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PAPER

Irrigating urban green space for cooling benefits: the mechanisms and management considerations

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Abstract

Evapotranspiration is an important cooling mechanism in urban green space (UGS). Irrigating vegetated surfaces with potable water, collected stormwater or recycled sewage water has the potential to increase the cooling effect of UGS by increasing evapotranspiration. Such cooling effect may not always be strong because evapotranspiration is dependent on local and regional factors such as background climate, seasonality and vegetation type. When using irrigation for cooling, city managers also need to consider management issues such as irrigation water supply and amenity use of the UGS. This study aims to develop a theoretical framework that explains the physical and energetic mechanisms of irrigation cooling effect and a framework to assist city managers to make decision about the use of irrigation for urban cooling. This is achieved by reviewing the impacts of irrigation on local climate reported in the literature and identifying the regional and local factors that influence irrigation cooling effect in warm seasons. The literature suggests that irrigation can potentially reduce daily maximum air temperature and ground surface temperature by approximately 2.5 °C and 4.9 °C, respectively, depending on weather conditions and irrigation amount. Background climate is an important factor that influences the cooling potentials of irrigation. Cities with dry and warm climates have the highest cooling potentials from irrigation. The cooling potentials are also influenced by seasonality and weather, vegetation type, irrigation time of day and irrigation amount. Cities with a dry and warm season can consider using irrigation to mitigate urban heat within UGS because such climatic conditions can increase cooling potentials. To maximise irrigation cooling effect, cities with abundant irrigation water supply can use a soil moisture-controlled irrigation regime while those with limited supply can use a temperature-controlled regime. More studies are required to understand the cooling potentials of irrigating small, individual UGS.

1. Introduction

Urban green space (UGS) is an important landscape in cities because it offers a variety of ecosystem services (Derkzen *et al* 2015, Livesley *et al* 2016). One of the key ecosystem services that UGS provides is cooling effect in warm seasons (Masoudi *et al* 2021). A systematic review study has shown that UGS is, on average, 0.94 °C cooler in air temperature than its surrounding areas (Bowler *et al* 2010). Shading and increased evapotranspiration are the two main cooling mechanisms of the vegetation in UGS (Oke *et al* 1989, Tan *et al* 2018). The vegetation canopy in UGS, particularly trees, is effective in reducing the amount of solar radiation reaching the ground surface (Konarska *et al* 2014), and thereby reducing the air temperature within the UGS (Cheung and Jim 2018). Evapotranspirative cooling is also enhanced in UGS because of the presence of vegetation (Qiu *et al* 2017) and the increase in infiltration and soil moisture storage from rainfall (Yang *et al* 2015, Yao *et al* 2015).

There are many factors that can influence the cooling potentials of UGS, such as its size, shape, vegetation composition, fraction of impervious surface and whether it is irrigated. The cooling potential of UGS generally increases with its size (Chang *et al* 2007, Cheung and Jim 2019a) and its irregularity in shape (Shih 2017, Shah *et al* 2021). Tree and shrub covers have higher cooling potentials than grass cover (Cheung and Jim 2019b). A lower fraction of impervious surface is also conducive to higher cooling potentials of UGS (Qiu and Jia 2020). The impact of irrigation on the cooling potentials of UGS is under-researched, but the existing evidence shows that the irrigated part of a UGS tend to be cooler than the unirrigated part because the extra soil moisture supplied by irrigation can support a stronger evapotranspirative cooling effect (Spronken-Smith and Oke 1998). Irrigation thus offers an opportunity for unirrigated and under-irrigated UGS to increase their cooling potentials by increasing evapotranspiration.

The impact of irrigation on the microclimate of grass-covered areas in UGS is strong because evapotranspiration is the sole cooling mechanism in the absence of shading. Soil moisture status therefore has a direct impact on the microclimate because it supports evapotranspiration and the impact is particularly strong in the dry climate regions (Pearlmutter *et al* 2007). The daytime surface temperature of the irrigated grass-covered area in a park in Vancouver, Canada, was only 16 °C, whereas that of the unirrigated was 34 °C (Spronken-Smith and Oke 1998). Such cooling effect originates from the increase in latent heat flux and modifications of other surface energy fluxes and storage of the surface energy balance. Briefly, the addition of soil moisture through irrigation allows more available energy at the ground surface to be transformed into latent heat flux instead of sensible heat flux, causing a reduction in air temperature and ground surface temperature (Spronken-Smith *et al* 2000).

Irrigation has been principally used to support the growth and health of turfgrass in urban areas because the evapotranspiration from turfgrass in summer months often exceeds rainfall received (Nouri *et al* 2013, Litvak and Pataki 2016, Awal *et al* 2019). The growth of urban vegetation can be further hampered by insufficient soil volume and excessive pavement (Jim 2019), which limits their access to soil water. Therefore, irrigation is necessary to maintain a healthy and actively-transpiring layer of turfgrass. Moreover, other urban vegetation such as shrubs and trees may also need supplementary water irrigation to support their health (Connellan *et al* 2002), particularly during heatwaves. Urban trees may lose up to 50% of their leaves during heatwaves (Sanusi and Livesley 2020) due to high air temperature and low soil moisture content (Tyree *et al* 1993). The loss of leaves in trees significantly reduces their cooling effects through shading and evapotranspiration. Irrigation may help urban trees to retain their leaves during heatwaves and thus enhancing their shade and transpiration cooling effects.

UGS irrigation has been proposed as an urban cooling strategy (Coutts *et al* 2013, Daniel *et al* 2018, Livesley *et al* 2021). However, the physical and energetic mechanisms of such irrigation cooling effect have not been well-established with the support of the findings from the literature. It is important to develop a theoretical framework that provides the mechanistic basis of irrigation cooling effect by considering the storage and fluxes of the surface energy balance in order to justify the application of irrigation for urban cooling. Moreover, since irrigation cooling effect is dependent on evapotranspiration, its effectiveness is in turn dependent on other factors that influence evapotranspiration such as background climate, seasonality, vegetation type, irrigation time of day and soil moisture achieved (irrigation amount). It is necessary to consider these factors when making a decision about using UGS irrigation to mitigate urban heat in cities around the world. Decisions regarding UGS irrigation should also consider issues such as irrigation water supply and UGS characteristics such as soil properties, ecological values and amenity use.

This study aims to develop a theoretical framework that explains the physical and energetic mechanism of irrigation cooling effect, and a decision framework that assists city managers to make decision about the use of irrigation for urban cooling. This is achieved by reviewing the impacts of irrigation on climate and surface energy balance reported in the literature and identifying the regional and local factors that influence irrigation cooling effect in warm seasons. A comprehensive literature review was conducted to search for studies that can support the above-mentioned study aims. We began the search on Google Scholar (2020) using the Boolean search terms: ('watering' OR 'irrigation') AND ('effect' OR 'impact') AND ('air temperature'). We screened the titles and abstracts of the first 1000 results sorted by relevance. Only peer-reviewed journal articles written in English language were included in this study. We identified 41 studies that provided relevant evidence to support the study aims (tables 1 and 2). The selection criteria were that the study has reported the mean impacts of irrigation on air temperature over the study period and investigated the impacts of at least one of the regional and local factors that influences irrigation cooling effect, namely background climate, seasonality, weather, vegetation type, irrigation time of day and daily irrigation amounts (table 2). Section 2 will review the impacts of irrigation on soil moisture content, surface

Table 1. List of studies that reported the impacts of irrigation on daily mean soil moisture content, surface energy fluxes and local climate.

Variable	Impact	References
Soil moisture content	+	(Kanamaru and Kanamitsu 2008, Lobell *et al* 2009, Harding and Snyder 2012, Zou *et al* 2014, Yang and Wang 2015, Yang *et al* 2016, Gao and Santamouris 2019)
Soil heat flux (into soil)	+	(Kanamaru and Kanamitsu 2008, Vahmani and Ban-Weiss 2016, Yang *et al* 2016, Wang *et al* 2019)
	Not specified	(Ozdogan *et al* 2010, Huber *et al* 2014, Chen *et al* 2017)
Latent heat flux and sensible heat flux	+	(Adegoke *et al* 2003, Sacks *et al* 2009, Lobell *et al* 2009, Ozdogan *et al* 2010, Harding and Snyder 2012, Huber *et al* 2014, Zou *et al* 2014, Cook *et al* 2015, Vahmani and Hogue 2015, Yang *et al* 2016, Thiery *et al* 2017, Chen *et al* 2017, 2018, Broadbent *et al* 2018, Daniel *et al* 2018, Sugimoto *et al* 2019, Wang *et al* 2019, Gao *et al* 2020)
Ground surface temperature	−	(Boucher *et al* 2004, Yang and Wang 2015, Vahmani and Ban-Weiss 2016, Thiery *et al* 2017, Wang *et al* 2019, Gao *et al* 2020)
Air temperature	+	(Vahmani and Ban-Weiss 2016)
	−	(Geerts 2002, Adegoke *et al* 2003, Sacks *et al* 2009, Lobell *et al* 2009, Puma and Cook 2010, Sorooshian *et al* 2011, Wen and Jin 2012, Harding and Snyder 2012, Zou *et al* 2014, Huber *et al* 2014, Cook *et al* 2015, Hancock *et al* 2015, Yang and Wang 2015, Yang *et al* 2016, Yang *et al* 2017, Thiery *et al* 2017, Chen *et al* 2018, Broadbent *et al* 2018, 2019, Wang *et al* 2019, Gao *et al* 2020, Valmassoi *et al* 2020)
	No change	(Kanamaru and Kanamitsu 2008, Chen *et al* 2017)
Vapour pressure	+	(Geerts 2002, Boucher *et al* 2004, Sorooshian *et al* 2011, Huber *et al* 2014, Yang *et al* 2017, Chen *et al* 2018)
Human thermal stress	−	(Shashua-Bar *et al* 2009, Yang and Wang 2015, Broadbent *et al* 2018)

energy fluxes (soil heat flux (G), latent heat flux (Q_E) and sensible heat flux (Q_H)) and local climate (ground surface temperature (T_{sfc}), air temperature (T_a), vapour pressure (VP) and human thermal stress). Section 4 will discuss the regional and local factors that influence the cooling effect of irrigation. Five key factors were discussed, namely background climate, seasonality and weather, vegetation type, irrigation time of day and daily irrigation amounts. The duration of cooling effect after irrigation will also be discussed. After understanding of the impacts of irrigation on local climate and the factors that influence those impacts, section 5 will develop a decision framework to assist city managers to decide whether or not to use UGS irrigation as an urban cooling strategy.

2. Impacts of irrigation on soil moisture content, surface energy fluxes and local climate

This section will review the impacts of irrigation on soil moisture, three surface energy fluxes (G, Q_E and Q_H), three climate variables (T_{sfc}, T_a and VP) and human thermal stress (table 1). Understanding the impacts of irrigation on these variables are necessary for the development of the theoretical framework of irrigation cooling effect in section 3. Unless specified, we report the mean changes in these eight variables over the summer (northern hemisphere: June–August (JJA); southern hemisphere: December–February (DJF)) because the findings are most relevant to UGS irrigation in summer when cooling effect is needed most.

2.1. Soil moisture content

Lobell *et al* (2009) modelled the impacts of irrigation on climate in eight major irrigated regions in the world using the Community Atmosphere Model 3.3. They set the soil moisture to 40% (fraction of saturation point) every half an hour if the soil moisture dropped below 40%. The soil moisture in all eight regions increased except northeast China, which had a high initial soil moisture. The increase in soil moisture varied between 2.3% (fraction of saturation point) in Indo-Gangetic Plains to 20.7% (fraction of saturation point) in Aral Sea Basin. The differences reflected the variations in soil type and rainfall regime (consequently initial soil moisture) between the regions; a more significant change was detected in drier regions. Yang and Wang (2015) modelled the impact of irrigation on the climate in mesic residential landscapes in Phoenix, USA. They applied 1.4 mm of irrigation to the top soil layer whenever the soil moisture dropped below 24% (v/v). The mean soil moisture increased from 10.7% (v/v) without irrigation to 27.6% (v/v) with irrigation. Other modelling studies have also predicted an increase in mean soil moisture with irrigation, ranging from 1.4% (v/v) (Harding and Snyder 2012, Zou *et al* 2014), 11.1% (v/v) (Kanamaru and Kanamitsu 2008) to 17.1% (v/v) (Gao *et al* 2020). None of the four observational or experimental studies identified in this review has

Table 2. List of studies that modelled or measured the impacts of a regional or local factor on irrigation cooling effect.

Factor	Irrigation cooling effect	References
Background climate	Stronger in warm and dry regions	(Kueppers *et al* 2007, Sacks *et al* 2009, Lobell *et al* 2009, Ozdogan *et al* 2010, Puma and Cook 2010, Cook *et al* 2015, Thiery *et al* 2017, Wang *et al* 2019, Gao *et al* 2020, Li *et al* 2020, Cheung *et al* 2021)
Seasonality and weather	Stronger in warm and dry seasons	(Geerts 2002, Kueppers *et al* 2007, Bonfils and Lobell 2007, Lobell and Bonfils 2008, Lobell *et al* 2009, Ozdogan *et al* 2010, Puma and Cook 2010, Zou *et al* 2014, Yang and Wang 2015, Cook *et al* 2015, Yang *et al* 2016, Thiery *et al* 2017, Chen *et al* 2018, Nocco *et al* 2019, Wang *et al* 2019, Li *et al* 2020, Thiery *et al* 2020)
	Stronger during heatwaves	(Gao *et al* 2020, Lam *et al* 2020)
Vegetation type	Stronger in maize than soybean	(Chen *et al* 2018)
	Stronger in densely vegetated areas	(Lam *et al* 2020)
	Stronger when vegetation types are not classified in detail	(Ozdogan *et al* 2010)
	Stronger in trees than grass	(Shashua-Bar *et al* 2009)
Irrigation time of day	No significant impact	(Yang and Wang 2015, Broadbent *et al* 2018, Gao *et al* 2020)
	Stronger when irrigation is frequent enough to replenish soil moisture such that evapotranspiration is not limited by soil moisture	(Lobell *et al* 2009, Puma and Cook 2010)
	Significantly stronger when irrigated at noon than at night	(Sacks *et al* 2009)
	Highly variable	(Valmassoi *et al* 2020)
Daily irrigation amount	Stronger when irrigates more but the relationship is not explicitly examined	(Kanamaru and Kanamitsu 2008, Sorooshian *et al* 2011, Zou *et al* 2014, Daniel *et al* 2018, Nocco *et al* 2019)
	Stronger when irrigates more but additional cooling diminishes as daily irrigation amount increases	(Gober *et al* 2010, Broadbent *et al* 2018)
	Stronger when irrigates more but limited by atmospheric demand	(Lobell *et al* 2009, Wang *et al* 2019)
Duration of cooling after irrigation	A few hours	(Lam *et al* 2020)
	A few days	(Chen *et al* 2018)
	A few months	(Sorooshian *et al* 2011, Yang *et al* 2016)

Note: not all reviewed studies are discussed in the text due to word limit.

reported the impacts of irrigation on soil moisture. It is difficult to make a meaningful comparison between studies because changes in soil moisture from irrigation is dependent on multiple factors, such as the interception loss from the vegetation canopy (in the case of sprinkler irrigation), soil type, initial soil moisture, atmospheric demand for evapotranspiration and irrigation amount. The differences in the impact of irrigation upon soil moisture reflect the variation in soil moisture conditions before irrigation, and unsurprisingly there are more significant changes (increase) in soil moisture in drier regions. This is very much related to the underlying soil type of a location and local rainfall inputs and potential evaporative outputs.

2.2. Soil heat flux (G)

All reviewed studies reported a net storage of heat into the ground, i.e. a positive G (Kanamaru and Kanamitsu 2008, Vahmani and Ban-Weiss 2016, Yang *et al* 2016 and Wang *et al* 2019). The common findings of these studies were that irrigation did not reverse the direction of mean G over the study period and the changes in magnitude were usually small (<5 W m^{-2}). However, it is still helpful to analyse the impacts of irrigation separately on daytime and night-time G, as measures of daily mean G can hide significant and dynamic changes in the diurnal pattern of G. In two modelling studies (Kanamaru and Kanamitsu 2008, Vahmani and Ban-Weiss 2016), it was predicted that irrigation would increase soil thermal conductivity because of an increase in soil moisture, which thereby would increase storage (positive G) during the day and subsequent release (negative G) of that heat at night. Vahmani and Ban-Weiss (2016) also predicted from their model that this would lead to a significant increase in night-time T_a, resulting in a net increase in daily mean T_a despite the important reduction in daytime T_a. Kanamaru and Kanamitsu (2008) also predicted from their modelling a similar diurnal variation in G, but they predicted a small reduction in daily mean T_a.

The uncertainties in the predictions of G were attributed to the lack of detailed observational data regarding the response of soil thermal conductivity to the changes in soil moisture from irrigation (Kanamaru and Kanamitsu 2008).

2.3. Latent heat flux (Q_E) and sensible heat flux (Q_H)

There is a general consensus in the literature that irrigating vegetated surfaces can lead to an increase in Q_E and a concurrent reduction in Q_H. Using the Regional Atmospheric Modelling System, Adegoke *et al* (2003) simulated the effect of irrigation in Nebraska, USA, by keeping the upper 0.2 m of soil saturated. They estimated that mean Q_E would increase from 74.5 to 98.2 W m^{-2}, while Q_H would decrease from 86.9 to 79.8 W m^{-2}. Chen *et al* (2017) initiated irrigation in their modelling study only when the root-zone soil moisture availability dropped below 50% during the growing season. The root-zone soil moisture availability was defined as the ratio of the difference between the current root-zone soil moisture and the wilting point and the difference between field capacity and wilting point. Simulated irrigation led to a daily mean increase in Q_E of 2.4 W m^{-2} and a reduction in Q_H of 2.1 W m^{-2}. Broadbent *et al* (2018) studied a range of daily irrigation amounts from 5 up to 30 mm in their modelling study in a North Adelaide suburb. At 3 pm local time, the model predicted that with daily irrigation of 30 mm all the available energy was consumed in evapotranspiration ($Q^* = Q_E$) because of the nearly unlimited soil moisture supply. This evaporation from the land surface caused the T_{sfc} to drop below the T_a, resulting in a negative Q_H (-40 W m^{-2}).

This shift in the partitioning of surface energy fluxes is confirmed by a 12year experimental study, which measured Q_E and Q_H over maize-soybean rotation fields using eddy-covariance flux tower systems in Nebraska, USA (Chen *et al* 2018). They measured a mean increase in Q_E in irrigated maize fields of approximately 20 W m^{-2} and a reduction in Q_H of 25 W m^{-2}. However, the changes in the partitioning of surface energy fluxes were more subdued in the soybean fields. As such, the measured cooling effect in terms of T_a was greater in the irrigated maize fields than in the irrigated soybean fields. This comparison between maize and soybean suggests that vegetation type has an important impact on surface energy balance and the cooling effect of irrigation.

2.4. Ground surface temperature (T_{sfc})

Most modelling studies predicted a reduction in daily mean T_{sfc} with irrigation. Vahmani and Ban-Weiss (2016) modelled the climate impacts of irrigating xeric landscapes in Los Angeles, USA. Although they predicted an increase in daily mean T_a with irrigation, because of the increased release of soil heat storage at night, their model predicted a small reduction (0.2 °C) in mean T_{sfc}. Kanamaru and Kanamitsu (2008) modelled the hourly differences in T_{sfc} between the irrigated and unirrigated crops in the California Central Valley, USA and noted that irrigation decreased the daily maximum T_{sfc} by 5.1 °C at 3 pm, but increased the daily minimum T_{sfc} by 3.1 °C at 5 am. A small daily mean reduction in T_{sfc} (0.5 °C) was achieved despite the irrigation causing an extended warming period (8 pm–6 am). Using an urban canopy model, Yang and Wang (2015) predicted a decrease of 4.6 °C in the T_{sfc} of a mesic residential landscape in Phoenix, USA when applying a daily irrigation amount of 1.4 mm. Other regional modelling studies, using the Weather Research and Forecasting model, predicted that irrigation would lead to a reduction in mean daily T_{sfc} of between 1 °C and 2 °C (Wang *et al* 2019, Gao *et al* 2020). Irrigation is likely to reduce daily mean and daytime T_{sfc} although night-time T_{sfc} may increase due to the increased soil heat storage during the day and subsequent release at night.

2.5. Air temperature (T_a)

In terms of daily mean T_a, the vast majority of studies reported a cooling effect from irrigating vegetated surfaces. Broadbent *et al* (2018) modelled an increase in cooling effect from -0.5 °C for 5 mm d^{-1} of irrigation to -2.3 °C for 30 mm d^{-1} during a heatwave in Mawson Lake, North Adelaide, Australia. There was a diminishing cooling efficiency as the daily irrigation amount increased because the surface soil became saturated and the evapotranspiration rate was limited by the atmospheric demand. Chen *et al* (2018) measured the cooling effect from irrigating a soybean field and from a maize field in Nebraska, USA. The cooling effect was much higher in the maize field (-0.43 °C) than the soybean field (-0.09 °C); the difference was confirmed by the contrast in surface energy fluxes between the two crops (see section 4.3). The authors explained the stronger cooling effect of the maize field by crop phenology such as plant height and leaf area index). In a recent observational study, the irrigation cooling effect measured in two urban parks in Melbourne, Australia was -2 °C to -1 °C during a non-heatwave period, and the effect strengthened to -4 °C to -2 °C during the heatwave period (Lam *et al* 2020).

Vahmani and Ban-Weiss (2016) used the Weather and Regional Forecasting model to predict that irrigation would lead to an increase in the daily mean T_a because of increased soil heat storage during the day; the storage would release at night, offsetting the smaller cooling benefit by day. Several other modelling studies have similarly predicted an increase in the daily minimum T_a, again as a result of stored heat releasing at night (Kanamaru and Kanamitsu 2008, Broadbent *et al* 2018, Valmassoi *et al* 2020). However, not all modelling studies have reported a night-time warming in response to irrigation (Sorooshian *et al* 2011, Gao *et al* 2020).

The impact of irrigation on the daily maximum T_a is more consistent amongst modelling studies as most of them have predicted a reduction in the daily maximum T_a with irrigation (Kanamaru and Kanamitsu 2008, Sorooshian *et al* 2011, Gao *et al* 2020). The reduction in the daily maximum T_a seems to be associated with the magnitude of the daily maximum T_a. For example, Gao *et al* (2020) predicted a small reduction of 0.4 °C when the maximum T_a in the unirrigated scenario was 27.9 °C, whereas Kanamaru and Kanamitsu (2008) modelled a larger reduction of 2.1 °C when the maximum T_a was 34.6 °C, and Sorooshian *et al* (2011) modelled a 5.1 °C reduction from irrigation when the maximum T_a was 38.0 °C. Weather conditions are clearly an important factor in determining the strength of the cooling effect from irrigation (see detailed discussion in section 4.2).

2.6. Vapour pressure (VP) or humidity

As expected, research literature unanimously indicates there will be an increase in VP or other air humidity indices with irrigation. A controlled experiment in maize-soybean rotation fields in Nebraska, USA, measured irrigation increased the mean mixing ratio by 0.52 g kg^{-1} (∼4%) over a 12 years study period (Chen *et al* 2018). Geerts (2002) compared specific air humidity inside and outside of the Murrumbidgee–Coeambally–Murray irrigation area in Australia using historic data (1968–1996) from 28 weather stations. They observed that irrigation increased the mean specific humidity inside the irrigated areas by 0.9 g kg^{-1}. Similar humidity increases were predicted in other agricultural modelling studies (Sorooshian *et al* 2011, Yang *et al* 2017). For example, Harding and Snyder (2012) modelled the impacts of irrigation on climate in the Great Plains, USA by keeping soil moisture in the top 2 m at saturation. They predicted a 0.19 g kg^{-1} (∼2%) rise in mixing ratio over the irrigated area.

2.7. Human thermal stress

Only a few studies have considered the impact of irrigation on human thermal stress. Broadbent *et al* (2018) modelled the impact of irrigation on human thermal stress in North Adelaide, Australia using the humidex index. Humidex integrates the effect of T_a and VP on human thermal stress into a single index. It is the dry T_a (with a negligible moisture content) at which its corresponding thermal stress level equates to that of a given combination of T_a and VP (Masterton and Richardson 1979). The 'comfortable' Humidex range is between 20 °C and 29 °C, while the 'varying degrees of discomfort' range is between 30 °C and 39 °C. Their model predicted that irrigation reduced Humidex from 36.9 °C to 34.6 °C at 3 pm for a daily irrigation amount of 20 mm, suggesting a mitigation of heat stress on humans. They noted that the background humidity in North Adelaide was so low that the rise in humidity from irrigation would barely increase human heat stress. Yang and Wang (2015) modelled the impacts of irrigation on human thermal stress using the Index of Thermal Stress. The Index of Thermal Stress measures the rate of heat dissipation that the human body needs to achieve through sweating in order to maintain thermal equilibrium with the surrounding environment (Givoni 1963). An Index of Thermal Stress above 400 W indicates a 'very hot' condition. They modelled that irrigation reduced the Index of Thermal Stress in all but one month of the year, and the greatest thermal stress reduction would be 32.5 W in June. In a field experiment, Shashua-Bar *et al* (2011) measured the Index of Thermal Stress in an exposed area with irrigated grass to that in an exposed area with bare soil. The irrigation kept the thermal stress level in the lawn at 'warm' for most of the day, whereas the 'hot' and 'very hot' levels persisted in the area with bare soil. However, this comparison did not only reflect the impact of irrigation because the surface type and albedo of the two sites were different.

3. Mechanisms of irrigation cooling effect

In this section, we develop a theoretical framework to explain the physical and energetic mechanisms of irrigation cooling effect with the support of the findings in the previous section.

3.1. Surface energy balance

UGS irrigation has the potential to induce a cooling effect by modifying the urban surface energy balance. Assuming that the net horizontal advective heat flux and the anthropogenic heat flux are negligible, the urban surface energy balance (all in W m^{-2}) for a grass-covered surface can be expressed as:

$$Q^* = Q_E + Q_H + \Delta Q_S \qquad (1)$$

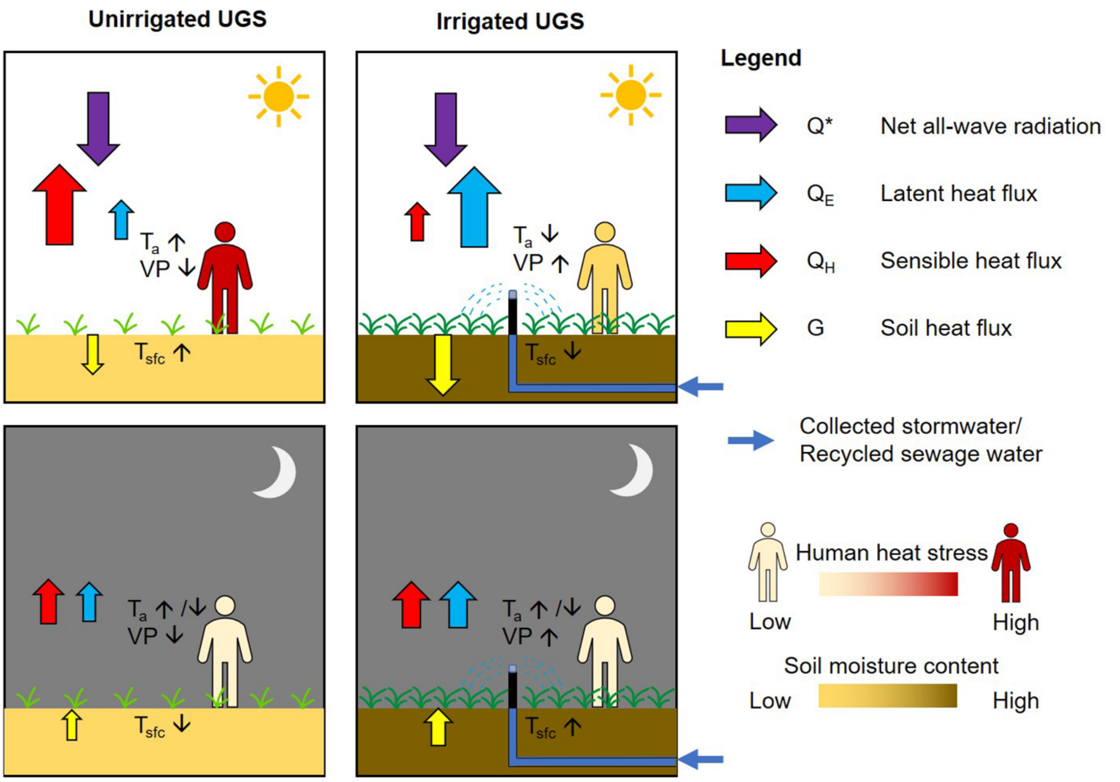

Figure 1. A theoretical framework that explains the cooling mechanism of UGS irrigation based on the differences in surface energy fluxes between an unirrigated and an irrigated UGS in the daytime and night-time in summer. The direction and relative strength of the energy fluxes are indicated by the coloured arrows. The black upward and downward arrows for the climate variables compare the magnitudes of the variables between the irrigated and unirrigated UGS at the same time of the day. In the daytime, UGS irrigation increases soil moisture content and evapotranspiration, which promotes latent heat flux (Q_E) and reduces sensible heat flux (Q_H). This in turn reduces air temperature (T_a), ground surface temperature (T_{sfc}) and human heat stress. The wetter soil in the irrigated UGS increases the downward soil heat flux (G) and soil heat storage. The increased evapotranspiration raises VP, offsetting part of the cooling benefit. However, a net reduction in human heat stress is expected. In the night-time, the higher soil moisture content in the irrigated UGS increases Q_E. The increased soil heat storage in the irrigated UGS increases upward G and T_{sfc}, which raises Q_H. The resultant impacts of irrigation on night-time T_a and human thermal stress are unclear because the increased Q_E tends to reduce T_a and thermal stress while the increased G and Q_H tend to increase them.

where Q^* is the net all-wave radiation, Q_E the latent heat flux, Q_H the sensible heat flux and ΔQ_S the net storage heat flux (Oke 1988). The partitioning of Q^* into Q_E, Q_H and ΔQ_S is primarily dependent on surface type and soil moisture status (Williams and Torn 2015). In the case of grass, soil moisture becomes the sole factor in the partitioning.

The theoretical cooling mechanism of UGS irrigation is depicted in figure 1. The figure describes the differences in soil moisture, surface energy fluxes and some climate variables between an unirrigated and an irrigated UGS in the daytime and night-time in summer. In the daytime, irrigation increases soil moisture and promotes evapotranspiration in the irrigated UGS (Chen *et al* 2018). More energy is converted to Q_E and less to Q_H, resulting in a lower (T_a, T_{sfc} and human thermal stress (Broadbent *et al* 2018). Downward G may slightly increase because a higher soil moisture is associated with a higher soil thermal conductivity, which increases the heat conduction into the soil (Kanamaru and Kanamitsu 2008). However, G is usually one order of magnitude smaller than Q_E and Q_H during the day (Spronken-Smith *et al* 2000), making it less influential on the daytime T_a. Direct evaporation of water from the soil surface increases, leading to a lower T_{sfc} (Lobell *et al* 2009). Irrigation may also support a lusher growth of grass, which further promotes Q_E through transpiration (Valmassoi *et al* 2020). The enhanced evapotranspiration from the irrigated surface also raises VP (Sorooshian *et al* 2011). In contrast, the unirrigated UGS lacks evapotranspiration and Q_E, causing a higher Q_H (Chen *et al* 2018). The resultant effects are a higher T_a and T_{sfc}, but a lower VP (Gao *et al* 2020). In the night-time, Q_E and VP remain higher in the irrigated UGS than the unirrigated UGS because of the higher soil moisture (Valmassoi *et al* 2020). The increased soil heat storage in the irrigated UGS from the daytime promotes the upward G at night, leading to a higher T_{sfc} and Q_H (Vahmani and Ban-Weiss 2016). However, it is unclear whether the night-time T_a and human thermal stress in the irrigated UGS are higher or lower than that in the unirrigated UGS because the increased Q_E tends to reduce T_a and thermal stress while the increased G and Q_H tend to increase them.

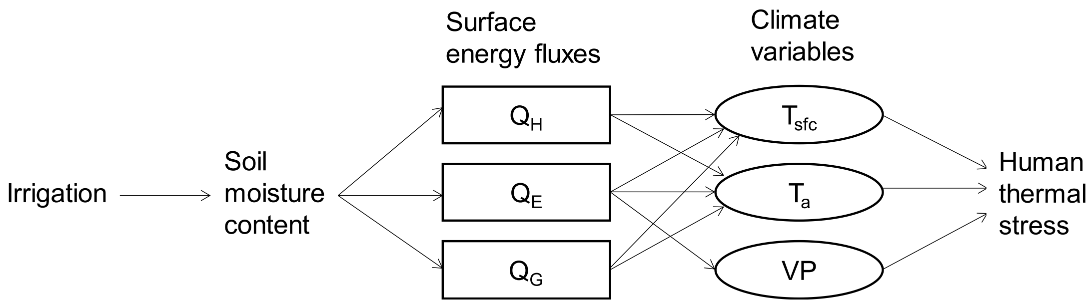

Figure 2. The sequence of the impacts of UGS irrigation. The impacts of irrigation begin with an increase in soil moisture content. The higher soil moisture modifies the partitioning of surface energy fluxes (sensible heat flux (Q_H), latent heat flux (Q_E) and soil heat flux (G)) by allowing more evapotranspiration. The increase in evapotranspiration generally leads to a smaller Q_H and a larger Q_E and G (see section 2 for details). The changes in the three energy fluxes are expected to lead to a cooling in ground surface temperature (T_{sfc}) and air temperature (T_a). The increased Q_E is also associated with a higher VP. Human thermal stress is eventually affected by the changes in T_{sfc}, T_a and VP.

3.2. Human thermal stress

In addition to metabolic rate and clothing insulation, human thermal stress is determined by four climate variables, namely T_a, VP, mean radiant temperature and wind speed (Fanger 1970, Höppe 1999, Bröde *et al* 2012). The theoretical cooling mechanism suggests that human thermal stress can be reduced by UGS irrigation (figure 2). The impacts of irrigation on human thermal stress begin with increasing soil moisture, which then modifies the partitioning of surface energy fluxes (Q_H, Q_E and G) by increasing evapotranspiration. The increased evapotranspiration is generally associated with a smaller Q_H and a larger Q_E and G. The changes in these three energy fluxes are expected induce a reduction in T_{sfc} and T_a. The larger Q_E also inevitably increases VP. Eventually, the changes in T_{sfc}, T_a and VP affect human thermal stress. The lower T_a directly reduces human thermal stress, while the lower T_{sfc} reduces the stress by reducing the mean radiant temperature. The enhanced evapotranspiration from irrigation can increase VP and offset part of the cooling benefit, but irrigation is likely to cause a net reduction in thermal stress (Broadbent *et al* 2018). Different human thermal indices have been developed to integrate the effects of some of the four essential climatic variables e.g. Humidex (Masterton and Richardson 1979), or all of them, e.g. Index of Thermal Stress (Givoni 1963) and Universal theraml climate index (UTCI) (Bröde *et al* 2012). The impacts of irrigation on human thermal stress are best assessed by these thermal indices.

4. Regional and local factors that influence irrigation cooling effect

This section will review the impacts of five regional and local factors on irrigation cooling effect in terms of air temperature. The five factors include background climate, seasonality and weather, vegetation type, irrigation time of day and daily irrigation amount(table 2). In addition, the duration of cooling after irrigation will be reviewed. These factors are pertinent to the development of the decision framework for using UGS irrigation for urban cooling
in section 5.

4.1. Background climate

Background climate is the average weather conditions of a specific region over multiple decades. Both global (Sacks *et al* 2009, Thiery *et al* 2017) and regional (Gao *et al* 2020) modelling studies have agreed that background T_a and rainfall are important factors that influence irrigation cooling effect. From their global modelling results, Sacks *et al* (2009) developed a simple linear relationship between irrigation cooling effect and daily irrigation amount separately for areas with a higher rainfall (>2.43 mm d^{-1}) and for those with a lower rainfall ($\leqslant$2.43 mm d^{-1}). They predicted that, for a 1 mm d^{-1} increase in irrigation, the additional cooling effect in the drier areas was −0.7 °C stronger than the wetter areas. Thiery *et al* (2017) modelled the irrigation cooling effect in seven heavily irrigated regions in the world. Given a similar irrigation amount, they predicted a mean cooling effect of <−1 °C in T_{sfc} in western North America and central North America in summer, and no cooling effect in Southeast Asia and East Asia. The main reason is that Western North America and central North America have a drier climate than Southeast Asia and East Asia. Irrigation in drier regions will induce a stronger evapotranspirative cooling effect because evapotranspiration is dependent on the availability of soil moisture (Koster *et al* 2006). A similar conclusion was drawn by a regional modelling study (Gao *et al* 2020), which predicted an increasing irrigation cooling effect from the coast towards the inland area in metropolitan Sydney, which coincided with the increasing background T_a gradient.

The quantitative relationship between irrigation cooling effect and background climate was established by a systematic review study (Cheung *et al* 2021). Cheung *et al* (2021) reviewed 17 studies that have reported the summertime mean irrigation cooling effect. They established a multiple linear regression model to predict irrigation cooling effect by background climate variables, namely T_a, rainfall, specific humidity, wind speed and net radiation. Only T_a and rainfall were the statistically significant variables that remained in the regression model after a stepwise elimination procedure. The model predicted that the irrigation cooling effect can strengthen by approximately -0.1 °C for every 1 °C increase in background mean T_a or 10 mm month^{-1} reduction in rainfall. In principle, this regression model corroborated with the findings in the literature because it suggested that background T_a and rainfall are the main factors that influence irrigation cooling effect.

4.2. Seasonality and weather

Notable seasonal variations in the magnitude of irrigation cooling effect have been reported by two modelling studies which applied a constant daily irrigation amount throughout the year. Lobell *et al* (2009) modelled the monthly irrigation cooling effect in eight major irrigated regions in the northern hemisphere to be -5 °C in the dry season, while the cooling effect was hardly noticeable in the wet season. Zou *et al* (2014) modelled the monthly irrigation cooling effect in Haihe River Basin, China. They predicted a strengthening cooling effect from -2 °C in April to -4 °C in July as background T_a increased. They also predicted a warming effect up to 4 °C in the winter months because of the constant irrigation throughout the year.

Day-to-day variations in irrigation cooling effect were also evident in an observational study in two urban parks in Melbourne, Australia (Lam *et al* 2020). Comparing to the non-heatwave period, the irrigation cooling effect in several lawn areas was -4 °C to -2 °C stronger during heatwaves. Similar to background climate, a warmer weather can increase irrigation cooling effect on a seasonal and daily basis because it provides more energy for evapotranspiration and increases VP deficit.

4.3. Vegetation type

In an experimental study, the daily mean irrigation cooling effect in maize fields (-0.43 °C) in Nebraska, USA was significantly higher than that in soybean fields (-0.09 °C) (Chen *et al* 2018). The cooling effect from irrigation correlated with a decrease in sensible heat flux in the maize fields, whereas irrigation induced little change in sensible heat flux in the soybean fields. The difference in the cooling effect between maize and soybean may be attributed to their differences in plant height and leaf area index which affect the transport of heat. There is a paucity of studies that compare irrigation cooling effects among vegetation types, partly because the majority of the current land surface models do not account for different vegetation types (Ozdogan *et al* 2010). One exception is a modelling study that compared the latent heat flux between a scenario where only one generic crop type was used and a scenario where the crop types where classified in detail (Ozdogan *et al* 2010). The latent heat flux of the scenario with only one generic crop type was approximately 5 W m^{-2} higher, indicating a stronger cooling effect.

Different vegetation types can influence irrigation cooling effect because of their differences in water demand and physical characteristics. For example, cool-season grasses generally have a higher crop factor ($\sim$0.65) than warm-season grasses ($\sim$0.25) (Handreck and Black 2001). Trees and shrubs can have a crop factor >0.7 (Connellan *et al* 2002). Crop factor is the proportion of water used by the plant in comparison to the water evaporated from a evaporation pan (Doorenbos and Pruitt 1977). Cool-season grasses, trees and shrubs may therefore induce a stronger irrigation cooling effect than warm-season grasses with irrigation because they transpire more water per unit area.

Turfgrasses, shrubs and trees are common urban vegetation types that provide cooling benefits to UGS visitors by reducing air temperature. Their cooling effect is dependent upon their ability to transpire and shade (Rahman *et al* 2019), as well as their impacts on aerodynamic roughness (Meili *et al* 2021) and wind speed (Xing *et al* 2019). In comparison to tall shrubs and trees, turfgrasses do not provide overhead shading and therefore their cooling effect is mainly dependent upon their transpiration rate and albedo, which is further dependent upon their species, root system and plant area index. Short shrubs (<1 m) behave similarly to turfgrasses because they are not tall enough to provide shade for humans or nearby dark impervious surfaces. Appropriate irrigation can support the growth and health of both turfgrasses and shrubs, increasing their plant area index. A vigorously-growing turfgrass can have a crop factor of 0.7, whereas a moderately-growing turfgrass may only have a crop factor of 0.25 (Handreck and Black 2001), meaning that a vigorously-growing grass transpires more water per unit area and induces a stronger cooling effect. Turfgrasses and shrubs with a higher plant area index also have a higher albedo, which further reduces air temperature by reducing the amount of radiation absorbed and later released by the ground surface (Shiflett *et al* 2017). The impacts of turfgrasses and short shrubs on aerodynamic roughness and wind speed are smaller than those of trees and therefore their cooling benefits may be easily diluted by near-surface turbulent mixing and advection (Spronken-Smith and Oke 1998). Nevertheless, the advected cool air can benefit the urban areas downwind (Sugawara *et al* 2015).

In the case of tall shrubs and trees, shading may contribute approximately 70% of their cooling effect and transpiration the rest 30% (Tan *et al* 2018). Appropriate irrigation can support the growth and health of tall shrubs and trees, increasing their plant area index. Tall shrubs and trees with a higher plant area index can induce a stronger cooling effect from increasing overhead shading for humans and dark impervious surfaces, as well as increasing overall transpiration (de Abreu-harbich *et al* 2015, Sanusi *et al* 2017). Moreover, the presence of tall shrubs and trees in UGS can reduce wind speed at the pedestrian level (Xing *et al* 2019) and therefore retain the cool air within the UGS for longer. The impact of irrigation on the cooling effect of tall shrubs and trees are more complex than turfgrasses and short shrubs. Most UGSs have a combination of turfgrass areas with and without trees and shrubs, such that their impacts upon the energy balance and therefore cooling effects are complex. UGSs will often contain vegetation with high and low transpiration rates, high and low leaf area indices, taller vegetation will shade lower vegetation and taller vegetation will change wind speed, aerodynamic roughness and turbulent exchange (Kent *et al* 2017). More studies are required to understand the complex interactions between irrigation, plant area index and cooling effect of these common urban vegetation types.

4.4. Irrigation time of day

Irrigation time refers to the time in 24 h diurnal period when irrigation is applied. Only a limited number of studies have examined the impact of irrigation time. Broadbent *et al* (2018) modelled a negligible (<0.2 °C) difference in the daily mean cooling effect between daytime (11 am–5 pm) and night-time (11 pm–5 pm) irrigation in Mawson Lake, North Adelaide, Australia; however, the diurnal variation of the cooling effect was not reported. Valmassoi *et al* (2020) modelled the diurnal variations in the irrigation cooling effect of night-time (5 UTC), midday (12 UTC) and afternoon (15 UTC) irrigation with sprinklers in Po Valley, Italy. The night-time irrigation regime would induce a cooling effect of $\geqslant -0.4$ °C after 2 h from the starting time and it would have almost no impact on T_a in the rest of the day. The midday irrigation regime would induce a cooling effect of $\geqslant -0.2$ °C at 15 UTC and a warming of a similar magnitude at night. The afternoon irrigation would induce a cooling effect of $\geqslant -0.7$ °C which sustained for most of the time at night. Although the daily mean cooling effect was not explicitly reported, night-time and afternoon irrigation seemed to induce a stronger daily mean cooling effect than midday irrigation.

4.5. Daily irrigation amount

Studies that modelled two levels of daily irrigation generally predicted an increase in cooling effect with increased irrigation amount (Kanamaru and Kanamitsu 2008, Sorooshian *et al* 2011, Zou *et al* 2014). However, the results were mixed for studies that modelled the cooling effects from more than two levels of daily irrigation (Lobell *et al* 2009, Broadbent *et al* 2018, Wang *et al* 2019). In a global modelling study, Lobell *et al* (2009) predicted that the cooling effect would be almost the same for keeping soil moistures at 30%, 40% and 90% of saturation, because energy would become the greatest limiting factor upon evapotranspiration and latent heat flux, when soil moisture exceeds 30%. In a local-scale modelling study, however, daily irrigation amounts of 5, 15 and 30 mm d^{-1} would lead to mean daily cooling effects of -0.5 °C, -1.5 °C to -2.3 °C, respectively (Broadbent *et al* 2018). This local-scale model predicted a non-linear or 'diminishing return' in cooling effect with increasing daily irrigation amount. A direct comparison between these two studies is impossible because the equivalent daily irrigation amounts of keeping soil moisture at 30%, 40% and 90% are unknown and dependent upon factors such as soil type, regional climate and vegetation type. This concept of diminishing cooling effect with increasing irrigation amount is supported by Wang *et al* (2019), who modelled the irrigation cooling effects at four irrigation amounts in the contiguous USA. They predicted that the evapotranspiration and latent heat flux can be enhanced with large daily irrigation amounts only in the semi-arid and arid regions because of the large VP deficit in these regions, and only up to an amount of 10 mm d^{-1}. Background regional climate appears to be an important factor in determining how much cooling effect is possible with increasing daily irrigation amounts.

4.6. Duration of cooling after irrigation

Irrigation cooling effect can persist after irrigation stops as water continues to evaporate from the soil surface and plants continue to transpire. Experimental and observational studies have provided evidence that the cooling effect after irrigation can last for hours (Lam *et al* 2020) and days (Chen *et al* 2018), while modelling studies predicted that it would last for months after continuous, daily irrigation in the warm season (Sorooshian *et al* 2011, Yang *et al* 2016). The cooling effect of evening and night-time irrigation (8 pm–7 am) in Melbourne Gardens, Melbourne, Australia persisted for several hours into the morning (Lam *et al* 2020).

The cooling effect from irrigating maize fields in an experimental farmland in Nebraska, USA was <−0.5 °C in the first 6 d after irrigation and was still evident (<−0.2 °C) 11 d after irrigation (Chen *et al* 2018).

The cooling effect of irrigation applied from May to August in the Central Valley, California, USA, was modelled (NCAR/Penn State MM5) to persist into September (−1.1 °C) and October (−0.3 °C) (Sorooshian *et al* 2011). Yang *et al* (2016) modelled the climate impacts of springtime (March–April–May) irrigation in the Huang-Huai-Hai Plain, China. The latent heat flux in the irrigated scenario was predicted to reduce significantly in the 3 months (June–July–August) after irrigation stopped, with only a minor reduction in T_a (0.1 °C). Modelling studies reported a much longer duration of cooling after irrigation than experimental and observation studies mainly because they tracked the impacts of irrigation for a much longer period (a few months) after irrigation stopped. In comparison, the experimental study only measured the duration of cooling after irrigation up to 11 d because the irrigation was designed to applied every 4–11 d (Chen *et al* 2018). The cooling effect might have lasted longer than 11 d, but the experiment did not measure it.

5. Decision framework for using UGS irrigation for urban cooling at a local scale

To assist city managers and private property owners to make decisions about the use of UGS irrigation for local cooling, we present a three-stage decision support framework that steps through a sequence of practical issues (figure 3). Background climate is the first issue to consider because the cooling potential of UGS irrigation is higher in cities with a warm and dry season. Cities without a warm and dry season are unlikely to benefit greatly from UGS irrigation and should consider other cooling strategies or combinations. If a city manager of private property owner decides that UGS irrigation is suitable for their climate, the next issue to consider is irrigation water supply. The abundance of irrigation water is not restricted to potable water because bore water, recycled wastewater and stored stormwater are suitable for UGS irrigation too. Cities with an abundant water supply, preferably an alternative to potable water, can practice soil moisture-controlled irrigation throughout the warm, dry season, whereas those cities with a limited water supply can practice temperature-controlled irrigation to restrict irrigation to hotter days only. Under both irrigation-control regimes, there are three major management issues to consider: soil properties, fauna and flora ecology and types of amenity use.

5.1. Background climate

The background climate of a city, primarily background mean T_a and rainfall, determines whether UGS irrigation is an effective cooling strategy. A higher background T_a and lower rainfall will increase the cooling potential of irrigation, and vice versa. To demonstrate the impact of background climate we use the simple regression model developed by Cheung *et al* (2021), to estimate the cooling potential of UGS irrigation in three global cities of contrasting climate: Hong Kong, Melbourne and Phoenix. This regression model predicts the cooling potential of UGS irrigation as the difference in daily mean T_a between an irrigated and an unirrigated UGS. The cooling potential of irrigation is presented for four seasonal periods: DJF, March–May (MAM), JJA and September–November (SON) (figure 4).

Hong Kong has a dry-winter humid subtropical climate (Köppen–Geiger climate classification: Cwa). It is a city without a warm and dry season (figure 3). The winter (DJF) in Hong Kong is dry (mean rainfall = 30 mm month^{-1}) but not warm (mean T_a = 17.3 °C) (figure 4(a)); the other three seasons are warm (mean T_a > 22.9 °C) but not dry (mean rainfall >160 mm month^{-1}). As a result, the impact of UGS irrigation in the four seasons in Hong Kong is positive (warming) except in DJF (figure 4(a)). This warming is likely due to the increased soil thermal conductivity of wet soil after irrigation (Kanamaru and Kanamitsu 2008). This leads to an increased soil heat storage during the day which releases during the night, causing a substantial night-time warming which outweighs the daytime cooling effect. Other urban cooling strategies such as urban greening and canopy shade (Cheung and Jim 2018), improving urban ventilation (Tan *et al* 2017) and increasing albedo of impervious surfaces (Akbari *et al* 2012) should be considered.

Melbourne has an oceanic climate (Köppen–Geiger climate classification: Cfb). It is a city with at least one warm and dry season (figure 3). The summer (JJA) in Melbourne is warm (mean T_a = 17.3 °C) and dry (mean rainfall = 43 mm month^{-1}) (figure 4(b)). The estimated cooling potential of UGS irrigation under these summer climate conditions is −0.6 °C, whereas the irrigation impact in the other three seasons is neutral. Since the cooling potential of irrigation in this simple model is the daily mean difference in T_a the cooling effect during the middle of the day is likely to be <−0.6 °C, suggesting that USG irrigation can be considered an effective cooling strategy to reduce daytime T_a.

Phoenix has an arid, hot desert climate (Köppen–Geiger climate classification: BWh). It is a city with more than one warm and dry season (figure 3). The background mean T_a and rainfall in MAM, JJA and SON are >23.0 °C and <18 mm month^{-1}, respectively (figure 4). Under such warm and dry climate conditions,

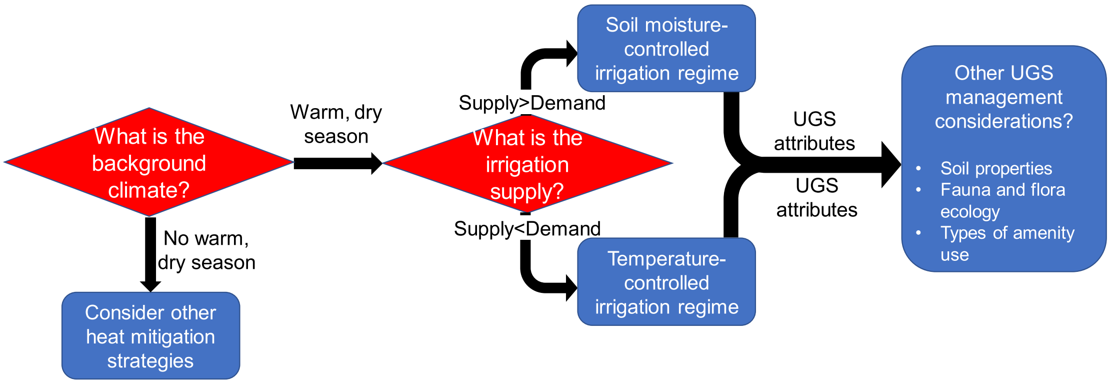

Figure 3. A three-stage decision support framework for city managers and private property owners to decide whether or not to use UGS irrigation for cooling on a local scale. Background climate is the first issue to consider because the cooling potential of UGS irrigation is higher in cities with a warm and dry season; cities without a warm and dry season should consider other cooling strategies. If UGS irrigation is adopted, the next issue to consider is irrigation water supply. With the aim of maximising the cooling effect of UGS irrigation, cities with abundant irrigation water supply can practice a soil moisture-controlled irrigation regime, while those with limited irrigation water supply can practice a temperature-controlled irrigation regime. In both irrigation regimes, some management issues need to be considered: soil properties, fauna and flora ecology and types of amenity use.

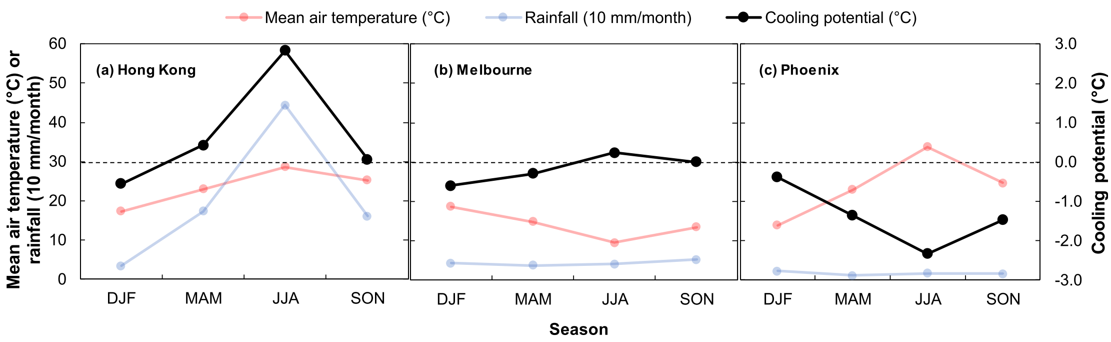

Figure 4. The background mean air temperature, rainfall and cooling potential from irrigation in (a) Hong Kong, (b) Melbourne and (c) Phoenix, in December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON). The cooling potential is the difference between an irrigated and an unirrigated UGS in daily mean air temperature. A negative difference represents cooling and a positive one warming. The regression model in Cheung *et al* (2021) is used to estimate the cooling potentials from the 30 years mean air temperature and rainfall. Data source: Hong Kong (Hong Kong Observatory, www.hko.gov.hk/en/index.html); Melbourne (Bureau of Meteorology, www.bom.gov.au/); Phoenix (National Oceanic and Atmospheric Administration, www.ncdc.noaa.gov/cdo-web/datatools/normals).

the estimated cooling potential of UGS irrigation in these three warm, dry seasons are −1.4 °C, −2.3 °C and −1.5 °C, respectively. UGS irrigation is a very effective cooling strategy for Phoenix.

As global climate change progresses, many cities are likely to become warmer with more variable rainfall patterns (Peck *et al* 2012, Darmanto *et al* 2019). Urban expansion is also likely to increase the intensity of urban heat islands because of reduced evapotranspiration and increased heat stored in urban structures which releases as sensible heat (Argüeso *et al* 2014). Thus, this decision framework may be used to consider the projected climate of a city to determine whether or when UGS irrigation will become an effective urban cooling strategy in the future.

5.2. Irrigation water supply and irrigation regimes

After determining the cooling potentials of UGS irrigation in a city based on its background climate, the next decision step is to consider irrigation water supply (figure 3). Although potable water remains the most common source of irrigation water supply in global cities, alternative water sources are being developed in many forward-thinking cities to support UGS irrigation and to reduce potable water consumption (Grant *et al* 2012). Cities can increase their irrigation water supply by harvesting stormwater and roof water runoff (Hamlyn-Harris *et al* 2018) and storing this in ponds or above-ground or below-ground (Livesley *et al* 2021). Stormwater harvesting schemes in new developments in Melbourne, Australia can increase the city's non-potable water supply by seven times (9.8% of municipal water consumption) until 2050 (Environment and Natural Resources Committee 2009). Irrigation water supply can also be enhanced by treating municipal sewage using conventional and advanced techniques (Leverenz *et al* 2011). The majority of Israel's municipal sewage (73%) is treated and reused for agricultural irrigation (5% of national-wide water consumption) (Tal 2006).

5.2.1. Soil moisture-controlled irrigation

For cities with abundant irrigation water supply which exceeds their water demand during warm and dry seasons, the soil moisture-controlled irrigation regime can be used to keep soil moisture high (Yang and Wang 2015) to ensure that evapotranspiration is only limited by the atmospheric demand and the transpiration rate of vegetation. Keeping the soil moisture at or just below field capacity of soil by irrigation is likely sufficient to ensure that evapotranspiration rate and Q_E are always at their maxima to achieve the strongest cooling effect. Field capacity is the soil moisture content when all macropores have emptied under gravity, whereas saturation is the moisture content when all pores (micro-, meso- and macro-) are filled with water. There are two ways to determine the amount of irrigation required to restore soil moisture to field capacity: (a) direct sensor measurement of soil moisture (Haley and Dukes 2012), and (b) estimation from daily reference evapotranspiration data from the local meteorological bureau (Allen *et al* 1998). Applying the estimated amount of irrigation during the day is likely to induce a stronger cooling effect than night-time irrigation (Valmassoi *et al* 2020), because the greater VP deficit during the day will promote direct evaporation as the irrigation water passes through the air, and a greater proportion of irrigation water can evaporate from the surface of vegetation and the soil, before it infiltrates and contributes to soil moisture content.

5.2.2. Temperature-controlled irrigation regime

For cities with limited irrigation water supply which just meets their demand during warm and dry seasons, the temperature-controlled irrigation regime can be used to trigger irrigation when T_a, or other human thermal stress indices, exceeds a certain level, e.g. 30 °C (Yang and Wang 2015). As discussed in section 4.2, irrigation can induce a stronger cooling effect when the weather is warmer. A temperature-controlled irrigation regime can ensure that the limited water supply is only used when human heat stress is greatest. Irrigation may be applied whenever the human heat stress exceeds a certain threshold. This threshold to thermal stress can be determined by local questionnaire surveys within the UGS or the city itself (Lam and Lau 2018, Cheung and Jim 2019c).

5.3. Urban green space (UGS) management considerations

5.3.1. Soil properties

Under both irrigation regimes, the field capacity of the soil needs to be considered to determine the irrigation amount and the frequency with which irrigation can be applied to support evapotranspiration without exceeding infiltration capacity and thereby surface ponding of water or excessive runoff. Direct soil moisture monitoring can prevent irrigation exceeding soil field capacity or the predefined level (Haley and Dukes 2012) under both irrigation regimes. If the UGS is actively used for recreational or sports activities, soil compaction is an additional issue to be considered because the susceptibility of soils to compaction increases greatly at high soil moisture contents (Mosaddeghi *et al* 2000), particularly for fine-textured soils (Kolka *et al* 2012).

5.3.2. Fauna and flora ecology

Applying irrigation for cooling in UGS may keep the soil moisture at a relatively high level for an extended period of time, especially in the soil moisture-controlled irrigation regime. Wet soils may suppress the establishment and growth of the desired vegetation species in the UGS (Fay and Schultz 2009, González-Muñoz *et al* 2011) and promote the establishment of unwanted invasive species (Fay and Schultz 2009). On the other hand, the cooling effect from UGS irrigation can reduce maximum T_a and provide cool refuge to vulnerable flora (McCarthy and Pataki 2010) and fauna (Tanner *et al* 2017, Nowakowski *et al* 2018), especially during heatwaves. UGS managers and owners have to carefully weigh up the cooling effect against the potential ecological impacts (positive or negative) upon flora and fauna that use the UGS as habitat.

5.3.3. Types of amenity use

The soil moisture-controlled irrigation regime tends to maintain the soil moisture content in the UGS at a relatively high level, which can make recreational and sports activities difficult as the soils be more susceptible to compaction, and may lead to users getting wet from sitting or lying on the ground, or from direct water spray during daytime irrigation events. Moreover, the temperature-controlled irrigation regime may frequently interrupt the usage of the UGS in hot days because irrigation may be triggered multiple times. Similar to the management concerns in ecology, irrigation can reduce human heat stress in the UGS but at the same time cause inconvenience to UGS users.

6. Conclusion

Irrigation inarguably increases soil moisture content, which leads to an increase in daytime latent heat flux and a decrease in sensible heat flux. The resultant effect is a reduction in daytime T_a and T_{sfc}. However, the increase in soil moisture content also increases daytime soil heat storage, causing a greater release of heat from the soil at night and a possible night-time warming effect in T_a and T_{sfc}. Overall, irrigation may reduce daily mean human thermal stress despite the increase in VP or humidity from evapotranspiration.

The cooling effect of UGS irrigation in T_a and T_{sfc} can be influenced by a number of regional and local factors, with background climate being the most important factor. Dry and warm climates are most conducive to a strong irrigation cooling effect. Moreover, irrigation cooling effect is strongest in the warm season and on warm days. Vegetation type has a measurable impact on cooling effect but very few studies have examined this factor. Irrigation time of day mainly changes the diurnal temperature patterns and its impact on daily mean cooling effect remains unexplored. Increasing daily irrigation amount can strengthen cooling effect but a diminishing cooling impact can be expected as irrigation amount increases.

Based on the regional and local factors that influence irrigation cooling effect, a three-stage decision framework was developed in this study to assist city managers and private property owners to make decisions about the use of UGS irrigation for local cooling. First, cities with a warm and dry season have a higher potential to use irrigation to mitigate urban heat on a local scale. Second, cities with abundant irrigation water supply can use a soil moisture-controlled irrigation regime to maximise the cooling effect and those with limited supply can use a temperature-controlled irrigation regime to achieve the same goal. Third, these two irrigation regimes can be adjusted for each UGS, taking into account its soil type, ecology and usage.

USG irrigation is an emerging urban cooling strategy and there remains many important knowledge gaps. We suggest that future studies should:

- Measure the cooling effect from irrigation in different climate regions and use the empirical data to validate the predictions from climate models.
- Model the cooling effect from irrigating a small, individual UGS instead of irrigating all the pervious surfaces in the whole city because the cooling effect from irrigation is likely to be highly localised (Coutts *et al* 2013).
- Use more realistic irrigation schemes (Lobell *et al* 2009) and more specific vegetation parameters (Ozdogan *et al* 2010) to model the cooling effect from irrigation.
- Quantify the benefits of UGS irrigation in human thermal comfort using advanced thermal indices such as physiological equivalent temperature (PET) (Matzarakis *et al* 1999), modified physiological equivalent temperature (mPET) (Lin *et al* 2018) and UTCI (Bröde *et al* 2012).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Conflict of interest

The authors declare no competing interests.

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