The five nozzles in a plot were operated at 280 kPa, delivering 4 mm of water in approximately 24 min. The Hunter MP Rotator nozzles irrigate by creating multiple water streams (Hunter, 2023) while traditional impact sprinklers irrigate by creating fine droplets of water (Jiang et al., 2021). The Hunter MP Rotator nozzles were chosen for this experiment because it would not create fine droplets of water that rest on and affect the temperature and humidity sensors. The nozzles were also carefully adjusted such that the water streams would not hit the climate station.

2.3. *Weather conditions of the study period*

The study was conducted from 2022 to 01-18 to 2022–03-06. The irrigated plots were irrigated daily in this period. The data collected in this period was included in the data analysis, regardless of the weather conditions. The total rainfall in this period was 120.4 mm and the mean air temperature was 21.6 °C (Fig. 2). There were seven days when daily maximum air temperature ≥ 35.0 °C. The differences between daily minimum and maximum air temperatures were generally ≥ 10.0 °C. The daily mean vapour pressure was 0.94 kPa with a range between 0.19 and 1.92 kPa. The daily mean wind speed was 0.33 m s^{-1} with range between 0.00 and 0.33 m s^{-1}. The daily mean incoming shortwave radiation was 254 W m^{-2} with a range between 89 and 377 W m^{-2}.

2.4. *Data analysis*

Six dependent variables were analysis in this study: soil moisture content, air temperature, vapour pressure, turf surface temperature, mean radiant temperature and UTCI. Soil moisture content, air temperature, vapour pressure and turf surface temperature were directly measured. Mean radiant temperature was calculated from air temperature, black globe temperature and wind speed measurements, according to ISO 7726 (1998). UTCI was calculated using the 'rBiometeo' package in

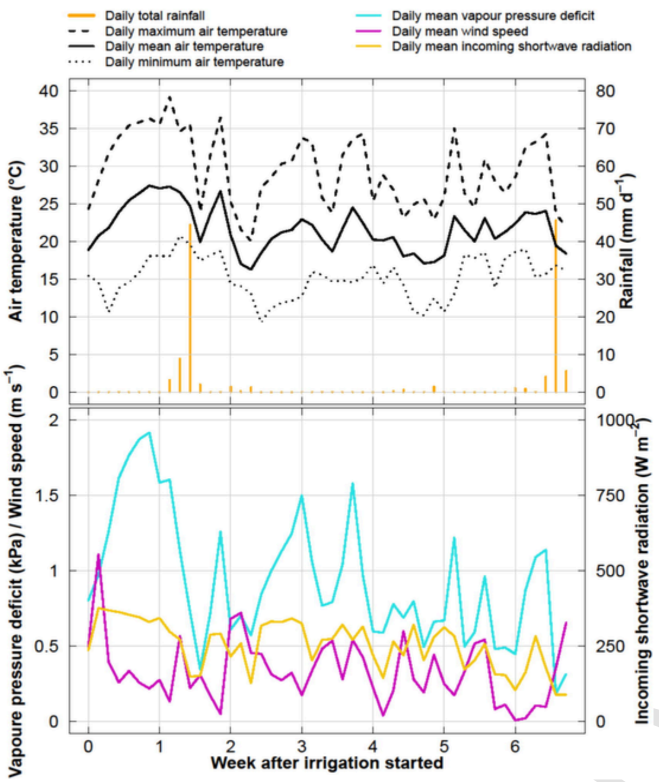

Fig. 2. Daily total rainfall, daily maximum, mean and minimum air temperatures, daily mean vapour pressure deficit, daily mean wind speed and daily mean incoming shortwave radiation of the study period from 2022 to 01-18 (Week 0) to 2022–03-06.

R Studio 4.1.1 (R Core Team, 2023). UTCI is a thermal index that integrates the impacts of air temperature, vapour pressure, mean radiant temperature and wind speed on human thermal stress (Bröde et al., 2012). UTCI is measured in ˚C and can be classified into one of the ten UTCI thermal stress categories from 'extreme cold stress' and 'extreme heat stress'. Albedo was used as a proxy of the grass coverage in the plots because a higher grass coverage should lead to a higher albedo. Albedo was computed as the ratio of outgoing shortwave radiation to incoming shortwave radiation (Table 1).

The average diurnal cycles of the three replicated plots were similar for all four irrigation treatments and all analysed variables except there were ~ 5 ˚C differences in mean radiant temperature between the replicates in U0, D1 and D4 from 10:00 to 16:59 (Fig. S2). Black globe temperature is commonly used to estimate mean radiant temperature in outdoor thermal comfort research (Guo et al., 2020). Using black globe temperature to estimate mean radiant temperature in the outdoor environment is known to have a larger uncertainty than the radiation integral method because wind speed is involved in the estimation to account for free convection and wind speed is inherently variable in time and space (Teitelbaum et al., 2020). To reduce the impacts of the uncertainties of measurements on the results, the mean of the three replicated plots was used in the analysis for all variables.

To investigate the impacts of irrigation scheduling on the afternoon (12:00–15:59) cooling effects, the 1-minute average cycle between 10:00 and 15:59 of the study period was plotted for all three irrigated treatments and the one unirrigated treatment. The plotted variables included soil moisture content, air temperature, vapour pressure, turf surface temperature, mean radiant temperature and UTCI. In a separate figure, the cooling effect of each irrigated treatment in the same cycle was plotted. The cooling effect was defined as the differences between the irrigated treatment and the unirrigated treatment (Δ = irrigated – unirrigated). The afternoon (12:00–15:59) mean cooling effects were computed for each irrigated treatment for each day of the study period (number of days, N = 48). The 48 values from each treatment were subsequently used in two statistical tests: (i) Tukey's Honest Significance Difference test was used to assess the significance of differences between the three irrigated treatments in their afternoon (12:00–15:59) mean cooling effects, and (ii). One-sample *t*-test was used to assess whether the afternoon (12:00–15:59) mean cooling effects of each of the three irrigated treatments were significantly different from zero.

To investigate the relationship between the cooling effects of irrigation and weather conditions, the daily afternoon (12:00–15:59) mean cooling effects (air temperature and turf surface temperature) were plotted against the daily afternoon (12:00–15:59) mean weather conditions (air temperature, vapour pressure deficit, wind speed, and incoming shortwave radiation). Only the cooling effects on air temperature and turf surface temperature were analysed because irrigation did not consistently reduce mean radiant temperature and UTCI. After initial examination of the graphs, both the cooling effects on air temperature and turf surface temperature were linearly correlated with the background air temperature, vapour pressure deficit and incoming shortwave radiation while they were correlated with background wind speed in an inverted bell curve shape. Linear and Gaussian models were established if the estimates of the models were statistically significantly. The linear model takes the following form:

$$y = mx + c \tag{1}$$

where y is the afternoon (12:00–15:59) mean cooling effect, x the afternoon (12:00–15:59) mean weather conditions (air temperature, vapour pressure deficit, wind speed, or incoming shortwave radiation), m the slope of the model, and c the intercept of the model.

The Gaussian model with parametric extension takes the following form:

$$y = a\exp\left(\frac{-(x-b)^2}{2c^2}\right) \tag{2}$$

where y is the afternoon (12:00–15:59) mean cooling effect, x the background weather conditions, a the height of the curve's peak, b the position of the centre of the peak a c the width of the bell curve. The coefficient of determination (R^2) was computed for the linear models but not the Gaussian models because its meaning in linear regression does not hold when used in non-linear regression (Kvålseth, 1985). In linear regression, R^2 is the proportion of variance explained by the regression model (Nagelkerke, 1991).

The impacts of rainfall on the afternoon mean cooling effects were assessed by examining the time series of daily total rainfall and the afternoon mean cooling effects.

3. Results

3.1. Changes in soil moisture content and albedo in the study period

The soil moisture contents of N1, D1 and D4 were always higher than U0 throughout the study period (Fig. 3). When the irrigation amount was 2 mm d^{-1}, the soil moisture contents of N1, D1 and D4 were 5–10 % higher than U0. When the irrigation amount increased to 4 mm d^{-1}, the difference increased to as much as 25 %. The 2 mm d^{-1} irrigation was insufficient to increase the soil moisture contents in N1, D1 and D4, but the 4 mm d^{-1} irrigation was sufficient. After the rainfall in Week 1–2, the soil moisture content of U0 increased from 8 % to 25 % and it took approximately four weeks to return to 8 %. N1 had a higher initial soil moisture content (21 %) than D1 (14 %) and D4 (16 %).

The albedo of U0 was always lower than that of N1, D1 and D4 (Fig. 3). The dry period of U0 in Week 0–1 (soil moisture content ≈ 10 %)

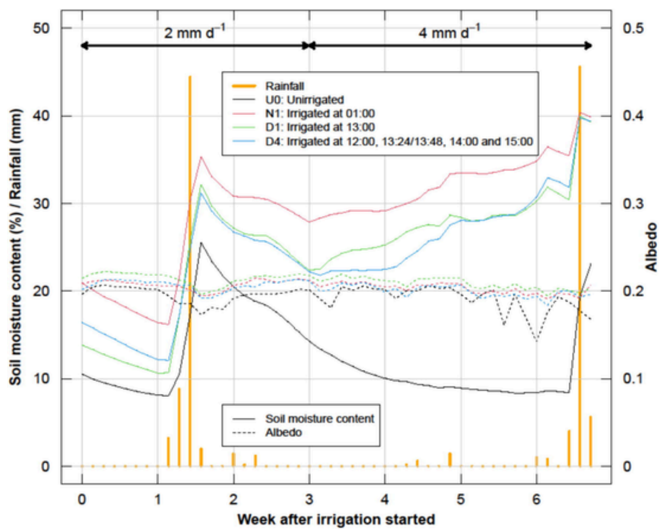

Fig. 3. Changes in daily mean soil moisture content and albedo of plot U0 (unirrigated), plot N1 (irrigated 2 or 4 mm d^{-1} at 01:00), plot D1 (irrigated 2 or 4 mm^{-1} at 13:00) and plot D4 (irrigated 0.5 or 1 mm at 12:00, 13:24/13:48, 14:00 and 15:00 = 2 or 4 mm d^{-1}), and rainfall at the reference climate station. Each plot had three replicates and the mean of the three replicates was used.

was followed by a reduction in its albedo in Week 1–2. Similarly, the dry period in Week 4–5 (soil moisture content ≈ 10 %) was followed by a reduction in its albedo in Week 5–6. The albedos of N1, D1 and D4 were relatively stable as their soil moisture contents have never dropped below 10 %.

3.2. Impacts of irrigation scheduling on afternoon mean soil moisture content and cooling effects

From 10:00 to 15:59, the soil moisture content of N1 was stable and that ofD1 and D4 increased during irrigation. The air temperature of U0 was always higher than those of N1, D1 and D4 (Fig. 4d–f). The air temperatures of N1, D1 and D4 were similar except that it reduced in D1 and D4 during and immediately after irrigation. The vapour pressures of U0, N1 and D1 were similar except for a slight increase during irrigation in D1 (Fig. 4g–i). The turf surface temperature of U0 was always higher than N1, D1 and D4 (Fig. 4j–l). The turf surface temperature of N1, D1 and D4 were similar except for a slight reduction during and immediately after irrigation in D1 and D4. The mean radiant temperature of N1 and D4 were higher than U0 and D1 (Fig. 4m–o). The mean radiant temperatures of D1 and D4 were unaffected by irrigation and that of N1 only responded to weather changes in this period (10:00–15:59) because it was irrigated at night. The UTCI of all four plots were similar (Fig. 4p–r). The UTCI of D1 and D4 were unaffected by irrigation and that of N1 only responded to weather changes in this period (10:00–15:59) because it was irrigated at night.

The afternoon (12:00–15:59) mean impacts of all three irrigated treatments (N1, D1 and D4) on all analysed variables (soil moisture content, air temperature, vapour pressure, turf surface temperature, mean radiant temperature and UTCI) were statistically significant ($p < 0.05$) (Fig. 5), except for the UTCI of N1 (Fig. 5p). The afternoon (12:00–15:59) mean impacts of N1 on soil moisture content (16.9 %) was significantly larger ($p < 0.05$) than D1 (12.5 %) and D4 (11.8 %) (Fig. 5a–c) because it had a larger initial soil moisture content (Fig. 3).

The afternoon (12:00–15:59) mean cooling effect of D4 on air temperature (–0.9 °C) was significantly stronger ($p < 0.05$) than N1 (–0.7 °C) and D1 (–0.5 °C) (Fig. 5d–f). The accuracy of the air temperature sensor was ± 0.2 °C. In the afternoon (12:00–15:59), the cooling effect of N1 was stable. The cooling effect of D1 strengthened as the irrigation started and reached its strongest (–1.0 °C) at the end of the irrigation event, then it weakened and returned to the pre-irrigation level (–0.4 °C) by 15:00. In comparison, the cooling effect of D4 maintained at approximately –0.8 °C after the first irrigation event and the second, third and fourth irrigation events further strengthened the cooling effect to < –1.0 °C.

The afternoon (12:00–15:59) mean impacts of N1, D1 and D4 on vapour pressure were small (≤0.05 kPa) (Fig. 5g–i) comparing to the accuracy of the sensor (±0.05 kPa). The afternoon (12:00–15:59) mean cooling effect of D4 on turf surface temperature (–4.91 °C) was significantly stronger ($p < 0.05$) than N1 (–3.4 °C) and D1 (–4.0 °C) (Fig. 5j–l). The cooling effects were one order of magnitude larger than the accuracy of the sensor (±0.2 °C). In the afternoon (12:00–15:59), the cooling effect of N1 was stable. The cooling effect of D1 on turf surface temperature was strongest during the irrigation (–6°C) and it weakened to approximately –4°C in less than one hour. In comparison, the cooling effect of the first irrigation of D4 managed to induce a similar cooling effect (–5.8 °C) during irrigation. Although the cooling effect also weakened to approximately –4°C in less than one hour, subsequent irrigation events strengthened the cooling effects to < –6°C.

The afternoon (12:00–15:59) mean impacts of D4 on mean radian temperature (4.1 °C) were significantly larger ($p < 0.05$) than N1 (1.3 °C) and D1 (–0.6 °C) (Fig. 5m–o). This was not expected and will be discussed in section 4.1. The afternoon (12:00–15:59) mean impacts of N1, D1 and D4 on UTCI were significantly different ($p < 0.05$) from each other but the impacts were small (≤0.5 °C) (Fig. 5p–r).

3.3. Relationships between afternoon mean cooling effects and weather conditions

The afternoon (12:00–15:59) mean air temperature cooling effects of irrigation strengthened with increasing background air temperature, vapour pressure deficit and incoming shortwave radiation for all three irrigated treatments (Fig. 6a, Fig. 6b and Fig. 6d). The slopes of the three irrigated treatments were not significantly different from each other, meaning that the changes in background air temperature, vapour pressure deficit and incoming shortwave radiation had the same impacts on the cooling effects of all three irrigated treatments. For every 1 °C increase in background air temperature, the cooling effects from irrigation strengthened by 0.03, 0.03 and 0.04 °C for N1, D1 and D4, respectively. For every 1 kPa increase in background vapour pressure deficit, the cooling effect strengthened by 0.17, 0.15 and 0.23 °C for N1, D1 and D4, respectively. For every 10 W m^{-2} increase in background incoming shortwave radiation, the cooling effect strengthened by 0.01 °C for N1, D1 and D4. The regression lines of D4 were below those of N1 and D1, suggesting that the cooling effects of D4 were stronger on average at any point within the measured ranges of the four background weather variables. The afternoon (12:00–15:59) mean air temperature cooling effects from irrigation changed with wind speed in an inverted bell curve shape for all irrigation treatments (Fig. 6d). The cooling effects strengthened when wind speed increased from 0 and peaked at 0.52 m s^{-1} for N1, 0.45 m s^{-1} for D1 and 0.52 m s^{-1} for D4. The cooling effects weakened as wind speed increased beyond these peaks. The R^2 were low (≤0.35) except for incoming shortwave radiation.

The afternoon (12:00–15:59) mean turf surface temperature cooling effects of irrigation strengthened with increasing background air temperature, vapour pressure deficit and incoming solar radiation (Fig. 7a, Fig. 7b and Fig. 7d). The slopes of the three irrigated treatments were not significantly different from each other, meaning that the changes in background air temperature, vapour pressure deficit and incoming shortwave radiation had the same impacts on the cooling effects of all three irrigated treatments. For every 1 °C increase in background air temperature, the cooling effects from irrigation strengthened by 0.38,

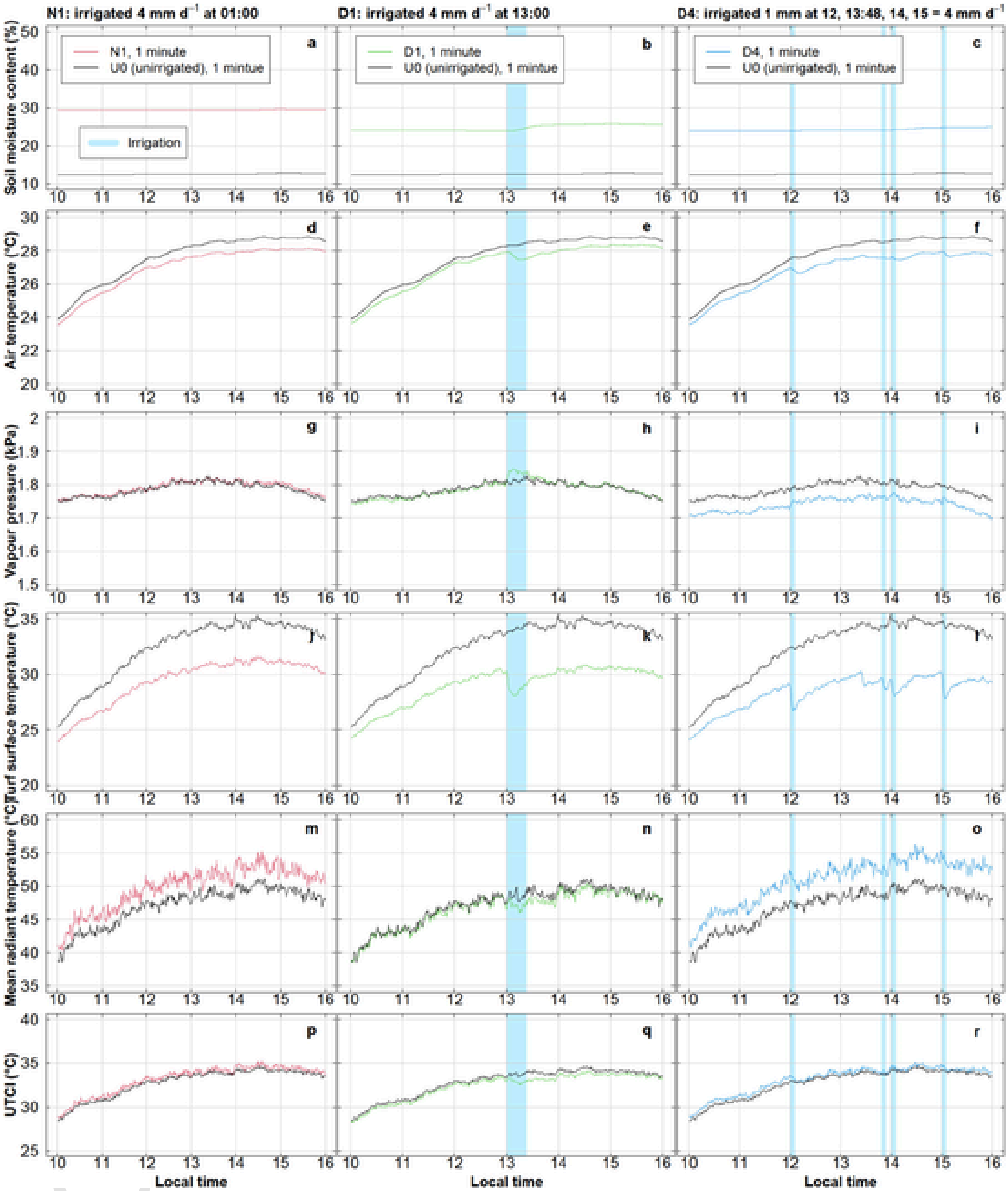

Fig. 4. Average cycles (1-minute) of soil moisture content, air temperature, vapour pressure, turf surface temperature, mean radiant temperature and universal thermal climate index (UTCI) of plot U0 (unirrigated), plot N1 (irrigated 4 mm d^{-1} at 01:00), plot D1 (irrigated 4 mm d^{-1} at 13:00), plot D4 (irrigated 1 mm at 12:00, 13:48, 14:00 and 15:00 = 4 mm d^{-1}) from 10:00 to 15:59 in the whole study period (2 mm d^{-1}: 2022–01-18 to 2022–02-08 and 4 mm d^{-1}: 2022–02-09 to 2022–03-06). For simplicity, the irrigation times of the 4 mm d^{-1} period is used.

0.35, 0.30 °C for N1, D1 and D4, respectively. For every 1 kPa increase in background vapour pressure deficit, the cooling effects from irrigation strengthened by 2.17, 2.09 and 1.84 °C for N1, D1 and D4, respectively. For every 10 W m^{-2} increase in background incoming shortwave radiation, the cooling effects from irrigation strengthened by 0.1 °C for N1, D1 and D4. The regression lines of D4 were below those of N1 and D1, suggesting that the cooling effects of D4 were stronger on average at any point within the measured ranges of the four background weather variables. The afternoon (12:00–15:59) mean turf surface temperature cooling effects of irrigation only strengthened with increasing

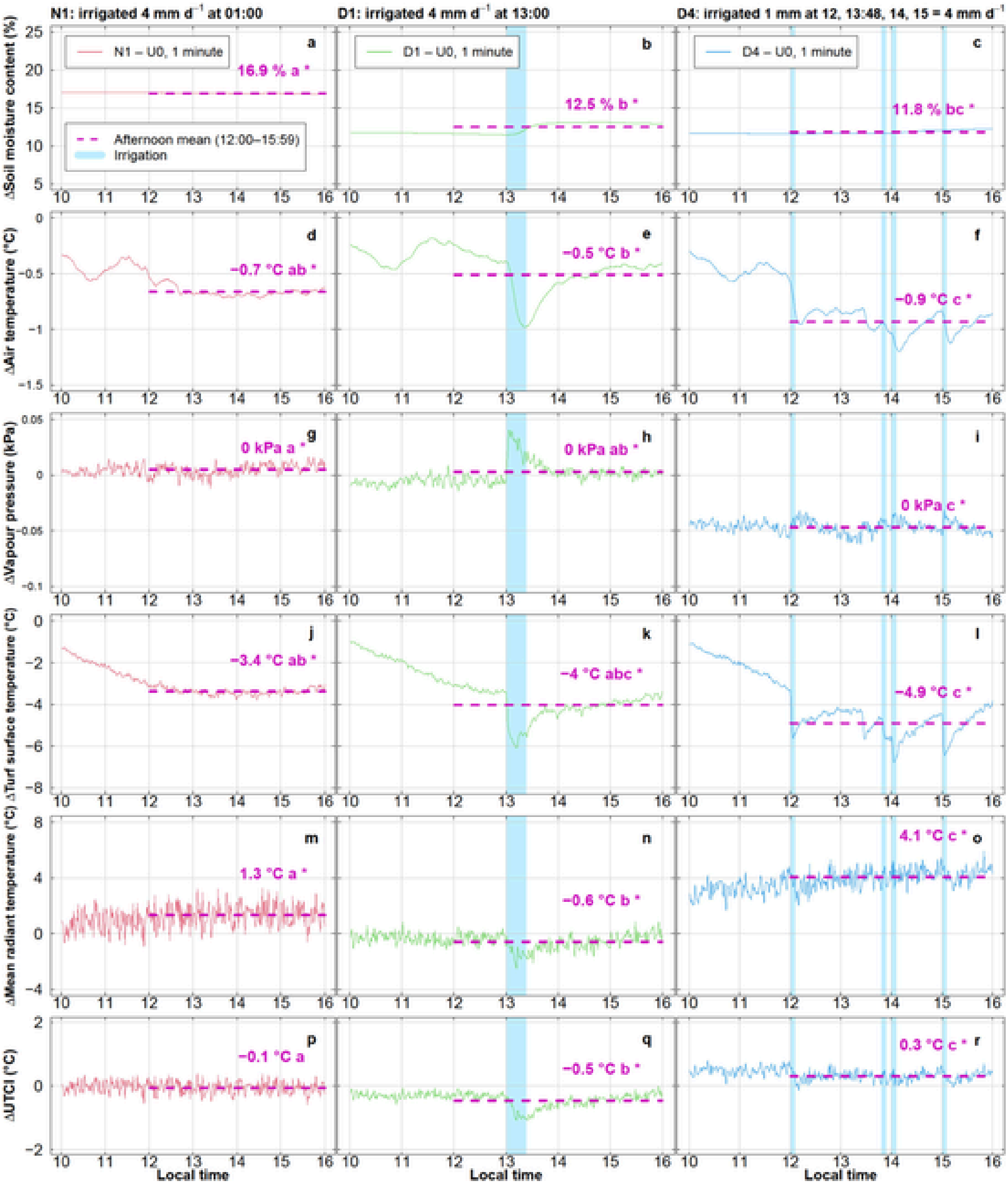

Fig. 5. Average impacts (1-minute) of irrigation on soil moisture content, air temperature, vapour pressure, turf surface temperature, mean radiant temperature and universal thermal climate index (UTCI) for plot N1 (irrigated 4 mm d^{-1} at 01:00), plot D1 (irrigated 4 mm d^{-1} at 13:00) and plot D4 (irrigated 1 mm d^{-1} at 12:00, 13:48, 14:00 and 15:00, respectively) from 10:00 to 15:59 in the whole study period (2 mm d^{-1}: 2022–01-18 to 2022–02-08 and 4 mm d^{-1}: 2022–02-09 to 2022–03-06). For simplicity, the irrigation times of the 4 mm d^{-1} period is used. The impacts were measured as the differences between the irrigated and unirrigated plots (Δ = irrigated – unirrigated). The horizontal dashed lines represent the afternoon (12:00–15:59) mean impacts. The letters, 'a', 'b' and 'c', indicate the significance of

Fig. 5.—*continued*
differences between the three irrigated plots in their afternoon (12:00–15:59) mean cooling effects. The pairs that do not have the same letter are significantly different from each other ($p < 0.05$, Tukey's Honesty Significant Difference test). The presence of the symbol, '*', indicates that the afternoon (12:00–15:59) mean cooling effect is significant ($p < 0.05$, *t* test).

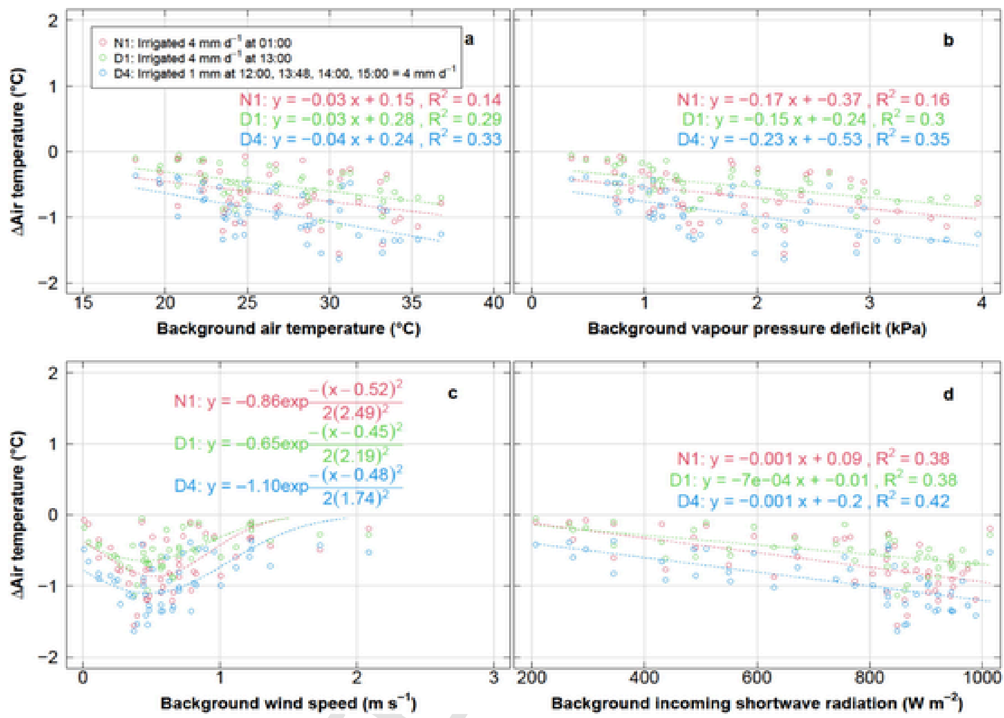

Fig. 6. Scatter plots of the afternoon (12:00–15:59) mean cooling effect of irrigation (Δ = irrigated – unirrigated) in air temperature against background (a) air temperature, (b) vapour pressure deficit, (c) wind speed and (d) incoming shortwave radiation. Linear regression models were used for background air temperature, vapour pressure and incoming shortwave radiation, and Gaussian regression models for wind speed. Only the models with a significant slope/parameter estimate were plotted.

background wind speed for N1 (Fig. 7c). The cooling effects from irrigation strengthened when wind speed increased from 0 and peaked at 0.49 m s^{-1}.

With regards to the impacts of rainfall on the cooling effects on air temperature, the four rainy days (3.2, 8.8, 44.4, and 2.0 mm) in Week 1–2 reduced the cooling effects by approximately 0.5 °C for all three irrigated treatments (Fig. 8a). The cooling effects of all three irrigated treatments strengthened slowly from Week 2 to Week 6 as the differences in the soil moisture content between the irrigated and unirrigated plots increased (Fig. 3). Similarly, the three rainy days (4.0, 45.6, and 5.6 mm) at the end of the study period reduced the cooling effects by approximately 0.8 °C for all three irrigated treatments. D4 had the strongest cooling effects even on the rainy days. The smaller rainfall events (< 2 mm) in Weeks 2 and 4 did not have a notable impact on the cooling effects.

With regards to the impacts of rainfall on the cooling effects on turf surface temperature, the four rainy days (3.2, 8.8, 44.4, and 2.0 mm) in Week 1–2 reduced the cooling effects by > 6 °C (Fig. 8b). The cooling effects were strong (approximately –8°C) before the rainfall when air temperature, incoming shortwave radiation, and vapour pressure deficit were high (Fig. 2). Similar to air temperature, the cooling effects on turf surface temperature of all three irrigated treatments strengthened slowly from Week 2 to Week 6 as the differences in the soil moisture content between the irrigated and unirrigated plots increased (Fig. 3), but the cooling effects did not return to –8°C. The three rainy days (4.0, 45.6, and 5.6 mm) at the end of the study period reduced the cooling effects by approximately 3.5 °C for all three irrigated treatments. The reduction was not as large as that in Week 1–2, likely due to the lower air temperature, incoming shortwave radiation, and vapour pressure deficit.

4. Discussion

4.1. Impacts of irrigation time on afternoon mean soil moisture content and cooling effects

All three irrigated treatments induced significant afternoon (12:00–15:59) mean cooling effects on air temperature and turf surface temperature, whereas the cooling effects on mean radiant temperature and UTCI were inconsistent. This means that our results partially support Hypothesis 1 as measured cooling benefits from irrigation were evident for air temperature and turf surface temperature only. Gao et al. (2020) modelled that the strongest cooling effects of night-time irrigation on air temperature (–0.6 °C) and surface temperature (–2.7 °C) would occur at 13:00 local time. Their model predictions are comparable to our measurements. The cooling effects on air temperature in our study were measured at 1.1 m, which corresponds to the centre of gravity of a standing adult (Mayer & Höppe, 1987). The cooling effects would likely be weaker if the air temperature was measured above that height. The daytime cooling effect of multiple daytime irrigation on air temperature was comparable to that of tree shade in Melbourne (Sanusi et al., 2017), while those of night-time and single daytime irrigation were small in comparison to the accuracy of the sensor (± 0.2 °C). The cooling effects of the night-time irrigation on air temperature and turf

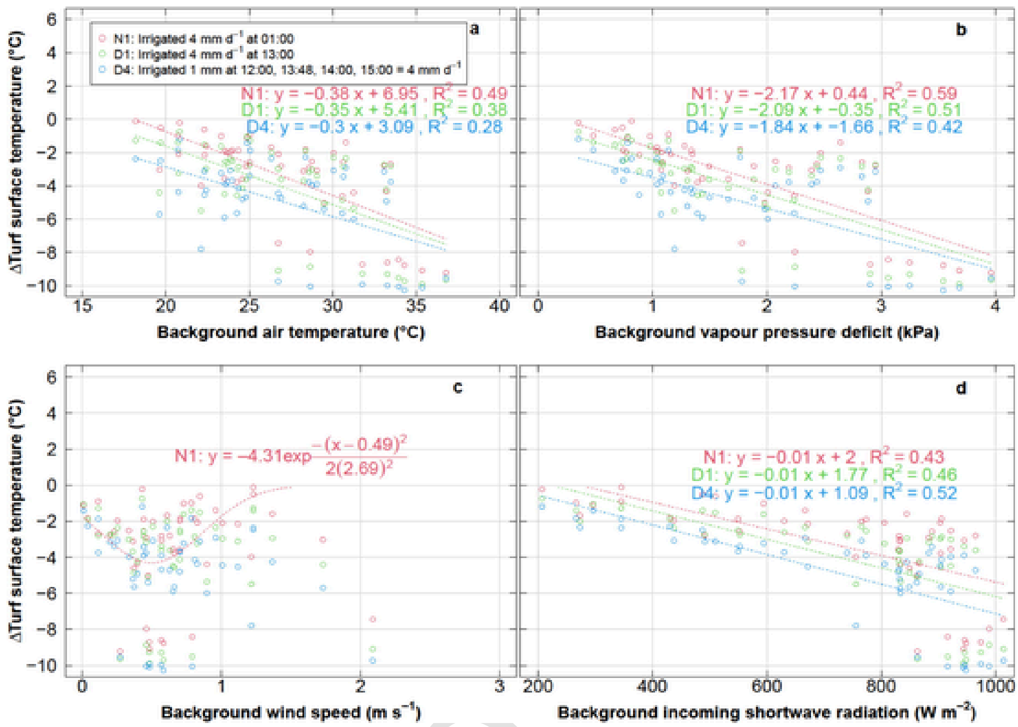

Fig. 7. Scatter plots of the afternoon (12:00–15:59) mean cooling effect of irrigation (Δ = irrigated – unirrigated) in turf surface temperature against background (a) air temperature, (b) vapour pressure deficit, (c) wind speed and (d) incoming shortwave radiation. Linear regression models were used for background air temperature, vapour pressure and incoming shortwave radiation, and Gaussian regression models for wind speed. Only the models with a significant slope/parameter estimate were plotted.

surface temperature in our study also reached their strongest at approximately 13:00 and maintained at the same levels for the rest of the afternoon. Such cooling effects were driven by the increase in evapotranspiration due to increased soil moisture content (Chen et al., 2018). The increased evapotranspiration increases the latent heat flux and reduces sensible heat flux, leading to the reductions in air temperature and turf surface temperature. Although the afternoon (12:00–15:59) mean vapour pressure of the multiple daytime irrigation treatment was significantly lower than that of the unirrigated treatment, the difference was smaller than the accuracy of the sensor (±0.05 kPa), meaning that the difference was so small that its cause cannot be ascertained. The field capacity of the soils can have a strong impact on the amount of soil moisture available for evapotranspiration (Mahmood & Hubbard, 2003), which in turns influences the cooling effect. The field capacity of soil depends on soil texture and soil organic matter (Bordoloi et al., 2019). The topsoil of the plots in this study was sandy loam, which had a good field capacity. If the soil were sandier, it would drain more quickly but also have a lower field capacity, providing less soil moisture that is readily available for evapotranspiration.

The mean radiant temperatures of the night-time irrigation and multiple daytime irrigation treatments were higher than that of the unirrigated treatment. This was not expected because the turf surface temperatures of the irrigated treatments were lower than that of the unirrigated treatment, meaning that the thermal radiation from the irrigated surface should be weaker and lead to a lower mean radiant temperature. The contradictory result could be explained by the deficiency of using the black globe temperature to estimate mean radiant temperature. In this study, we used the black globe temperature to estimate mean radiant temperatures (ISO 7726, 1998). This method is commonly used as an alternative to the more expensive six-directional radiation measurements. However, the main deficiency of this method is that the black globe temperature becomes highly variable when its temperature is high (Kántor et al., 2015). Our data confirmed that the black globe temperatures of the four treatments were similar on mild days (e.g. 2022-01-29) but the black globe temperatures of N1 and D4 were much higher than that of U0 on the hot days (e.g. 2022-01-26 and 2022-01-31) (Fig. S3). The black globe temperature of D1 was similar to that of U0 overall.

The afternoon (12:00–15:59) air temperature reduction from irrigating 4 mm through four separate 1 mm events (D4) was significantly stronger than applying all 4 mm in one irrigation event (N1 and D1). However, the air temperature cooling benefits of irrigating 4 mm at night (N1) were not significantly different from those when irrigating by day (D4). These results again provide partial support for Hypothesis 2 that greatest cooling benefit would be derived from irrigation scheduling that applies small amounts of water (1 mm) on multiple occasions (four) during the day, and least cooling benefit would be derived from irrigating the same amount through one irrigation event at night. This finding supports the suggestion of Broadbent et al. (2018) that optimising irrigation scheduling can strengthen the cooling effects of irrigation in certain periods of time using the same irrigation amount. Although N1 had a higher initial soil moisture content than D1, their afternoon (12:00–15:59) mean cooling effects on air temperature and turf surface temperature were not significantly different. Even though the soil moisture contents of N1 were higher than D4 in the whole study period, the afternoon (12:00–15:59) mean cooling effects of N1 on air temperature and turf surface temperature were significantly weaker than D4. This suggests that the total afternoon (12:00–15:59) evapotranspiration of D4 was higher than N1 because of the multiple irrigation events in the afternoon (see explanation below for Fig. 9).The differences between the irrigation treatments in their afternoon cooling effects can be explained by their differences in evapotranspiration processes in the afternoon (Fig. 9). For the unirrigated treatment, soil evaporation and transpiration were the only two evapotranspiration processes in the afternoon (Fig. 9a). Since the unirrigated treatment has the lowest soil moisture content among the four treatments, it had the smallest soil evapo-

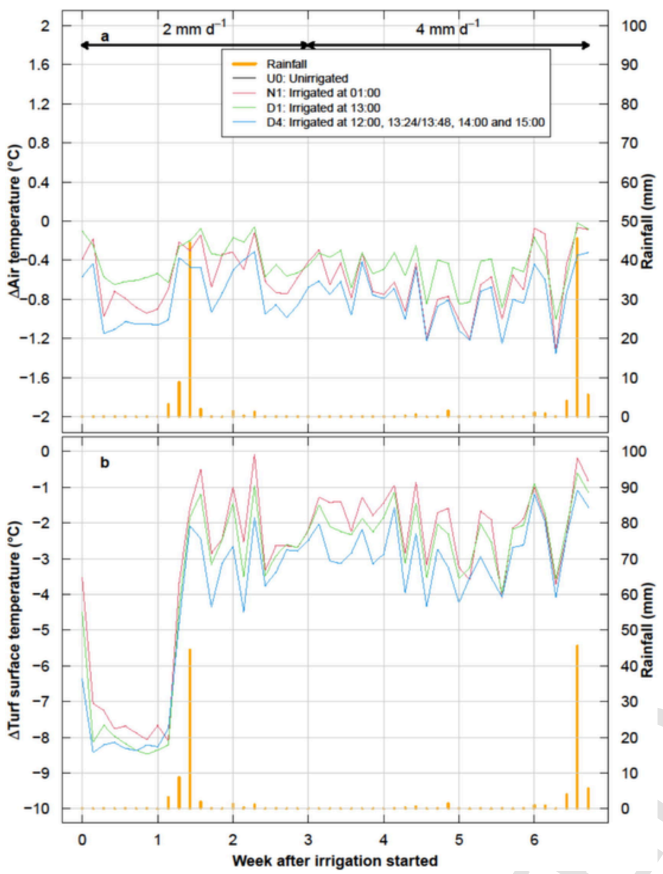

Fig. 8. Daily changes in the afternoon (12:00–15:59) mean cooling effects on (a) air temperature and (b) turf surface temperature of plot U0 (unirrigated), plot N1 (irrigated 2 or 4 mm d^{-1} at 01:00), plot D1 (irrigated 2 or 4 mm^{-1} at 13:00) and plot D4 (irrigated 0.5 or 1 mm at 12:00, 13:24/13:48, 14:00 and 15:00 = 2 or 4 mm d^{-1}) and total rainfall. Each plot had three replicates and the mean of the three replicates was used.

ration, transpiration and evapotranspiration. Consequently, the unirrigated treatment had the highest afternoon air temperature among the four treatments. For the single night-time irrigation treatment, soil evaporation and transpiration were also the only two evapotranspiration processes in the afternoon (Fig. 9b). Since it had a higher soil moisture content than the unirrigated treatment, it had a higher soil evaporation, transpiration and evapotranspiration. Consequently, the single night-time irrigation treatment had a significantly lower afternoon air temperature compared to the unirrigated treatment. For the single midday irrigation treatment, its soil moisture content was similar to the single night-time irrigation treatment because daily total irrigation amount was the same. In comparison to the single night-time irrigation, the single midday irrigation introduced two extra evaporation processes in the afternoon, namely droplet evaporation and canopy evaporation (Fig. 9c). Droplet evaporation is the evaporation that occurs when water droplets pass through the air before impact. Droplet evaporation is usually small (~1% of irrigation amount) when the irrigation amount is high (≥25 mm) (Thompson et al., 1997). Canopy evaporation is the evaporation of water stored on the canopy surface. Canopy evaporation can account for > 80 % of afternoon (12:00–15:59) evapotranspiration for a corn field that is irrigated by sprinkler during the day (Thompson et al., 1993). However, the afternoon cooling effects of the single midday irrigation and single night-time irrigation treatments on air temperature were not significantly different. It was likely because the afternoon soil evaporation and transpiration in the single midday irrigation were suppressed by the irrigation itself because of the humidification of the environment (Tolk et al., 1995). Consequently, the increase in afternoon canopy evaporation from the midday irrigation might be offset by the reduction in soil evaporation and transpiration.

For the multiple afternoon irrigation treatment, the multiple irrigation events were likely to increase the droplet evaporation and canopy evaporation compared to the single midday irrigation, causing a significantly higher afternoon evapotranspiration (Fig. 9d) and significantly lower afternoon air temperature. Droplet evaporation and canopy evaporation increase notably if the irrigation is short and frequent, causing almost all water evaporating, either in the air or on the canopy surface, before reaching the soil (Burt et al., 2005). There are two reasons for that. First, the vapour pressure deficit can increase quickly and return to the pre-irrigation level after one short irrigation event, leading to a relatively dry environment that is conducive to droplet evaporation and canopy evaporation for the next irrigation (Tolk et al., 1995). Second, the short irrigation events increase the total canopy evaporation by

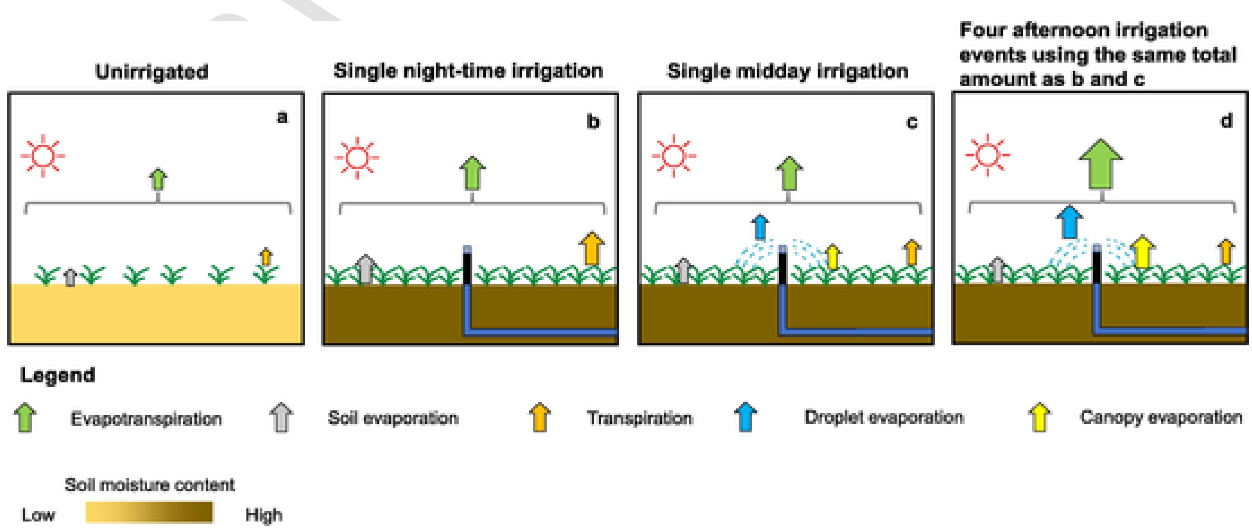

Fig. 9. A conceptual diagram that explains the impact of different irrigation schedules on evapotranspiration processes in the afternoon.

only depositing a small amount of water onto the canopy in each irrigation event, thereby limiting the amount of water dripping from the canopy onto the soil surface. This was reflected in the smaller increase in soil moisture content in the multiple afternoon irrigation treatment (0.2 %, Fig. 4c) than the single midday irrigation treatment (0.8 %. Fig. 4b) from the morning (10:00–11:59) to the afternoon (12:00–15:59). The wet turfgrass canopy in the multiple afternoon irrigation treatment after the first irrigation at 12:00 was likely to dry within 30 min (Burt et al., 2005), allowing the canopy to store and evaporate more water in the next irrigation event. Similar to the single midday irrigation treatment, the repeated wetting of turfgrass canopy in the multiple afternoon irrigation treatment was likely to suppress transpiration and soil evaporation because of the humidification of the environment. However, the air temperature data suggested that the afternoon total evapotranspiration was significantly higher in the multiple afternoon irrigation treatment than the single midday irrigation treatment. Air temperature has been demonstrated to reflect the evapotranspiration of vegetation before, during and after irrigation accurately (Thompson et al., 1993).

Apart from increasing the evapotranspiration, irrigating vegetation can change the microclimate by changing the growth of the vegetation. Unirrigated vegetation is likely to grow slower and cover a smaller area than irrigated vegetation, whereas irrigated vegetation is likely to have a larger biomass which in turn supports more transpiration and cooling (Fig. 9). It was estimated that the irrigation-induced crop growth contributed to 34.5 % of the cooling effect of irrigation (Liu & Wang, 2023). We used the albedos of the plots to estimate their grass coverage because a higher grass density should lead to a higher albedo. The albedo of the unirrigated plot in this experiment was lower than that of the irrigated plots in Week 1–2 and after Week 5–6. These periods were preceded by a dry period in the unirrigated plot in Week 0–1 and Week 4–5, respectively. The dry periods could have limited the growth and coverage of the grass and reduced the albedo. However, the growth and coverage of the grass need to be measured to ascertain their interactions with irrigation. Future studies are encouraged to account for the irrigation-induced changes in vegetation biomass and coverage to better understand the cooling mechanisms of irrigation.

The evapotranspiration processes in Fig. 9 can change notably with irrigation type. The irrigation nozzles (Hunter MP-1000 rotators) used in this study were different from traditional impact sprinklers because the MP-1000 rotators deliver water in multiple rotating streams instead of water droplets. The droplet evaporation in this study would have been higher if an traditional impact sprinklers were used because they would create smaller droplets than are more conducive to evaporation (Thompson et al., 1993). While the impacts of irrigation on air temperature and humidity were often reported in the literature, its impacts on human thermal comfort were seldom investigated. Broadbent et al. (2018) modelled that the cooling effect of continuous (24-hour) sprinkler irrigation would improve human thermal comfort by −2.3 °C at 15:00 pm in the afternoon. However, Broadbent et al. (2018) estimated this using the humidex index which does not account for the effect of mean radiant temperature, the most important microclimate variable that influences human thermal comfort (Thorsson et al., 2007). UTCI is a more comprehensive index of human thermal comfort because it integrates all relevant microclimate variables, namely air temperature, relative humidity, wind speed and mean radiant temperature (Bröde et al., 2012). The most important driver of daytime mean radiant temperature and therefore human thermal comfort is incoming and lateral shortwave radiation (Cheung & Jim, 2018a; Middel & Krayenhoff, 2019). Although a lower turf surface temperature may lead to a lower mean radiant temperature and UTCI due to a reduced emission of longwave radiation from the surface, the reduction in turf surface temperature in this study seemed to be insufficient to influence mean radiant temperature and UTCI in the afternoon. Since irrigation alone cannot reduce incoming and lateral shortwave radiation, additional cooling strategies, such as overhead tree canopy shading and green walls, will help to reduce incoming and lateral shortwave radiation and improve human thermal comfort.

The findings of this study also suggest that irrigation scheduling can change the diurnal patterns of microclimate variables. Air temperature, vapour pressure and turf surface temperature change substantially during and immediately after irrigation, even the irrigation amount is only 1 mm. The irrigation time(s) of day will determine the diurnal patterns of the microclimate of the irrigated vegetation. This has important implications for modelling studies because most urban irrigation modelling studies do not consider irrigation scheduling (Daniel et al., 2018; Gao et al., 2020; Wang et al., 2019). A soil moisture threshold is often used to trigger irrigation when the soil moisture content at any time step drops below the threshold, meaning that the irrigation can be applied anytime in a day without considering the weather conditions. This study shows that it is necessary to consider and optimise the irrigation time to maximise the cooling benefits of irrigation to people.

4.2. Relationships between afternoon mean cooling effects and weather conditions

In this study, the afternoon (12:00–15:59) mean cooling effects of irrigating turfgrass on air temperature and turf surface temperature were significantly and positively correlated with background air temperature, vapour pressure deficit and incoming shortwave radiation, but not wind speed. The results provide partial support for Hypothesis 3 that the cooling effects would significantly correlate with all four weather variables. Our findings were consistent with Vivoni et al. (2020)'s findings, which showed a significant linear correlation between daily total evapotranspiration and daily mean air temperature ($R^2 = 0.79$) and incoming shortwave radiation ($R^2 = 0.82$) in an irrigated turfgrass. With almost unlimited soil moisture supply throughout the year (soil moisture content ≥ 40 %), they measured a much higher evapotranspiration in summer (6–8 mm d^{-1}) than in winter (1–3 mm d^{-1}), suggesting that the evapotranspiration in a well-irrigated turfgrass was limited and controlled by available energy. The cooling effects of irrigating turfgrass were correlated with background air temperature and incoming shortwave radiation because they were the main sources of energy to support evapotranspiration, i.e. the cooling effects (Spronken-Smith et al., 2000). Studies that measured or modelled the cooling effects of irrigating vegetation provided more direct evidence for the correlation between the cooling effects and available energy. Lam et al. (2020) measured that the air temperature cooling effect of irrigating an urban green space in Melbourne, Australia was stronger during heatwaves (−4 to −2°C) than non-heatwave periods (−1.0 to −0.5 °C). Gao et al. (2020) modelled similar results for irrigating all pervious surface in Metropolitan Sydney. In a previous study, we used a *meta*-analysis of published studies to develop a linear regression model between the air temperature cooling effects of irrigating vegetation and background air temperature (Cheung et al., 2021). The model predicted that the daily mean cooling effects on air temperature would strengthen by 0.1 °C for every 1 °C increase in background mean air temperature. The effect estimate (0.1 °C $°C^{-1}$) was three times higher than that in this study (0.03 °C $°C^{-1}$). Although direct comparison of the magnitude between the two effect estimates is not meaningful because of the obvious differences in methods, both studies agree that the cooling effects of irrigating vegetation are stronger on warmer days or in warmer climate regions.

The afternoon (12:00–15:59) mean cooling effects of irrigating turfgrass on air temperature and turf surface temperature were significantly correlated with background vapour pressure deficit (Figs. 6 and 7). Vapour pressure deficit is the atmospheric demand for water (Seneviratne et al., 2010). Under unlimited soil moisture supply, evapotranspiration of turfgrass increases with vapour pressure deficit (Allen et al., 2005). Although transpiration may be suppressed by a high vapour pressure deficit because of stomatal closure (McAdam & Brodribb, 2015), transpiration only accounts for < 20 % of the total evapotranspiration in irrigated vegetation while soil evaporation and canopy evaporation account for > 80 % (Thompson et al., 1993). Since our turfgrass plots were well-irrigated (Fig. 3), increased vapour pressure deficit could lead to increased evapotranspiration and stronger cooling effects.

The afternoon (12:00–15:59) mean cooling effects of irrigating turfgrass on air temperature were significantly correlated with background wind speed in an inverted bell curve shape (Figs. 6 and 7). A high wind speed reduces the aerodynamic resistance of heat and vapour transfer from the evaporating surface to the air above the canopy, increasing evapotranspiration (Allen et al., 1998). A high wind speed also increases the vapour pressure deficit of the irrigated area if the surrounding surfaces are unirrigated, which in turn increases evapotranspiration. Our data showed that the cooling effects on air temperature reduced when wind speed was > 0.5 m s^{-1}. Since the irrigated plots were small (6 m × 6 m), it was likely that the cool air inside the irrigated plots dissipated and being replaced by the warm air from the surrounding unirrigated surfaces as wind speed increased. Playán et al. (2005) measured a short (a few minutes) cooling effect from irrigating a small area of bare soil (15 m × 15 m) under a wind speed of approximately 4 m s^{-1}. In contrast, Thompson et al. (1993) measured a loner (20 min) cooling effect from irrigating a larger area of corn (82 m × 165 m) under a wind speed of approximately 6 m s^{-1}. As the size of the irrigated area increases, the spatial scale of the impacts of urban green space irrigation on urban climate will resemble that of agricultural irrigation. Large-scale agricultural irrigation is capable of influencing regional and global climate (Cook et al., 2015; Lobell et al., 2008; Thiery et al., 2020). We expect that the cooling effect of irrigating a large urban green space would not be weakened by the surrounding unirrigated surfaces and high wind speeds. Instead, the cooling effects of irrigating a large urban green space will benefit the urban areas downwind (Spronken-Smith & Oke, 1998) and upwind (Vivoni et al., 2020) through advection.

The rainfall during the experiment had a notable impact of the cooling effects of irrigation. Both the cooling effects on air temperature and turf surface temperature weakened notably during the rainy days. The impact of the rainfall in Week 1–2 on turf surface temperature was particularly strong. The cooling effects on turf surface temperature after the rainfall in Week 1–2 never managed to recover to the pre-rainfall level (approximately –8°C) by the end of the study period. Although the soil moisture content of the unirrigated plot returned to a very low level (<10 %) in Week 5–6 as it was in Week 0–1, the cooling effects in Week 5–6 were not as strong as those in Week 0–1, possible because of the cooler weather conditions in Week 5–6. If it had not rained in Week 1–2, both the cooling effects on air temperature and turf surface temperature would be at least as strong as they were in Week 1–2. The cooling effects would likely strengthen as the soil moisture contents of the irrigated plots increase and that of the unirrigated plot decreases over time as they did from Week 2 to Week 6. The findings suggest that irrigating turfgrass or vegetation will likely induce stronger cooling effects in drier regions.

4.3. Practical implications for using irrigation to cool urban green spaces

When irrigation is used solely to maintain plant health, daytime irrigation is often undesirable because it is less water-efficient as it increases evaporation losses which do not contribute to plant uptake (Urrego-Pereira et al., 2013). In contrast, this study showed that when irrigation is used to prioritise the cooling of urban green spaces, daytime irrigation is desirable because it increases evaporation losses which directly contribute to significantly stronger cooling effects. Multiple short daytime irrigations are ideal for maximising the daytime mean cooling effects, in comparison to a single long daytime irrigation that uses the same amount of water. Yang and Wang (2015) reached a similar conclusion from their modelling study that predicted a stronger daily mean cooling effect by irrigating multiple times a day when soil temperature exceeded a certain threshold than irrigating once a day at a fixed time. The time between two short irrigations should be at least 0.5 h because the intercepted water on the canopy takes 0.5–2.0 h to dry during the day, depending on the plant species and weather conditions (Burt et al., 2005). It could be observed from Fig. 5f that the dip after the 3rd irrigation events of the multiple irrigation treatment were not as sharp as the 1st and the 4th irrigation events. There was likely not enough time for the wet canopy to completely dry (evaporate) and the humidity to dissipate between the 2nd and the 3rd irrigation events, thereby weakening the cooling effect of the 3rd irrigation event. This observation suggested that the time between two short irrigations should be at least 0.5 h (30 mins) to maximise the cooling effects of each separate irrigation event.

The significant correlations between irrigation cooling effects and weather conditions have important implications for scheduling irrigation, particularly when irrigation water supply is limited. When irrigation water supply is limited, irrigation can be applied to urban green spaces on a warmer day to obtain stronger cooling benefits. For example, the afternoon (12:00–15:59) mean cooling effect on air temperature is predicted to be –1.0 °C when the background mean air temperature was 35 °C, whereas it is only –0.6 °C when the background mean air temperature was 25 °C (Fig. 6). When irrigation water supply is abundant, irrigation can be applied on a daily basis throughout summer months. The total daily irrigation amount should not exceed the crop evapotranspiration given by the FAO-56 equation (Allen et al., 1998) unless the irrigation also aims to increase soil moisture content and issues of pedestrian access, wet ground and soil compaction are not of concern. The FAO-56 equation estimates the daily total crop evapotranspiration for a given crop under a given set of weather conditions when soil moisture is unlimited. This estimate is the maximum possible daily total crop evapotranspiration regardless of the daily total irrigation amount. In other words, the cooling effects of irrigation will not strengthen even if the daily total irrigation amount exceeds the estimated crop evapotranspiration.

It is crucial to establish alternative water supplies to support irrigation when irrigation is used to prioritise the cooling of urban green spaces, particularly in dry climate regions. Dry climate regions will benefit from a stronger irrigation cooling effect than wetter regions (Cheung et al., 2021), but there is also likely to be a greater demand on local freshwater resources. Water sensitive urban designs offer an opportunity for cities in the dry climate regions to collect non-portable water to support urban green space irrigation. Water sensitive urban designs are the approaches and technologies that collect and retain fit-for-purpose water in the urban areas to meet different needs (Coutts et al., 2013). Stormwater harvesting and wastewater treatment are two important approaches to collecting non-portable water for irrigating urban green spaces (Wong, 2006).

5. Conclusion

The afternoon mean (12:00–15:59) cooling effects of irrigating an urban green space at three different times of the day with the same daily total irrigation amount were measured in this study. All three irrigation time treatments induced significant afternoon mean cooling effects on air temperature (≥0.5 °C, sensor accuracy ± 0.2 °C) and turf surface temperature (≥3.4 °C, sensor accuracy ± 0.2 °C). The single night-time (N1) and single midday (D1) irrigation treatments induced similar afternoon mean cooling effects, while the multiple daytime (D4) irrigation treatment induced significantly stronger afternoon mean cooling effects than N1 and D1. The results suggested that applying short irrigation for multiple times during the day can increase the cooling benefits of irrigation without using more water.

The correlations between the afternoon mean (12:00–15:59) cooling effects of irrigation and background weather conditions were determined. The afternoon mean cooling effects on air temperature and turf surface temperature strengthened linearly with background afternoon mean air temperature, vapour pressure deficit and incoming solar radiation. The afternoon mean cooling effects strengthened with background afternoon mean wind speed from 0.0 to 0.5 m s^{-1} and weakened as wind speed increased beyond 0.5 m s^{-1}. The results suggested that, when irrigation water supply is limited, irrigation can be prioritised to warmer days to obtain stronger cooling benefits.

Uncited references

Mauder et al. (2008), Nakamura and Mahrt (2005).

CRediT authorship contribution statement

Pui Kwan Cheung: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Kerry A. Nice:** Writing – review & editing, Supervision, Methodology. **Stephen J. Livesley:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105103.

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