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Daytime irrigation leads to significantly cooler private backyards in summer

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ABSTRACT

Backyards play important roles for individual households because they provide a private and safe green space for social and environmental interactions, relaxation, gardening and children's activities. The use of backyards is highly dependent on their thermal conditions. Turf is a common surface type in backyards but unirrigated turf can be as warm as pavement, bringing thermal discomfort and discouraging people from using them. Under certain conditions, turf irrigation provides an opportunity to reduce thermal stress by increasing evapotranspiration. This study aims to measure the impacts of turf irrigation on microclimate in a backyard environment in the warm season in Melbourne, Australia. The experiment consisted of four 6 m × 6 m turf-covered plots. Daily irrigation was applied at four amounts: 0, 2, 4 and 7 mm for six weeks. In Week 6, the 4-mm irrigation reduced daytime soil temperature, turf surface temperature, air temperature and universal thermal climate index by 1.7, 2.3, 0.6 and 0.4 °C, respectively. All daytime impacts were significant ($p < 0.05$, *t*-test). Irrigation has the potential to significantly improve the thermal conditions of backyards in combination with the use of tree shade.

1. Introduction

1.1. Background

Urban green spaces offer a wide range of benefits to urban dwellers, such as climate regulation (Lin et al., 2016), noise reduction (Koprowska et al., 2018) and provision of space for physical and social activities (Jennings and Bamkole, 2019). Most studies have focused on public urban green spaces (Dewaelheyns et al., 2018). Private green spaces deserve more attention because they can constitute a large proportion of urban green space in many cities, for example, >30% in Brisbane, Australia (Rupprecht and Byrne, 2014), >35% in the UK cities (Loram et al., 2007) and > 50% in Dunedin, New Zealand (Mathieu et al., 2007). Private greens spaces may be commercially owned and used by members of, or visitors to, that organisation; or they may small private residential green

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spaces used byindividuals of a household. Private residential backyards have distinct roles for individual households because they provide a safe and enclosed green space for social gatherings, relaxation, gardening and children's activities (Hall, 2015).

The frequency of use of outdoor green spaces in summer is dependent upon the microclimate of the space (Cheung and Jim, 2018). Intense summer heat can prevent people from using outdoor green spaces, including private backyards. In a turfed green space, the microclimate can be strongly influenced by soil moisture availability because it directly affects evapotranspiration. The daytime surface temperature of unirrigated turf can be as high as pavement, whereas that of irrigated turf in summer can be 10 °C lower (Spronken-Smith and Oke, 1998) due principally to evapotranspiration. This highlights the potentials of turf irrigation in moderating the summer microclimate of private backyards to reduce air temperature and human heat stress.

Most studies in the literature used computer models to estimate the impact of irrigation on urban climate at a large spatial scale (Cheung et al., 2022). Using the Weather Research and Forecasting model, Gao and Santamouris (2020) predicted that irrigating both vegetated and impervious surfaces in Metropolitan Sydney, Australia (~800 km^2) can reduce daily mean air temperature by 0.5 °C.

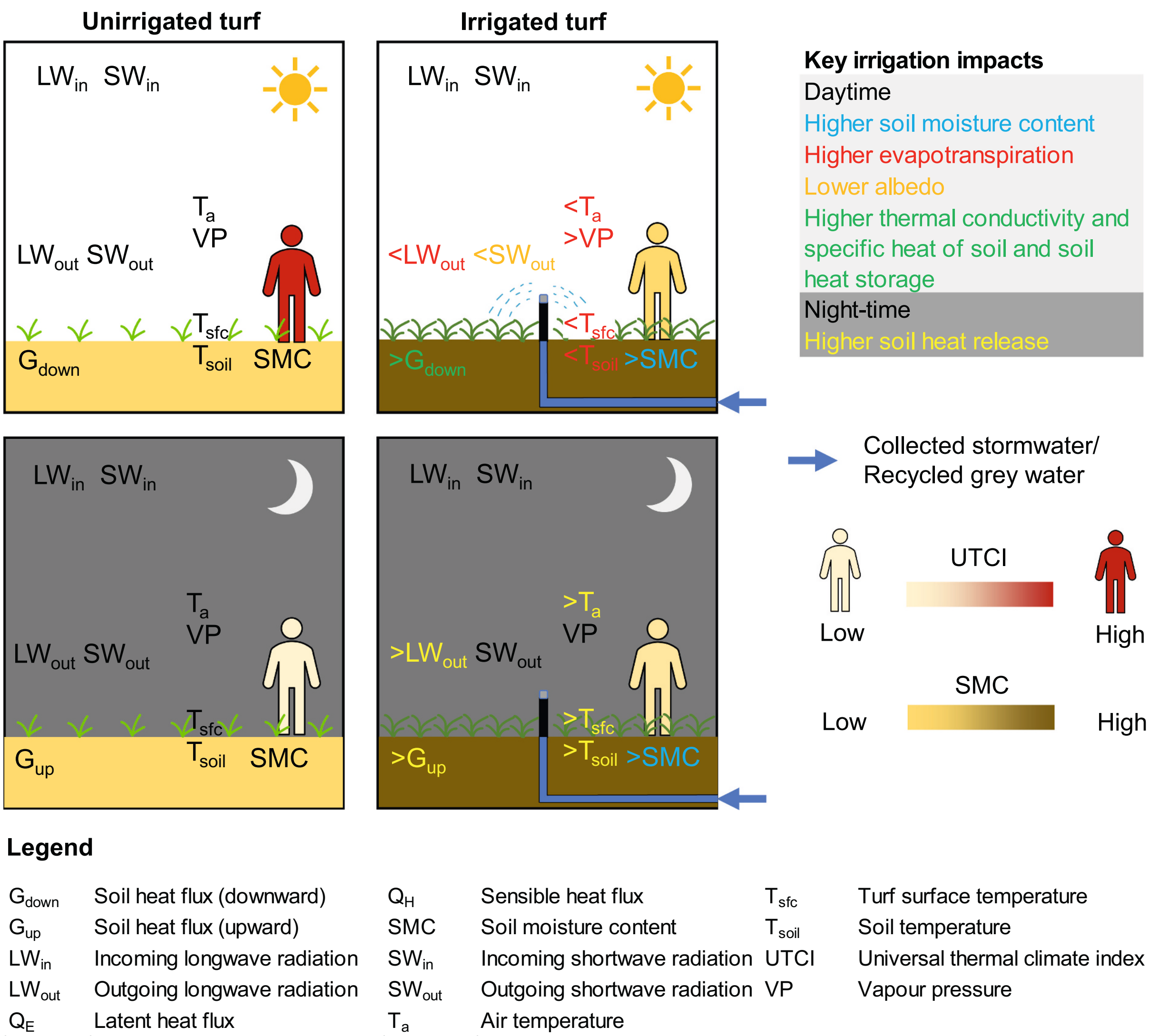

Fig. 1. Theoretical framework describing the key daytime and night-time energetic processes that are induced by irrigating turf and the likely impacts on soil moisture, microclimate and surface energy fluxes. Changed font colour indicates irrigations impact on a key property or process such as soil moisture, microclimate or surface energy fluxes. The greater than and less than symbols indicate the direction of impact from irrigation. During the day, irrigating turf increases soil moisture content, which increases evapotranspiration and latent heat flux while reducing sensible heat flux. The increased evapotranspiration decreases soil temperature, turf surface temperature, outgoing longwave radiation and air temperature, but can increase vapour pressure. Due to irrigation, the lower albedo of wet soil surfaces and lusher grass reduces outgoing shortwave radiation. In contrast, the higher thermal conductivity and specific heat of moist soils increase downward soil heat flux and soil heat storage. These changes in microclimate cause a net reduction in UTCI. During the night, the irrigated turf has a higher soil temperature due to increased daytime heat storage and increased upward soil heat flux. More soil heat release leads to a higher turf surface temperature, and in turn, higher air temperature and UTCI.

Using the SURFEX model, Broadbent et al. (2018) predicted that irrigating all the vegetated surfaces in a suburb of Adelaide, Australia (~7 km^2) can reduce the daily mean air temperature by 2.3 °C. Although other modelling studies also predicted a cooling effect from irrigation (Daniel et al., 2018; Li et al., 2015; Wang et al., 2019), there is a lack of experimental studies that directly measure the cooling benefits of irrigation. Moreover, most existing modelling studies have been undertaken at scales no more detailed than the city or regional scales. The impacts of small-scale irrigation on microclimate in the backyard environment are poorly understood. With the increasing availability of alternative irrigation water supplies, such as collected stormwater and recycled grey water (Coutts et al., 2013), irrigating private green spaces offers a unique and sustainable opportunity to enhance the climate resilience and well-being of cities (Livesley et al., 2021; Tapper, 2021). Thus, it is important to understand the potential cooling benefits of irrigating small private green spaces.

In view of the lack of empirical evidence for the cooling potential of irrigation in cities, this study aims to measure the microclimatic impacts of turf irrigation in a field experiment. With the support of the literature, section 1.2 will present a theoretical framework that explains the key daytime and night-time processes induced by irrigating turf and the likely impacts on soil moisture, microclimate and surface energy fluxes. This study will test seven hypotheses derived from the theoretical framework.

1.2. Theoretical framework and study hypotheses

The theoretical framework underpinning this study is based upon literature and energy-balance understanding from irrigation studies in agricultural and urban landscapes. This theoretical framework represents the key daytime and night-time processes induced by irrigating turf and the likely impacts on soil moisture, microclimate and surface energy fluxes (Fig. 1). During the day, irrigated turf has a higher soil moisture content, which induces three simultaneous effects. First, evapotranspiration increases, which increases latent heat flux and reduces sensible heat flux (Chen et al., 2018; Gao et al., 2020). The change in energy partitioning reduces soil temperature, turf surface temperature and air temperature (Broadbent et al., 2018) but increases vapour pressure (Harding and Snyder, 2012). The lower turf surface temperature reduces outgoing longwave radiation. Second, the albedo of irrigated turf is lower because of lusher grass and darker soils, causing a reduction in outgoing shortwave radiation (Roxy et al., 2010). Third, the wet soils have higher thermal conductivity and specific heat, causing an increase in downward soil heat flux and soil heat storage (Kanamaru and Kanamitsu, 2008). These changes in microclimate and surface energy fluxes cause a net reduction in UTCI (Daniel et al., 2018). During the night, in the absence of incoming solar radiation, the microclimate in a turf area is mainly determined by a strong radiative deficit and soil heat release (Kanamaru and Kanamitsu, 2008). Due to increased daytime storage, soil heat storage in an irrigated turf area is higher than that in an unirrigated area. At night-time, the warm soil releases more heat, i.e., an increase in heat flux out of the soils to raise turf surface temperature (Vahmani and Ban-Weiss, 2016). Higher turf surface temperature leads to a higher air temperature. These cascading changes in microclimate can cause a noticeable increase in UTCI in night-time.

This study will measure the microclimate in four 6 m × 6 m plots (one unirrigated and three irrigated at 2 mm/day, 4 mm/day and 7 mm/day). Based on the above theoretical framework, seven hypotheses will be tested in this study:

(i) Turf irrigation will induce daytime cooling effects in soil temperature, turf surface temperature, air temperature and UTCI;
(ii) The daytime cooling effects will strengthen with the increase in daily irrigation amount from 2 mm to 4 mm to 7 mm;
(iii) The daytime cooling effects are correlated with the differences in soil moisture content between the irrigated and the unirrigated plots;
(iv) Turf irrigation will induce night-time warming effects in soil temperature, turf surface temperature, air temperature and UTCI;
(v) The night-time warming effects will strengthen with the increase in daily irrigation amount from 2 mm to 4 mm to 7 mm;
(vi) The night-time warming effects are correlated with the difference in night-time upward soil heat flux between the irrigated and the unirrigated plots;
(vii) Irrigated plots will have a higher daytime latent heat flux and a lower sensible heat flux than the unirrigated plot, while the night-time latent heat flux and sensible heat flux will be similar in the four plots.

2. Methods and materials

2.1. Study area and climate

The study area was located at the Burnley Campus of the University of Melbourne, Australia. Melbourne has a temperate oceanic climate (Köppen climate classification: Cfb) (Peel et al., 2007). It has a warm and dry summer (Dec–Feb) with a mean daily maximum air temperature of approximately 26.2 °C and a mean total rainfall of 155.3 mm (Bureau of Meteorology, 2022a). The highest air temperature ever recorded in Melbourne was 46.4 °C during a heatwave in 2009 (Bureau of Meteorology, 2009). The intensity, frequency and duration of heatwaves in Australia have increased consistently in the past few decades (Trancoso et al., 2020). Melbourne is expected to experience sixteen days in a year with maximum air temperature > 35 °C in 2050, five days more than the present (City of Melbourne, 2022). Irrigation is likely to be an effective cooling strategy because of Melbourne's warm and dry summer climate (Cheung et al., 2021). This study was conducted from January to March 2020 to measure the impacts of turf irrigation on the microclimate of a small enclosed private green space in Melbourne's summer. The mean reference crop evapotranspiration rate between January and March in Melbourne is approximately 4 mm/day (Bureau of Meteorology, 2022b).

2.2. Experimental design and irrigation system

The experiment in this study consisted of four 6 m × 6 m plots that are 2 m apart on a level surface (Fig. 2). The four plots received four different daily irrigation amounts, namely 0 mm (unirrigated), 2 mm, 4 mm and 7 mm. The three irrigation amounts represented a low, normal and high irrigation amounts relative to Melbourne's mean reference crop evapotranspiration (4 mm/day) in the same period. Each plot was surrounded by 1.8-m tall 70% shade cloth (SOLARSHADE™) to mimic a fenced backyard environment and reduce air mixing between the plots and the surrounding environment. The shade cloth did not shade the climate station in the plots. In each plot, irrigation was applied every day through one MP1000–360 (Hunter Rotator) at the centre and four MP1000–90 at the corners. The irrigation times of the 2-mm, 4-mm and 7-mm plots were 13:00–13:11, 13:12–13:35 and 13:36–14:23, respectively. The flow volumes were measured by Nymet flow sensors. The exact daily mean(±SD) irrigation amounts for the 2-mm, 4-mm and 7-mm plots were 2.3 ± 0.0 mm, 4.2 ± 0.1 mm and 7.0 ± 0.3 mm, respectively. The MP Rotators created minimal mist during operation, and the water throw was adjusted to avoid hitting any sensors. In this way, the impacts of irrigation were only attributed to the direct evaporation of water droplets during irrigation and from the changes in evapotranspiration rate on the turf surface. Kikuyu (*Pennisetum clandestinum*) was the dominant grass species in the plots. The grass remained healthy and provided a complete cover of the plots in the course of the experiment. The grass was mowed to approximately 0.05 m tall every two weeks. The top soil (5–10 cm) of the site was sandy loam and the subsoil (50–55 cm) was sandy clay. The bulk density of the top soil and subsoil was 1.02 g/cm^3 and 1.58 g/cm^3, respectively. The pore volume of the top soil and subsoil was 61% and 40%, respectively. The soil was well-drained with an infiltration rate of approximately 650 mm/h.

2.3. Soil and microclimate measurements

One climate station was installed at the centre of each plot (Fig. 2). Wind speed, black globe temperature, air temperature and vapour pressure were measured at 1.1 m above ground. Incoming and outgoing shortwave and longwave radiation and turf surface temperature were measured at 1.5 m above ground. Soil moisture content and soil temperature were measured at 0.02 m and 0.04 m below ground and soil heat flux 0.05 m below ground to monitor the near-surface response of soil variables to irrigation. The specifications of the instruments used in this study are listed in Table 1. A reference climate station was installed approximately 8 m southwest of the 2-mm plot (Fig. 2). Wind speed, wind direction and rainfall were measured at 2 m. Air temperature and water vapour pressure were measured at 0.6 m and 1.1 m. The difference between the reference climate station and the non-irrigated climate station was that the reference site was not enclosed by a shade cloth and the anemometer was installed at a height of 2 m above ground level. All variables were measured every 10 s, and the 1-min averages were logged.

All data analysis was performed in R Studio 2021.09.0 (R Core Team, 2021). UTCI was calculated using the "rBiometeo" package in R.

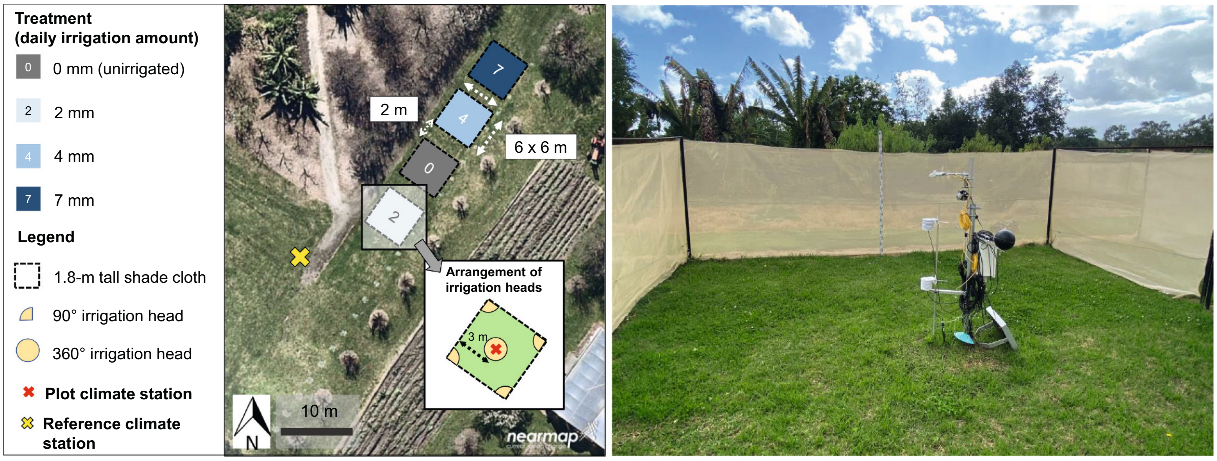

Fig. 2. An aerial photo showing the experimental site (Burnley Campus, the University of Melbourne) and the design of the experiment (left), and a ground photo showing one of the experimental plots (right). The experiment consisted of four 6 m × 6 m plots that received four different daily irrigation amounts: (1) 0 mm (unirrigated), (2) 2 mm, (3) 4 mm and (4) 7 mm. Each plot was surrounded by a 1.8-m tall 70% shade cloth (SOLARSHADE™) to mimic a backyard environment and reduce air mixing between the plots and with the surrounding environment. In each plot, irrigation was applied at the corners at 13:00 local time every day through one Hunter Rotator MP1000–360 at the centre and four Hunter Rotator MP1000–90 at the corners. Kikuyu (*Pennisetum clandestinum*) was the dominant grass species. One climate station was installed at the centre of each plot and a reference climate station was installed approximately 8 m southwest of the 2-mm plot.

Table 1
Specifications of the instruments used in this study.

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	0.6, 1.1
		Atmospheric pressure	±0.05 kPa @ 25 °C	0.6, 1.1
		Vapour pressure	±0.05 kPa @ 25 °C	0.6, 1.1
	CNR4, Kipp & Zonen	Incoming longwave radiation (4.5–42 μm)	<10% (daily total)	1.5
		Incoming shortwave radiation (0.3–2.8 μm)	<5% (daily total)	
		Outgoing longwave radiation (4.5–42 μm)	<10% (daily total)	
		Outgoing shortwave radiation (0.3–2.8 μm)	<5% (daily total)	
	CS650, Campbell Scientific	Soil moisture	±3%	−0.02, −0.04
		Soil temperature	±0.1 °C	−0.02, −0.04
	HFP01, Huskeflux	Soil heat flux	±2%	−0.05
	SI-111-SS, Apogee	Turf surface temperature	±0.2 °C (−10 °C to +65 °C)	1.5
Reference	05103, Campbell Scientific	Wind speed	±0.3 m/s	2
	03301, Campbell Scientific	Wind direction	±3%	2
	HMP155, Campbell Scientific	Air temperature	±(0.055 + 0.0057 × T_a)	1.1
		Relative humidity	±1%	1.1
	TB4, Campbell Scientific	Rainfall	±2%	2

2.4. Bowen ratio-energy balance method

Latent heat flux and sensible heat flux were calculated using the Bowen ratio-energy balance method (Kustas et al., 1996). The Bowen ratio (β, −) is defined as:

$$\beta = \frac{Q_H}{Q_E} \tag{1}$$

where Q_E (W/m^2) latent heat flux (positive when water vapour pressure decreases with height) and Q_H (W/m^2) sensible heat flux (positive when air temperature decreases with height). The meanings of the variables used in this section are described in Table 2.

On a uniform surface and in the absence of advection, the energy fluxes can be expressed as:

$$R_n = G + Q_E + Q_H \tag{2}$$

where R_n (W/m^2) is the net radiation (positive downward), G (W/m^2) the surface soil heat flux (positive when conducted downward).

With Eq. (1), Eq. (2) can be rewritten as follows:

$$Q_E = \frac{R_n - G}{1 + \beta} \tag{3}$$

$$Q_H = \frac{\beta}{1 + \beta}(R_n - G) \tag{4}$$

Over an averaging period (60 min), the empirical relationships between latent heat flux and vertical water vapour pressure gradient, and between sensible heat flux and vertical air temperature gradient can be expressed as:

Table 2
Symbol, unit and description of the variables used in the Bowen-ratio energy balance method.

Variable	Symbol	Unit	Description
Atmospheric pressure	p	kPa	Pressure caused by the gravitational force of the Earth on the air molecules within the atmosphere.
Bowen ratio	β	–	Ratio of the sensible heat flux density to the latent heat flux density.
Exchange coefficient for sensible heat	k_h	m^2/s	Rate of eddy diffusion for heat.
Exchange coefficient for water vapour	k_v	m^2/s	Rate of eddy diffusion for water vapour.
Latent heat flux density	Q_E	W/m^2	Heat release or absorbed by a system when it changes between soild, liquid and gas states per unit area and time.
Latent heat of vapourization of water	L_v	kJ/kg	Energy required to vaporise one mass unit of water.
Net radiation	R_n	W/m^2	The difference between all-wave incoming and outgoing radiant flux per unit area and time.
Psychometric constant	γ	kPa/°C	The ratio of specific heat of moist air at constant pressure to latent heat of vaporization of water.
Sensible heat flux density	Q_H	W/m^2	The heat energy able to be sensed that is released or absorbed by a system per unit area and time.
Specific heat of air	c_p	kJ/kg°C	Energy required to increase one mass unit of dry air by one degree Celcius at constant pressure.
Surface soil heat flux	G	W/m^2	Heat conducted into or out of the soil per unit area and time.

$$Q_E = -\frac{\rho_a c_p}{\gamma} k_v \frac{de}{dz} \tag{5}$$

$$Q_H = -\rho_a c_p k_h \frac{dT_a}{dz} \tag{6}$$

Under non-advective conditions, the exchange coefficient for water vapour (k_v, m^2/s) can be assumed to be equal to the exchange coefficient for sensible heat (k_h, m^2/s) such that:

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{dT_a/dz}{de/dz} = \gamma \frac{\Delta T_a}{\Delta e} \tag{7}$$

where $\gamma = c_p p / \epsilon L_v$ is the psychometric constant (kPa/°C). c_p is the specific heat of air at constant pressure (1.01 kJ/kg/°C), p the atmospheric pressure (kPa), ϵ (−) the ratio between the molecular weights of water vapour and air, and L_v the latent heat of vaporization (kJ/kg). $\Delta T_a = T_{a,0.6m} - T_{a,1.1m}$ and $\Delta e = e_{0.6m} - e_{1.1m}$ are the air temperature and water vapour pressure differences between the two measurement heights (0.6 and 1.1 m in this study), respectively.

By measuring the air temperature and water vapour pressure gradient, β can be obtained and substituted into Eqs. (3) and (4) to calculate latent heat flux and sensible heat flux.

There are three inherent problems in the Bowen ratio-energy balance method (Perez et al., 1999). First, the estimates of latent heat flux and sensible heat flux are totally dependent upon the measurements of air temperature and water vapour pressure gradients (Eqs. (3), (4) and (7)). The measurements can give incorrect signs to the fluxes when the fluxes change their signs during early morning and late afternoon, as well as during irrigation and precipitation. Second, the method fails when β is close to −1 because the denominators of Eqs. (3) and (4) will approach 0 and the calculated latent heat flux and sensible heat flux will lose their physical meanings. This situation usually happens during sunrise and sunset and precipitation when the direction of the air temperature gradient shifts to the opposite to that of the water vapour pressure gradient. Third, the Bowen ratio-energy balance method gives inaccurate results when the air temperature and water vapour pressure differences are in the same order of magnitude as the resolution limits of the sensors. We followed the criteria described in Perez et al. (1999) to discard the latent heat flux and sensible heat flux data with any of the three problems.

2.5. Study period

The irrigation began on 2021-01-20. We used the data from the second to the sixth week (2021-01-27 to 2021-03-02, study period) for analysis because there were missing data in the first week (2021-01-20 to 2021-01-26). The mean air temperature over the study period was 19.4 °C, and there were eight days with a daily maximum air temperature ≥ 30.0 °C (Fig. 3a). The total rainfall in the study period was 58.8 mm. The mean relative humidity and wind speed over the study period were 63% and 0.49 m/s, respectively (Fig. 3b).

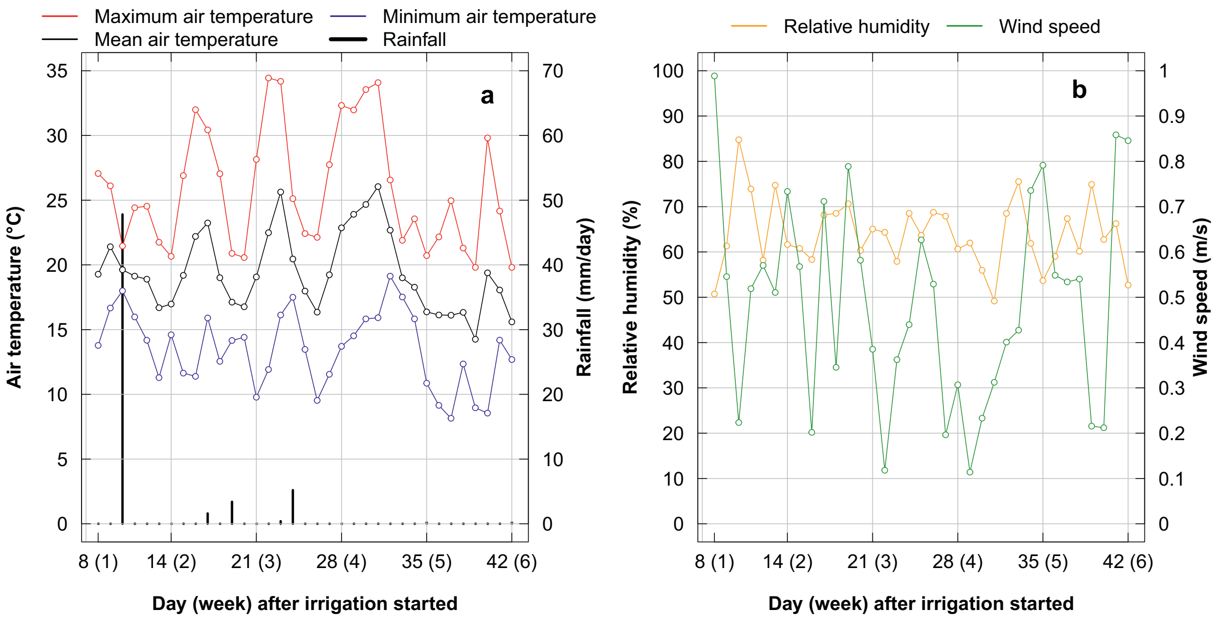

Fig. 3. Variations of (a) air temperature and rainfall, and (b) relative humidity and wind speed at the reference climate station in the study period. The study period is from the 8th to 42nd day (2nd to 6th week) after starting irrigation. The first seven days after irrigation started were excluded from the analysis because of incomplete data.

2.6. Definitions for daytime and night-time periods

Apart from measuring the impacts of irrigation on a daily mean basis, it is necessary to measure the daytime and night-time impacts separately because the impacts are controlled by different processes (Fig. 1). There are no universal definitions for daytime and night-time periods. Different studies have different definitions according to their measurement periods, geographical locations and study purposes (Cheung and Jim, 2019). This study observed sharp changes in various temperature metrics around 06:00 and 18:00 local time (Fig. 4a–d), which coincided with sharp changes in incoming shortwave radiation (Fig. 4e). The sharp changes in temperatures and incoming shortwave radiation were plausibly due to the shading from the trees next to the plots. It is necessary to avoid the above-mentioned periods in the daytime and night-time analyses. Considering the contrasting impacts of irrigation between the day and the night, as well as the potential shading effect from the trees, the daytime and night-time periods were defined as 10:00–16:59 and 21:00–05:59 local time, respectively.

3. Results

3.1. Initial responses of soil moisture to irrigation

The initial soil moisture contents of the four plots ranged from 10% to 22% by volume (Fig. 5). Before irrigation began, the soil moisture contents of the four plots decreased gradually at a similar rate. After four days of irrigation, the soil moisture contents in the 4-mm and 7-mm plots increased notably from approximately 20% to 35%, whereas the 2-mm plot remained rather stable at approximately 14%. The wetting-drying amplitudes were about 10% and 7% per annum for the 7 mm and 4 mm plots, respectively. In contrast, the 2 mm plot had considerably subdued fluctuations circumscribed at around 2%. The patterns indicated that more irrigation could bring more drawdown in the daily soil-moisture cycles. Meanwhile, the decreasing trend in soil moisture content in the unirrigated plot continued.

The 7.2-mm rainfall event on Day 6 and the 47.8-mm event on Day 9 promptly eliminated the differences in soil moisture content between the irrigated plots. The first low rainfall wetted the soil in the 2 mm plot notably more than the 0-mm, 4-mm and then 7-mm plots. The second high rainfall event wetted the 0-mm plot considerably, followed by the 2 mm and then 4 mm and 7 mm plots. From Day 10, the differences in soil moisture content between the unirrigated and irrigated plots enlarged quickly as the soils in the unirrigated plot dried up. Meanwhile, the diurnal soil moisture amplitudes of the irrigated plots stayed at ranges similar to the pre-rainfall period.

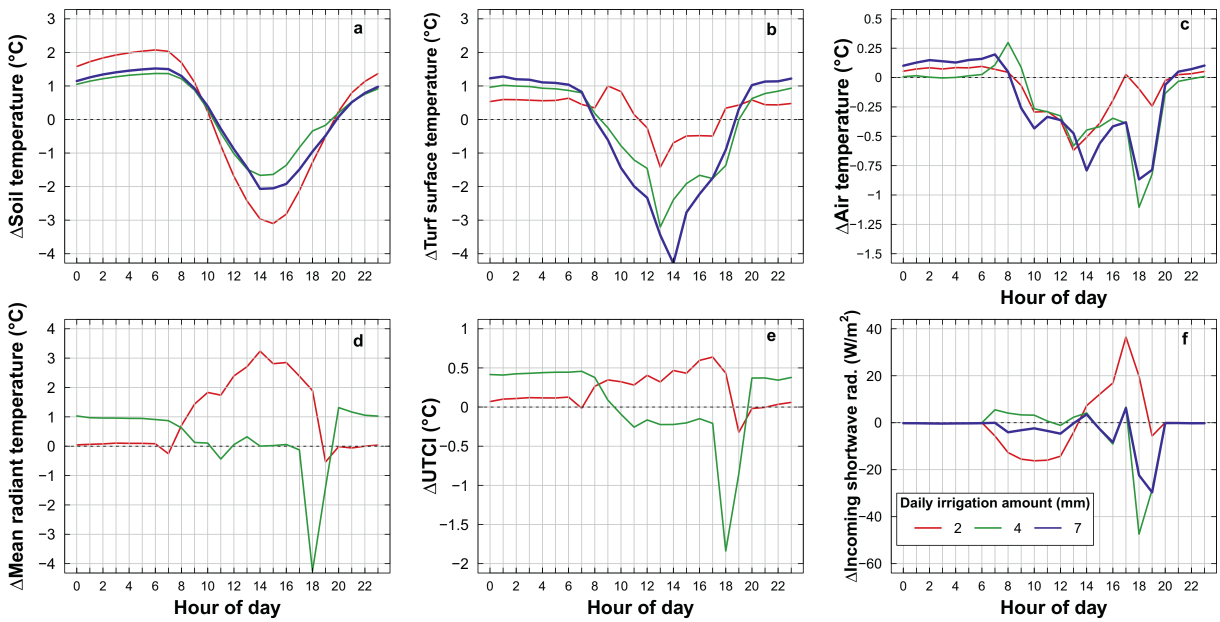

Fig. 4. Diurnal variations of the hourly mean differences between the irrigated plot and the unirrigated plot (Δ = irrigated – unirrigated) in (a) soil temperature, (b) turf surface temperature, (c) air temperature, (d) mean radiant temperature, (e) UTCI and (f) incoming shortwave radiation. Tree shade potentially impacted the incoming shortwave radiation received at the four plots at 06:00 and 18:00, causing sharp changes in various temperature metrics. Therefore, the daytime and night-time periods are defined as 10:00–16:59 and 21:00–05:59 local time, respectively. The mean radiant temperature and UTCI data in the 7-mm plot were missing due to instrument failure.

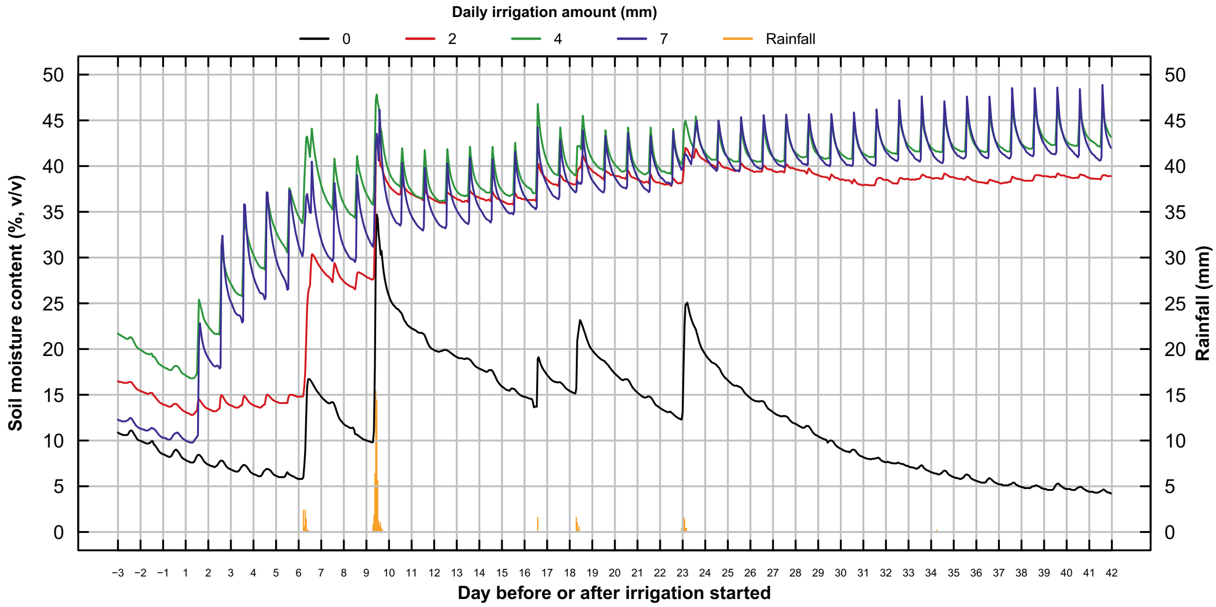

Fig. 5. Hourly variations in soil moisture content and rainfall from three days before irrigation started to 42 days after irrigation had begun in the four plots. We used the data in period between Day 8 and 42 for data analysis and presentation. Before irrigation started, soil moisture content in all four plots decreased gradually at a similar rate. After irrigation started, the soil moisture content increased sharply in the 4-mm and 7-mm plots, whereas the soil moisture content in the 2-mm plot was maintained at the pre-irrigation level while the unirrigated plot continued the decreasing trend. The rainfall events on Days 6 and 9 increased the soil moisture content to ≥35% in the three irrigated plots and maintained above that level since then. From Day 10, the differences in soil moisture content between the unirrigated and the irrigated plots gradually increased as the soils in the unirrigated plot dried up.

3.2. *Impacts of irrigation on daily mean soil moisture content, microclimate and soil heat flux*

When the daily mean impacts of irrigation is considered, irrigation supplemented by rainfall significantly increased daily mean soil moisture content by >25% ($p < 0.05$, *t*-test) in all three irrigated plots in the study period (Table 3). Irrigation also significantly reduced daily mean turf surface temperature, outgoing longwave radiation, air temperature and outgoing shortwave radiation ($p < 0.05$, *t*-test) in most irrigated plots, but the reductions were small. Irrigation increased soil temperature, vapour pressure and UTCI by a small amount, and the significance of the impacts depended on irrigation amount. Irrigation significantly reduced soil heat flux in the 2-mm and 4-mm plots. Since the daytime and night-time impacts of irrigation are likely in opposite directions and the effects can be masked when the daily mean impacts are considered (Fig. 1), it is necessary to investigate the diurnal variation of the impacts.

Table 3
Impacts of irrigation on daily mean soil moisture content, soil heat flux and eight microclimate variables in the study period. The impact of irrigation is calculated as the difference between the irrigated and unirrigated plots (Δ = irrigated – unirrigated).

Variable	Unit	Daily irrigation amount (mm)					
		2		4		7	
		Mean	CI	Mean	CI	Mean	CI
Soil moisture content	%, *v*/v	**25.0**	22.6 to 27.3	**28.1**	25.6 to 30.7	**26.7**	23.8 to 29.7
Soil temperature	°C	0.2	0.0 to 0.3	**0.2**	0.1 to 0.4	**0.2**	0.1 to 0.3
Land surface temperature	°C	**0.2**	0.1 to 0.3	**−0.2**	−0.3 to −0.1	**−0.3**	−0.4 to −0.2
Outgoing longwave radiation	W/m^2	**−3.4**	−4.3 to −2.5	**−3.7**	−4.6 to −2.8	**−4.5**	−5.8 to −3.3
Air temperature	°C	**−0.1**	−0.1 to −0.1	**−0.2**	−0.2 to −0.2	**−0.2**	−0.2 to −0.1
Vapour pressure	kPa	**0.010**	0.007 to 0.013	0.002	−0.004 to 0.009	0.004	−0.003 to 0.012
Outgoing shortwave radiation	W/m^2	**2.3**	1.7 to 2.8	**−2.0**	−2.4 to −1.6	**−4.1**	−4.8 to −3.4
Soil heat flux	W/m^2	**−1.3**	−1.7 to −1.0	−0.9	−2.0 to 0.2	**−2.6**	−3.3 to −1.8
UTCI	°C	**0.2**	0.2 to 0.2	0.0	0.0 to 0.1	NA^	NA^

Note: Significant differences are bold (*t*-test, $p < 0.05$); CI: confidence interval.
^ Incomplete data due to sensor failure.

3.3. Impacts of irrigation on daytime/night-time soil moisture, soil heat flux and microclimate

3.3.1. Does irrigation induce daytime cooling effects?

All three levels of daily irrigation induced significant daytime cooling effects ($p < 0.05$, *t*-test, indicated by open circles) in weekly mean soil temperature (Fig. 6a), turf surface temperature (Fig. 6b) and air temperature (Fig. 6c) for most of the weeks in the study period. The cooling effects in soil temperature, turf surface temperature and air temperature strengthened from Week 2 to Week 6, which coincided with the increasing soil moisture content (Fig. 6e). The impact of irrigation on UTCI was mixed (Fig. 6d). Although the cooling effects varied greatly from day to day (faint lines in Fig. 6), the strengthening cooling trends were consistent for all three

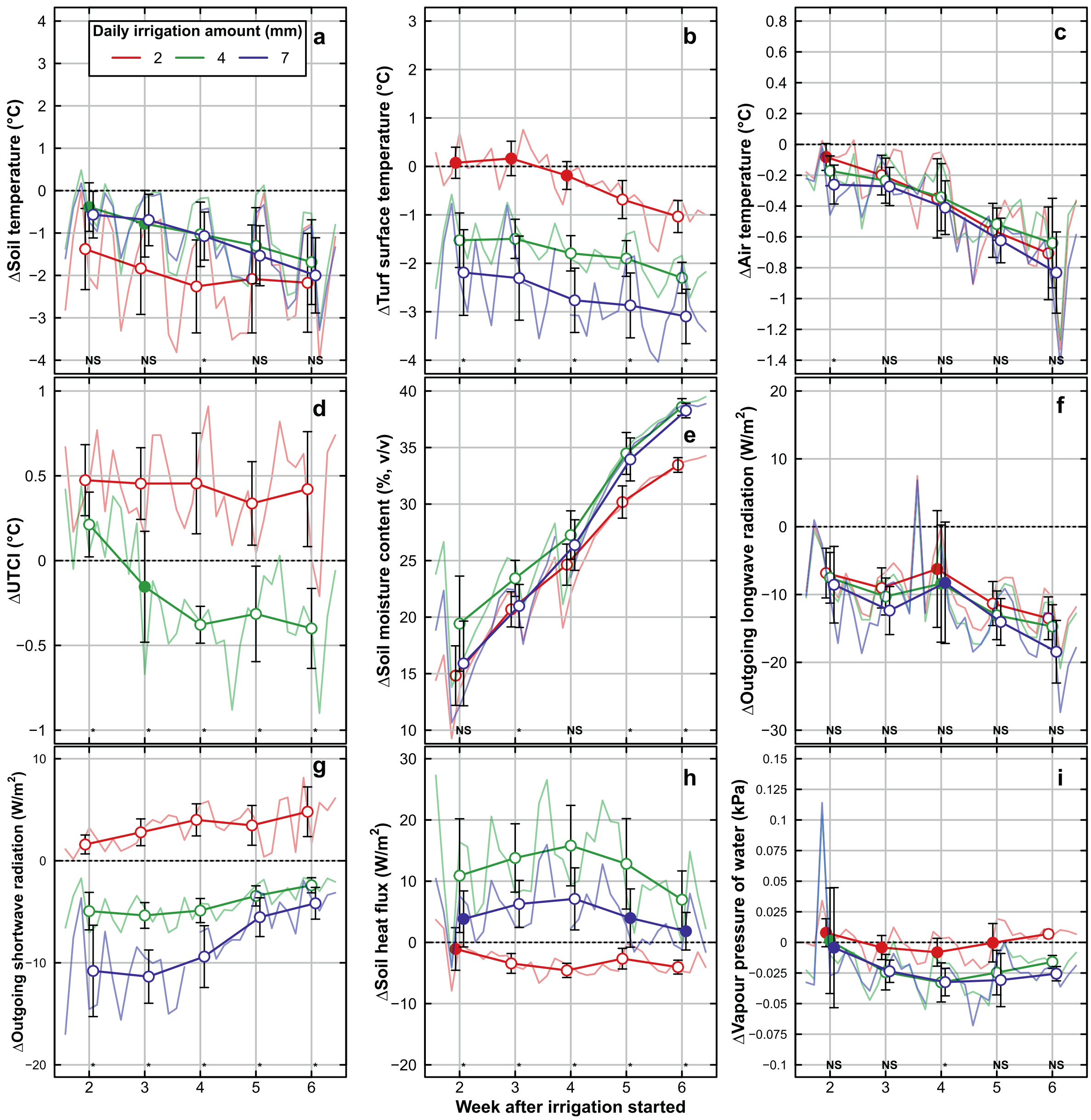

Fig. 6. Impacts of irrigation on daytime (10:00–16:59) mean (a) soil temperature, (b) turf surface temperature, (c) air temperature, (d) UTCI, (e) soil moisture content, (f) outgoing longwave radiation, (g) outgoing shortwave radiation (h) soil heat flux and (i) vapour pressure. The impact of irrigation is calculated as the difference between the irrigated and unirrigated plots (Δ = irrigated – unirrigated). The solid lines are the weekly means and the error bars are the 95% confidence intervals. The faint lines are the daily means. Open circles represent significant differences ($p < 0.05$, *t*-test) in the weekly means between the irrigated and the unirrigated plots and closed circles represent insignificant differences. Significant differences ($p < 0.05$, AONVA) in the weekly means between the three irrigated plots are represented by "*" and insignificant differences by "NS". The UTCI data of the 7-mm plot were missing due to sensor failure.

irrigated plots and all four temperature metrics. After six weeks of daily 4-mm irrigation, soil temperature, turf surface temperature, air temperature and UTCI were 1.7, 2.3, 0.6 and 0.4 °C cooler than the respective unirrigated plot ($p < 0.05$, *t*-test).

In addition, irrigation significantly reduced outgoing longwave radiation by >6 W/m^2 ($p < 0.05$, t-test) (Fig. 6f). Irrigation significantly increased outgoing shortwave radiation (Fig. 6g) in the 2-mm plot ($p < 0.05$, *t*-test), but significantly reduced it in the 4-mm and 7-mm plots ($p < 0.05$, *t*-test). Irrigation significantly reduced downward soil heat flux in the 2-mm plot ($p < 0.05$, t-test) but significantly increased it in the 4-mm and 7-mm plot ($p < 0.05$, t-test) (Fig. 6h). Except for the 2-mm plot, irrigation significantly reduced the vapour pressure by <0.03 kPa for most of the time in the study period ($p < 0.05$, t-test) (Fig. 6i). However, this change was smaller than the sensor's accuracy (±0.05 kPa) (Table 3).

3.3.2. *Do daytime cooling effects strengthen with irrigation amount?*

The daytime cooling effects in soil temperature (Fig. 6a), air temperature (Fig. 6c) and UTCI (Fig. 6d) did not strengthen with increasing daily irrigation amount ($p > 0.05$, ANOVA). In contrast, the cooling effect in turf surface temperature (Fig. 6b) strengthened significantly with daily irrigation amount ($p < 0.05$, ANOVA). Daily irrigation amounts had a significant ($p < 0.05$, ANOVA) but small impact on soil moisture content (<5%) (Fig. 6e) and vapour pressure deficit (<0.05 kPa) (Fig. 6i) in some of the weeks. Increasing daily irrigation amounts had no significant impact on outgoing longwave radiation ($p > 0.05$, ANOVA) (Fig. 6f), but it significantly reduced incoming shortwave radiation ($p < 0.05$, ANOVA) (Fig. 6g). Although the impacts of daily irrigation amount on soil heat flux were significant ($p < 0.05$, ANOVA), the direction of its impact was unclear because the daily mean soil heat flux of the 7-mm plot was between the 2-mm and the 4-mm ones (Fig. 6h).

3.3.3. *Do daytime cooling effects correlate with soil moisture difference?*

The difference in soil moisture content between the irrigated and the unirrigated plots was significantly and negatively correlated with the differences in all four temperature metrics, namely soil temperature, turf surface temperature, air temperature and UTCI ($p < 0.05$, *t*-test) (Fig. 7). In other words, as the difference in soil moisture content increased, the cooling effect became stronger (more

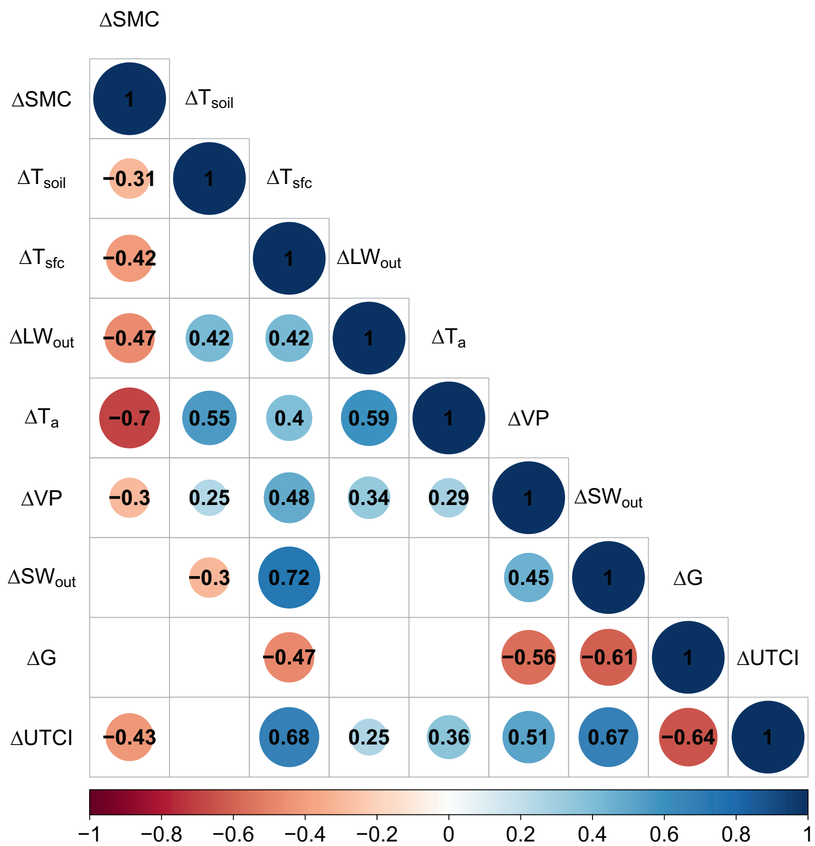

Fig. 7. A correlation matrix showing the Pearson's Correlation Coefficients between soil moisture content difference (ΔSMC), soil temperature difference (ΔT_{soil}), turf surface temperature difference (ΔT_{sfc}), outgoing longwave radiation difference (ΔLW_{out}), air temperature difference (ΔT_a), vapour pressure difference (ΔVP), outgoing shortwave radiation difference (ΔSW_{out}), soil heat flux difference (ΔG) and UTCI difference (ΔUTCI). The differences are the daytime (10:00–16:59) mean differences between the irrigated and unirrigated plots (Δ = irrigated – unirrigated). Data from all three irrigated plots are pooled. Only the statistically significant ($p < 0.05$, t-test) correlations are shown.

negative differences in temperature). In particular, air temperature had the strongest correlation ($R = 0.7$) with soil moisture content.

3.3.4. Does irrigation induce night-time warming effects?

All three levels of daily irrigation induced a significant night-time warming effect ($p < 0.05$, *t*-test) in weekly mean soil temperature (Fig. 8a), turf surface temperature (Fig. 8b) and UTCI (Fig. 8d) for most of the weeks in the study period. The warming effect in air temperature was small and not significant ($p > 0.05$, t-test) (Fig. 8c). The warming effects in all four temperature metrics strengthened from Week 2 to Week 6, which coincided with the increasing differences in soil moisture content between the irrigated and the

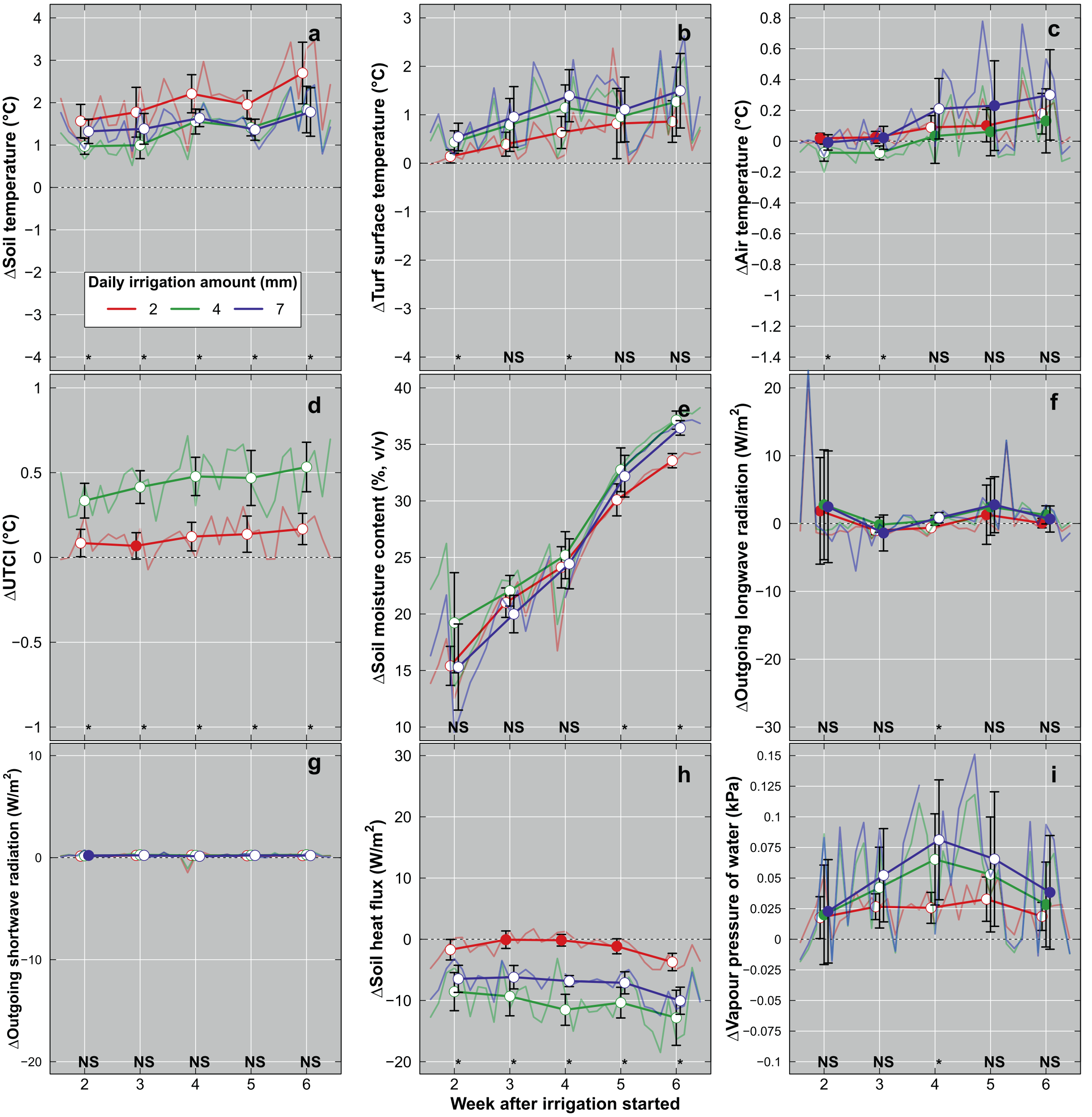

Fig. 8. Impacts of irrigation on night-time (21:00–05:59) mean (a) soil temperature, (b) turf surface temperature, (c) air temperature, (d) UTCI, (e) soil moisture content, (f) outgoing longwave radiation, (g) outgoing shortwave radiation (h) soil heat flux and (i) vapour pressure. The impact of irrigation is calculated as the difference between the irrigated and unirrigated plots (Δ = irrigated – unirrigated). The solid lines are the weekly means and the error bars are the 95% confidence intervals. The faint lines are the daily means. Open circles represent significant differences ($p < 0.05$, t-test) in the weekly means between the irrigated and the unirrigated plots and closed circles represent insignificant differences. Significant differences ($p < 0.05$, AONVA) in the weekly means between the three irrigated plots are represented by "*" and insignificant differences by "NS". The UTCI data of the 7-mm plot were missing due to sensor failure.

unirrigated plots (Fig. 8e). After six weeks of daily 4-mm irrigation, soil temperature, turf surface temperature, air temperature and UTCI were 1.4, 1.3, 0.1 and 0.5 °C warmer than the respective non-irrigated plot ($p < 0.05$, t-test, except for air temperature). The impacts of irrigation on outgoing longwave (Fig. 8f) and shortwave (Fig. 8g) radiation were small and not significant ($p > 0.05$, t-test). Irrigation significantly increased upward soil heat flux by >6 W/m^2 in the 4-mm and the 7-mm plot ($p < 0.05$, t-test), whereas the change in the 2-mm plot was not significant ($p > 0.05$, t-test) (Fig. 8h). Most of the impacts on vapour pressure (Fig. 8i) were still below the accuracy of the sensor (±0.05 kPa) (Table 3).

3.3.5. *Do night-time warming effects strengthen with irrigation amount?*

Different daily irrigation amounts had a significant impact ($p < 0.05$, ANOVA) on the night-time warming effects in soil temperature (Fig. 8a) and UTCI (Fig. 8d). However, the warming effect did not necessarily strengthen with increasing daily irrigation amount. The warming effect in the 2-mm plot was the strongest in soil temperature, contrary to UTCI. Daily irrigation amount had no significant impact ($p > 0.05$, ANOVA) on the warming effects in turf surface temperature (Fig. 8b) and air temperature (Fig. 8d) for most of the weeks in the study period. It also had no significant impact ($p > 0.05$, ANOVA) on soil moisture content (Fig. 8e), outgoing longwave radiation (Fig. 8f), outgoing shortwave radiation (Fig. 8g) and water vapour pressure (Fig. 8i). Different daily irrigation amounts had a significant impact ($p < 0.05$, ANOVA) on night-time soil heat flux (Fig. 8h).

3.3.6. *Do night-time warming effects correlate with night-time soil heat flux?*

The difference in night-time soil heat flux between the irrigated and the unirrigated plots was significantly and positively correlated with the warming effects in all four temperature metrics, namely soil temperature, turf surface temperature, air temperature and UTCI ($p < 0.05$, t-test) (Fig. 9). The difference in daytime soil heat flux between the irrigated and the unirrigated plots was significantly and negatively correlated with the night-time soil heat flux ($p < 0.05$, t-test). It implied that more heat stored in the soils during the day would lead to more heat released from the soils at night.

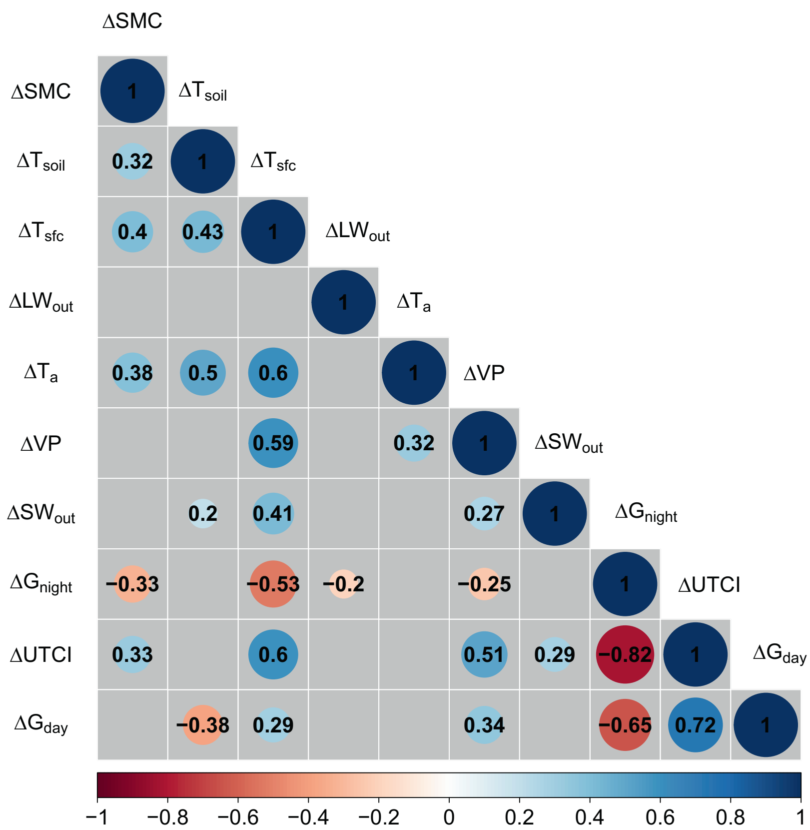

Fig. 9. A correlation matrix showing the Pearson's Correlation Coefficients between soil moisture content difference (ΔSMC), soil temperature difference (ΔT_{soil}), turf surface temperature difference (ΔT_{sfc}), outgoing longwave radiation difference (ΔLW_{out}), air temperature difference (ΔT_a), vapour pressure difference (ΔVP), outgoing shortwave radiation difference (ΔSW_{out}), night-time soil heat flux difference (ΔG_{night}), UTCI difference (ΔUTCI) and daytime soil heat flux difference (ΔG_{day}). Except specified, the differences are the night-time (21:00–05:59) mean differences between the irrigated and unirrigated plots (Δ = irrigated – unirrigated). Data from all three irrigated plots are pooled. Only the statistically significant ($p < 0.05$) correlations are shown.

3.3.7. Does irrigation shift daytime and night-time latent and sensible heat fluxes?

The daytime latent heat flux of the unirrigated plot was always higher than that of the three irrigated plots (Fig. 10). A sharp increase in the latent heat flux was evident in the three irrigated plots after irrigation (13:00–14:59). This coincided with a sharp reduction in sensible heat flux. The sensible heat flux of the unirrigated plot was lower than the irrigated plots for most of the day. However, the differences in daytime latent heat flux and sensible heat flux between the irrigated plots and the unirrigated plot were not significant ($p > 0.05$, Tukey HSD test), except for the latent heat flux between the 2-mm plot and the unirrigated plot. The daytime ratio of sensible heat flux to latent heat flux of the irrigated plots was 0.32, i.e., sensible heat was 32% that of latent heat.

The differences in night-time latent heat flux and sensible heat flux between the unirrigated and irrigated plots were not significant ($p > 0.05$, Tukey HSD test), except that the latent heat flux of the 4-mm plot was significantly higher than the unirrigated plot ($\Delta = 17$ W/m^2).

4. Discussion

4.1. Impacts of irrigation on daytime microclimate

This field study showed that irrigating turf in a simulated backyard environment can significantly reduce daytime soil temperature, turf surface temperature and air temperature, but not UTCI. Modelling studies have predicted that irrigating vegetated surfaces over a large spatial scale could reduce daily mean soil temperature by 4.2 °C (Gao et al., 2020), reduce daily mean surface temperature by 3.0 °C (Wang et al., 2019) and reduce daily mean air temperature by 2.6 °C (Broadbent et al., 2018). UTCI has been included in some model predictions but was not explicitly reported (Daniel et al., 2018). Irrigation was predicted to reduce the humidex index by 2.3 °C at 3 pm (Broadbent et al., 2018) but the reduction was insufficient to improve thermal comfort because it takes at least a 5 °C change in humidex in order to change the thermal comfort by one level on humidex's four-level scale (Masterton and Richardson, 1979). The predicted cooling effects from these modelling studies were all stronger than those measured in our field study. One possible explanation is that these modelling studies simulated irrigation at a much higher daily amount (10–30 mm) than the 2 to 7 mm applied in our experiment. In addition, it is important to note that the analysis of the modelling studies was conducted at a much larger spatial scale (from city scale to national scale) than our experiment's. The background climate and weather conditions used in their simulations were also different. Therefore, the climate context and the methods of analysis or simulation must be taken into account when interpreting the potential cooling effects of irrigation of measurement or modelling studies.

Most modelling studies predict that the cooling effect of irrigation will strengthen as the daily irrigation amount increases. Broadbent et al. (2018) predicted that the air temperature reductions from irrigating vegetated surfaces would strengthen from 0.5 °C to 2.3 °C as the daily irrigation amount increases from 5 mm to 30 mm. Similarly, Wang et al. (2019) predicted that the daily mean air temperature reductions from irrigating vegetated surfaces would strengthen from 0.5 °C to 1.9 °C as the daily irrigation amount increases from 4 mm to 13 mm. In our experiment, the relationship between the daily irrigation amount and cooling effect could not be directly measured because the differences in soil moisture contents of the three irrigated plots were small (<5%) throughout the study

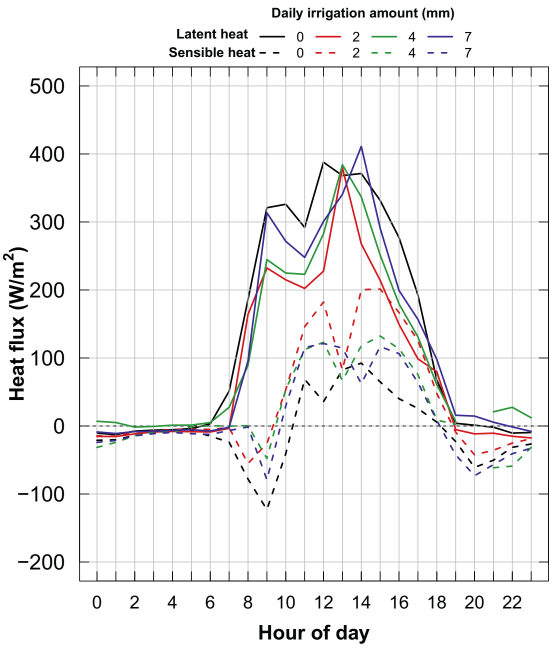

Fig. 10. Diurnal variations of the hourly mean latent heat flux and sensible heat flux of the unirigated and irrigated plots.

period, as a result of the 47.8-mm of rain on Day 9 which eliminated the difference in soil moisture content between the irrigated plots (Fig. 5). This event pushed all soil moisture contents to a high level, and reduced the irrigation treatment differences on soil moisture content (Fig. 6e).

Nevertheless, it is possible to infer the impacts of daily irrigation amount on the cooling effect because the cooling effect is strongly correlated with the difference in soil moisture content between the irrigated and the unirrigated plots (section 3.3.3). Based on the response of soil moisture content to irrigation before the rainfall event on Day 6, it is possible to infer that the soil moisture content in the 4-mm and 7-mm plots would have reached 35% on Day 10 without any rainfall (Fig. 5). Even if we increase the daily irrigation amount to 30 mm, the resulting soil moisture content trend will be the same as that of 4 mm after Day 10, meaning that the resulting cooling effect will also be the same. The almost linear increase in cooling benefit from increased irrigation up to 13 mm (Wang et al., 2019) or 30 mm (Broadbent et al., 2018) is highly unlikely as soil moisture contents will reach saturation at moderate rates of irrigation in all but the sandiest of soils. We expect that the cooling effect will only strengthen when the daily irrigation amount increases at the lower range, possibly from 2 to 4 mm, because irrigating 2 mm daily was insufficient to bring soil moisture content up to 35% based on its trend before Day 6 (Fig. 5).

We observed a strengthening cooling effect from Week 2 to 6 (Fig. 6). This could be driven by either a further cooling of the irrigated plots or warming of the unirrigated plot over time. Since the soil moisture contents of the irrigated plots had already reached the field capacity in Week 2 (Fig. 5), further cooling was impossible. Thus, the strengthening cooling effects were relative rather than absolute, driven by a warming of the unirrigated plot because the soils gradually dried up (Fig. 5) in the absence of major rainfall events after Week 1 (Fig. 3). The soil moisture contents of the irrigated plots were kept above 35% throughout the study period. It remains unknown whether a lower soil moisture content, e.g., 25%, can induce a similarly strong cooling effect as 35%. Future work should address this important question because the daily irrigation amount can be reduced to <2 mm if a 25% soil moisture content is sufficient to achieve the highest possible evapotranspiration and cooling effect. The daytime part of the theoretical framework (Fig. 1) is generally accurate, except that irrigation cannot reduce human thermal stress.

The results implied that the irrigated soils attained the field capacity early in the experiment and were maintained at field capacity by continual irrigation. The cyclical daily drawdown could be attributed mainly to evaporation plus some gravitational drainage of water held in larger pores. Closer to the field capacity of circa 35% soil moisture content which is the readily available water (RAW) zone, the adequate water supply can satisfy the evaporative needs of the turf to sustain the cooling effect at an optimal level. If soil moisture drops well below the field capacity point, entering the less available water (LAW) zone, the turfgrass could begin to experience moisture stress. In the circumstances, the turf cooling effect can be correspondingly trimmed. In the interest of water conservation, it will be helpful to find the interface between RAW and LAW, and adopt an irrigation rate that can keep the soil moisture content above it most of the time.

There were inconsistent results in UTCI (Fig. 6d), outgoing shortwave radiation (Fig. 6g) and soil heat flux (Fig. 6h) in the three irrigated plots, i.e. these variables increased in some of the irrigated plots and decreased in others increased these variables while other reduced them. There were probably inconsistencies in UTCI and outgoing shortwave radiation data because the changes were small in comparison to the accuracy of the sensors (Table 1). In particular, UTCI was calculated from air temperature, relative humidity, wind speed and mean radiant temperature; therefore, the uncertainties in the measurements of each of these variables have accumulated. The inconsistency in soil heat flux can be attributed to the high spatial variability of soil thermal properties (Usowicz et al., 1996). It is recommended that more soil heat flux plates should be installed to minimise the impacts of spatial variability on soil heat flux measurement (Sauer and Horton, 2005).

4.2. Impacts of irrigation on night-time microclimate

Irrigation induced a small night-time warming effect due to increased soil heat storage during the day and the subsequent release at night. The 4-mm daily irrigation increased night-time mean UTCI by 0.5 °C, which is unlikely to cause any change in thermal stress because it takes at least a 6 °C change in UTCI in order to shift thermal stress by one level on UTCI's 10-level thermal stress classification scale (Bröde et al., 2012). Despite the night-time warming, irrigation reduced daily mean air temperature. The impacts of irrigation on night-time temperatures are not as clear as on daytime (Cheung et al., 2022). Some modelling studies reported a night-time cooling effect (Gao et al., 2020; Sorooshian et al., 2011), while others reported a night-time warming effect (Kanamaru and Kanamitsu, 2008; Vahmani and Ban-Weiss, 2016). Kanamaru and Kanamitsu (2008) predicted that irrigation in the California Central Valley, USA, will increase night-time minimal air temperature by 2.1 °C, but irrigation has no impact on daily mean air temperature. They attributed night-time warming to the increased thermal conductivity in wet soil. Vahamani and Ban-Weiss (2016) predicted irrigation in Los Angeles, USA, will increase night-time minimum air temperature by 2.1 °C and daily mean air temperature by 0.9 °C. Similarly, they attributed the warming to increased heat flux into the soil. In an experimental study in Nebraska, USA, irrigating maize reduced night-time minimum air temperature by approximately 0.5 °C whereas irrigating soybean had mixed impacts on it (Chen et al., 2018). Vegetation type is likely to influence the impacts of irrigation on daytime and night-time microclimate but few studies have directly compared the responses of different types of vegetation to irrigation.

4.3. Impacts of irrigation on latent and sensible heat fluxes

The daytime latent heat flux of the irrigated plots was not significantly different from the unirrigated plot, except for the 2-mm plot. This finding was somewhat inconsistent with the cooling effects observed in the irrigated plots. The Bowen ratio-energy balance method has been successfully used to monitor the latent heat flux and sensible heat flux of contrasting landscapes (Cellier and Olioso,

1993) or a single landscape (Todd et al., 2000). Since the microclimatic differences between the irrigated and the unirrigated plots were somewhat small, the differences in latent heat flux and sensible heat flux were likely to be small too. In fact, the daytime and night-time differences in latent heat flux and sensible heat flux between the irrigated and the unirrigated plots were mostly not significant. As the measurement error of the instruments can accumulate, propagate and enlarge through the calculation procedures, the Bowen ratio-energy balance method may not be accurate enough to differentiate the small differences in heat fluxes between the sites in this experiment. However, this method could capture the sharp increase in latent heat flux and the concurrent sharp reduction in sensible heat flux in a short period after irrigation (Fig. 10).

4.4. Irrigation as an urban cooling strategy

Rainwater collection and grey-water recycling systems have become more readily available as part of water-sensitive urban design in old and new residential development in Australia and other parts of the world (Cook et al., 2018). They can provide a sustainable water source to support active irrigation for urban cooling in private green spaces. Under the simulated backyard conditions in this field study, irrigation effectively reduces daytime air temperature. Since the frequency with which outdoor spaces are used or visited depends upon the microclimate of that space (Cheung and Jim, 2018; Lin et al., 2013), daytime irrigation can encourage the use of backyards. In principle, irrigation can also increase the evapotranspiration and cooling effect of other vegetated areas such as lawns in public green spaces and treed street canyons. Irrigation has the potential to cool these urban environments and encourage their use. The 0.6 °C reduction in daytime mean air temperature from turf irrigation (cf. section 3.3.1) is a significant reduction for Melbourne compared to other cooling strategies such as tree planting. Daytime air temperature in a treed street canyon in Melbourne was only 0.2 °C lower than an open street canyon (Coutts et al., 2016). In another observational study, the daytime mean air temperature directly below a tree was 0.7–1.5 °C lower than that without tree shade (Sanusi et al., 2017). However, it is difficult to predict the cooling magnitude of irrigating other vegetation in public green spaces and street canyons because the cooling magnitude is dependent upon plant phenology such as microclimatic conditions (Cheung et al., 2022), height and leaf area index (Chen et al., 2018), wind speed (Lam et al., 2020) and soil types (Kanamaru and Kanamitsu, 2008). More studies are needed to assess the cooling potentials of irrigation in different urban environments with different vegetation types.

Although irrigation significantly reduced UTCI by 0.4 °C in the 4-mm plot, the reduction was marginal in terms of thermal stress, because it takes a 6 °C reduction to reduce heat stress by one level on UTCI's 10-level thermal stress classification scale (Bröde et al., 2012). Mean radiant temperature and incoming shortwave radiation are usually the most important climate variables influencing UTCI in the outdoor environment (Krüger et al., 2014). Irrigation has minimal impacts on UTCI because our experiment showed that it cannot reduce mean radiant temperature and incoming shortwave radiation (Fig. 4). Tree shade remains critically important for improving outdoor thermal comfort, particularly for trees with a high plant area index (de Abreu-Harbich et al., 2015). Urban trees may lose up to half of their leaves during heatwaves, thus undermining their cooling effects (Sanusi and Livesley, 2020). The foliage loss is likely due to high air temperature and aggravated by low soil moisture content (Tyree et al., 1993). Although irrigation cannot directly reduce incoming shortwave radiation, it may help alleviate water stress in urban trees and increase their foliage density. More research is needed to examine the interaction between irrigation and the cooling effects of trees.

Identifying the optimal daily irrigation amount that maximises the cooling effect is one of the key questions regarding the use of irrigation for urban cooling. As mentioned in section 4.1, when the soil is at field capacity, evapotranspiration and the associated cooling effect will reach their maximum level. Further increase in daily irrigation will not strengthen the cooling effect because evapotranspiration will be limited by atmospheric demand but not soil moisture availability. For cities with a warm and dry climate and assuming that the soil moisture content is at field capacity, the optimal daily irrigation amount that maximises the cooling effect will be the amount that fully compensates the evapotranspiration extraction in the previous day. Evapotranspiration rate can be estimated using the FAO Penman-Monteith equation with the measurements of several climate variables (Allen et al., 1998). The maximum daily effect from turf irrigation in Melbourne is approximately 0.2 °C (Table 3), whereas daytime mean cooling may be up to 0.8 °C (Fig. 6c). These irrigation cooling potentials are likely to increase if the climate becomes warmer and drier in the future. Since evapotranspiration is highly dependent on background climate conditions (Seneviratne et al., 2010), the results of this study are only representative of Melbourne and regions with similar summer climate conditions. A systematic review suggested that the magnitude of irrigation cooling effect is positively correlated with mean air temperature and negatively correlated with rainfall (Cheung et al., 2021), meaning that irrigation will induce a stronger cooling effect in warmer and drier regions. The optimal daily irrigation amount is likely to vary with background climate conditions but maintaining soil moisture content at field capacity remains the key to maximise irrigation cooling effect while minimising water consumption.

4.5. Suggestions for future studies

From a broader perspective, more experimental and observational studies are required to gather empirical data about the microclimate impacts of irrigating vegetation because much of the current understanding comes from modelling studies (Cheung et al., 2022). The empirical data can serve two major purposes. First, they can provide a quick and realistic assessment of the potential cooling effect from irrigation for a specific location. Since background climate can strongly influence the strength of irrigation cooling effect (Cheung et al., 2021; Thiery et al., 2017), the findings from this study are only applicable to regions with a similar climate to Melbourne. Second, the empirical data is important for validating and improving mechanistic models. As we have mentioned in section 4.1, some of the model predictions for irrigation cooling effect are not in line with our measurements. Comprehensive microclimate and soil moisture and thermal data are required to identify the specific processes and parameters that need to be improved in urban climate models.

From the perspective of using irrigation to cool green spaces, more studies are required to understand the impacts of vegetation response from irrigation, irrigation time of day and daily irrigation amount on the strength of the cooling effect. Since irrigation may promote the growth of vegetation, it may create a synergistic cooling effect with the vegetation from the extra shading and increased transpiration due to the increase in leaf area index. The interaction between irrigation and plant growth is poorly represented in computer models (Ozdogan et al., 2010) and has rarely been examined in empirical studies. Irrigation time of day can directly impact the cooling benefits experienced by the green space users because the cooling effect will be the strongest immediately after irrigation (Fig. 4). More studies are needed to examine how irrigation time of day changes the daytime mean and instantaneous cooling effects of irrigation. In this study, we estimate that the daytime mean cooling effect in Melbourne can strengthen as daily irrigation amount increases from 2 to 4 mm. However, this range is likely to vary between climate regions and seasons. Climate-specific studies are required to provide guidance for optimising irrigation amount in different regions.

5. Conclusions

This study measured the impacts of turf irrigation on daytime and night-time microclimate and surface energy balance in a backyard environment during summer in Melbourne. Under the warm summer climatic conditions of Melbourne and in a backyard environment, turf irrigation (> 2 mm/day) can induce a strong daytime cooling effect in soil temperature, turf surface temperature and air temperature, but it cannot significantly reduce daytime human thermal stress (Hypothesis (i) is partially accepted). The increase in daily irrigation amounts from 2, 4 to 7 mm did not induce a stronger cooling effect because a large rainfall event eliminated the differences in soil moisture content between these three treatments (Hypothesis (ii) could not be tested properly). The strength of the daytime cooling effect is highly correlated with the difference in soil moisture content between the irrigated and the unirrigated spaces (Hypothesis (iii) is accepted).

Turf irrigation (>2 mm/day) can induce a weak night-time warming effect in soil temperature and turf surface temperature, but the impacts on night-time air temperature and human thermal stress were minimal (Hypothesis (iv) is partially accepted). The increase in daily irrigation amounts did not have an impact on night-time warming effect for the same above-mentioned reason (Hypothesis (v) could not be tested properly). The difference in night-time soil heat flux between the irrigated and the unirrigated plots was significantly and positively correlated with the warming effects (Hypothesis (vi) is accepted). There were no significant differences in daytime and nigh-time latent and sensible heat fluxes between the irrigated and unirrigated plots (Hypothesis (vii) is partially accepted).

Author contributions

Pui Kwan Cheung: Conceptualisation, Methodology, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualisation. **CY Jim:** Resources, Writing – Review & Editing, Funding acquisition. **Nigel Tapper:** Resources, Writing – Review & Editing, Funding acquisition. **Kerry Nice:** Conceptualisation, Writing – Review & Editing, Supervision. **Stephen Livesley:** Conceptualisation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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