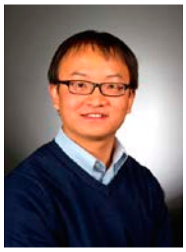

Optimizing urban irrigation schemes for a trade-off between energy and water consumption

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In the United States, building energy accounts for around 40% of the total energy consumption in cities, with an increase in cooling load due to urban heat island effect (Retzlaff, 2008). In recent years there has been a growing concern about the energy consumption as it is the largest contributor to global CO_2 emissions, which is the leading cause of climate change (Seto and Dhakal, 2014). While numerous means for reducing building energy consumption have been investigated during the past decades, the impact of various urban irrigation schemes on building energy efficiency has been less explored. Building energy consumption in cities is closely related to environmental temperatures (Akbari, 2009), on which irrigation has cooling effects by increasing the supply of surface moisture for evapotranspiration. Irrigation of private gardens consumes 16-34% of the total water supplied to an urban area, let alone the water used for irrigating large open space such as public parks and golf courses (Mitchell et al., 2001). Such amount of irrigation can increase evapotranspiration and cool the urban environment considerably, leading to significantly lower cooling load, especially in densely built areas.

Current irrigation practices in most cities are scheduled between sunset and sunrise in order to avoid rapid moisture loss. However, from an energy saving perspective, irrigation should be conducted during daytime as evaporative cooling is driven by available solar radiation at the surface. In this case, irrigating urban vegetation leads to improved building energy efficiency, albeit the trade-off and balance between water and energy resources need to be carefully measured. Different from agricultural irrigation whose objective is mainly on the yield of produces (Topak et al., 2010), urban irrigation apparently needs a new paradigm by considering the environmental sustainability of cities (e.g. mitigate urban heat islands and save building energy consumption).

In this study we applied a state-of-the-art urban canopy model (Wang et al., 2011, 2013), with realistic representation of urban hydrological processes, to identify the environmental impact of urban irrigation in the Phoenix metropolitan area. Located in a semi-arid environment, Phoenix has a tremendous demand for cooling compared to other cities, thus providing a large potential for building energy saving through optimizing irrigation schemes (Gober et al., 2010). We focus on irrigation of mesic neighborhoods, as it provides valuable environmental services by, e.g. reducing urban warming and improving stormwater management, as compared to the xeric residential landscape. A schematic of irrigation in the urban canopy layer is shown in Fig. 1.

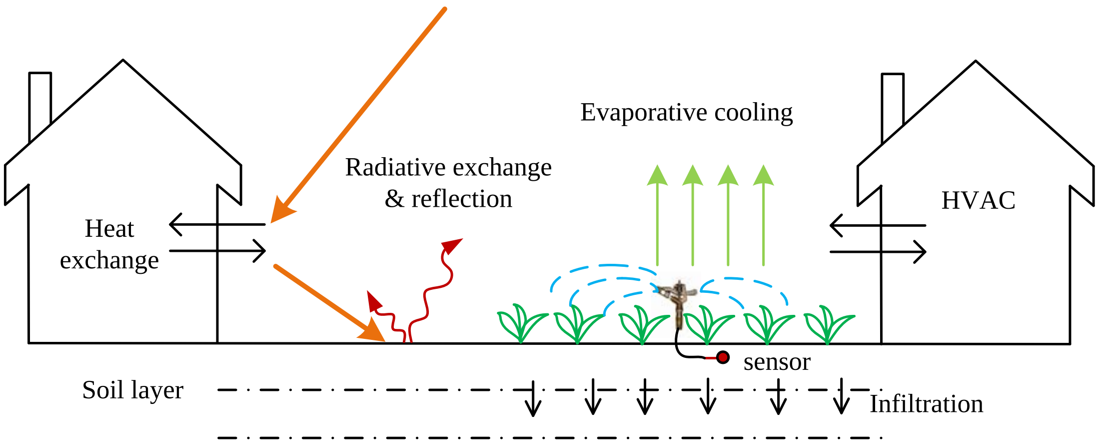

Fig. 1. A schematic of lawn irrigation in residential areas. The two-dimensional “big canyon” representation is adopted to represent the urban area with the longitudinal dimension (canyon length) much larger than the planar dimensions (building height and road width).

Focusing on irrigation of mesic neighborhoods, four different urban irrigation schemes are tested for Phoenix. Scheme 1 is the baseline case with no irrigation during the entire simulation period. Scheme 2 is a daily constant scheme that represents current irrigation practice over mesic residential landscapes in Phoenix. Following a previous study, irrigation is scheduled at 8 pm local time every day in this scheme (Yang et al., 2015). Sensitivity analysis finds that the irrigation time at night has limited impacts on model results. Scheme 3 is a soil-moisture-controlled scheme proposed as a potential urban irrigation paradigm. The idea is to maintain soil moisture at a certain level to keep evaporative cooling effective all the time. Whenever the moisture content of top soil layer (θ_{top}) drops below a critical value, irrigation is carried out to increase the moisture. In this study, a typical value 0.15 is used as the wilting point and 0.24 is used as the controlling moisture for irrigation activation. Scheme 4 is similar to the soil-moisture-controlled scheme but uses the soil temperature as the controlling variable. Targeted on reducing urban environmental temperature during hot periods, the scheme activates urban irrigation once the temperature of top soil layer exceeds a threshold value. A value of 22 ^{o}C is adopted as the first step to illustrate performance of the scheme. To avoid waste of water resource, the irrigation amount each time is regulated by either the daily irrigation amount of scheme 2 or the difference between θ_{top} and saturated soil moisture, whichever is smaller. For cool to cold months where soil temperature is consistently lower than the threshold value, essential irrigation is conducted to maintain the biological functions of mesic vegetation.

Accuracy of the UCM in capturing the energy and water budgets of Phoenix is crucial to accurately assess the impact of urban irrigation on environmental temperature and building energy consumption. Considering the monthly variation of meteorological conditions and irrigation demands, we tested the UCM with calibrated parameters at an annual scale. Half-hourly meteorological forcing is obtained from the eddy-covariance tower deployed at Maryvale, West Phoenix (Chow et al., 2014). Daily constant irrigation (i.e. scheme 2) is added into the model to represent practical supply for soil moisture. Predicted and observed average ground temperature (T_g), canyon air temperature (T_{can}), sensible heat flux (H), and latent heat flux (LE) agree with each other reasonably well. Root mean square errors are 1.39 ^{o}C, 1.02 ^{o}C, 12.51 W m^{-2}, and 7.36 W m^{-2} for T_g, T_{can}, H, and LE, respectively. With the calibrated urban canopy model, a series of simulations is conducted to investigate the effect of various irrigation schemes on environmental temperature, building energy consumption, and outdoor thermal comfort at an annual scale. A combination of 35% vegetative cover and 65% impervious surface is used to represent mesic residential landscape for Phoenix in the near future. Figure 2 shows the temporal distribution of θ_{top} and water consumption of all schemes. The annual variability is markedly different for different schemes: for daily constant irrigation scheme, water use pattern roughly follows a bell curve, with the peak consumption in the pre-monsoon summer, June; the soil-moisture-controlled scheme maintains θ_{top} at a relatively constant level, water consumption increases with soil temperature and the trend is similar to that of daily constant scheme. Irrigation of the soil-temperature-controlled scheme has the most drastic seasonal variation, with water use mainly concentrated in the summer owing to elevated temperatures. Peak water consumption in July and August for the soil-temperature-controlled scheme is 4 times more than that of other two schemes.

By replenishing soil moisture for evapotranspiration, urban irrigation has direct cooling impacts on the ground temperature. Figure 3 demonstrates the reduction of T_g by various irrigation schemes as compared to the no-irrigation case. The soil-moisture-controlled scheme has a larger reduction of T_g than other schemes during the winter, whereas the soil-temperature-controlled irrigation induces the greatest cooling in the summer. Maximum monthly reduction in T_g is about 2.1 ^{o}C in the winter and about 6.3 ^{o}C in the summer. When moisture content is relatively constant (e.g. the soil-moisture-controlled scheme), evapotranspiration of urban vegetation is regulated by available radiation at the surface, resulting in the larger cooling in summer compared to other seasons. Through the thermal interaction inside the street canyon, urban irrigation has indirect cooling impacts on building surface as lower ground temperature reduces thermal radiation emitted towards the wall. Reduced temperatures subsequently weaken the sensible heat flux arising from ground and wall surfaces, leading to the cooling of canyon air.

Figure 3 clearly illustrates that urban irrigation cools the built environment throughout the annual cycle. Reduced environmental temperature can save cooling load of buildings during warm to hot seasons, it nevertheless increases heating demand of buildings in cool to cold seasons. In this study we estimate the energy consumption as the heat flux entering the building via walls. Inner wall surface temperature is assumed to be maintained at 24 ^{o}C by indoor heating, ventilation, and air-conditioning (HVAC) systems for the entire simulation period. With this assumption, we neglect: (1) the contribution of heat flux entering buildings via roofs, (2) internal energy loads caused by people and equipment, and (3) the efficiency of air conditioning system and the variation of the building interior temperature.

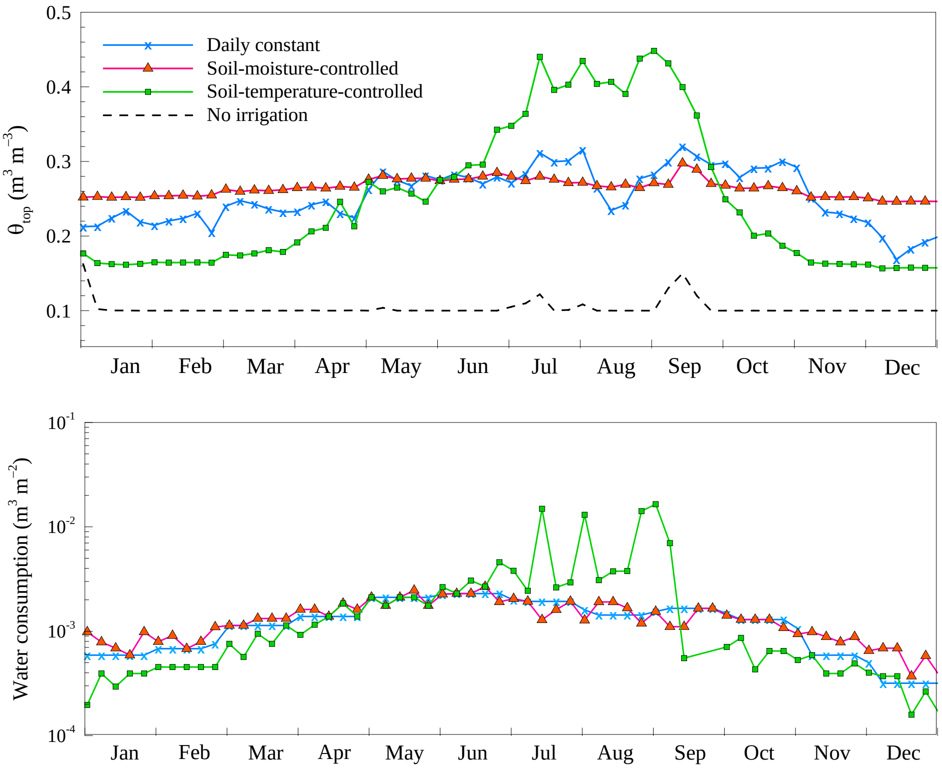

Fig. 2. Simulated temporal distribution of (top) θ_{top}, and (bottom) water consumption among different irrigation schemes in Phoenix in 2012.

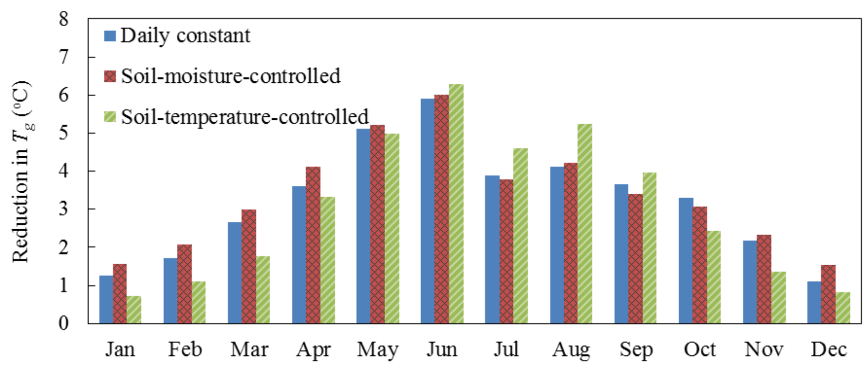

Fig. 3. Monthly reduction in T_g by various irrigation schemes as compared to the no-irrigation case.

Figure 4 presents the monthly water consumption, heating penalty, and cooling saving by different irrigation schemes as compared to the no-irrigation case. In cool to cold season (November to March), the soil-moisture-controlled scheme consumes about 0.29 cubic meter water per square meter vegetated ground area for irrigation, notably larger than 0.22 m^3 m^{-2} in daily constant scheme and 0.16 m^3 m^{-2} in the soil-temperature-controlled irrigation. Relatively high moisture level maintained by the soil-moisture-controlled scheme significantly increases the heating demand of buildings. Monthly maximum penalty can be up to about 6.3 kWh m^{-2} in early spring and the annual heating penalty is more than 45 kWh m^{-2}. On the other hand, with irrigation concentrated in summer, the soil-temperature-controlled scheme has the least heating penalty as well as the largest cooling saving. Total water consumption of the scheme in summer is 1.23 m^3 m^{-2}, which is about tripled compared to the consumption of 0.38 m^3 m^{-2} in other two schemes. Compared to the control case (no-irrigation), the maximum monthly saving is more than 20 kWh m^{-2} in June. For the entire simulation period, total heating penalty and cooling saving is about 32 and 116 kWh m^{-2}, respectively.

The saving of summer cooling load by lawn irrigation is concomitant with the cost of increased water usage: it takes water to cool an arid city. The trade-off between water and energy consumption naturally leads to the classic question of cost-benefit: Is the saving of cooling energy from urban irrigation worth the cost of water resources? To address this question, a cost-benefit analysis by combing water and energy consumptions is carried out, serving as a reasonable economic measure of the environmental sustainability:

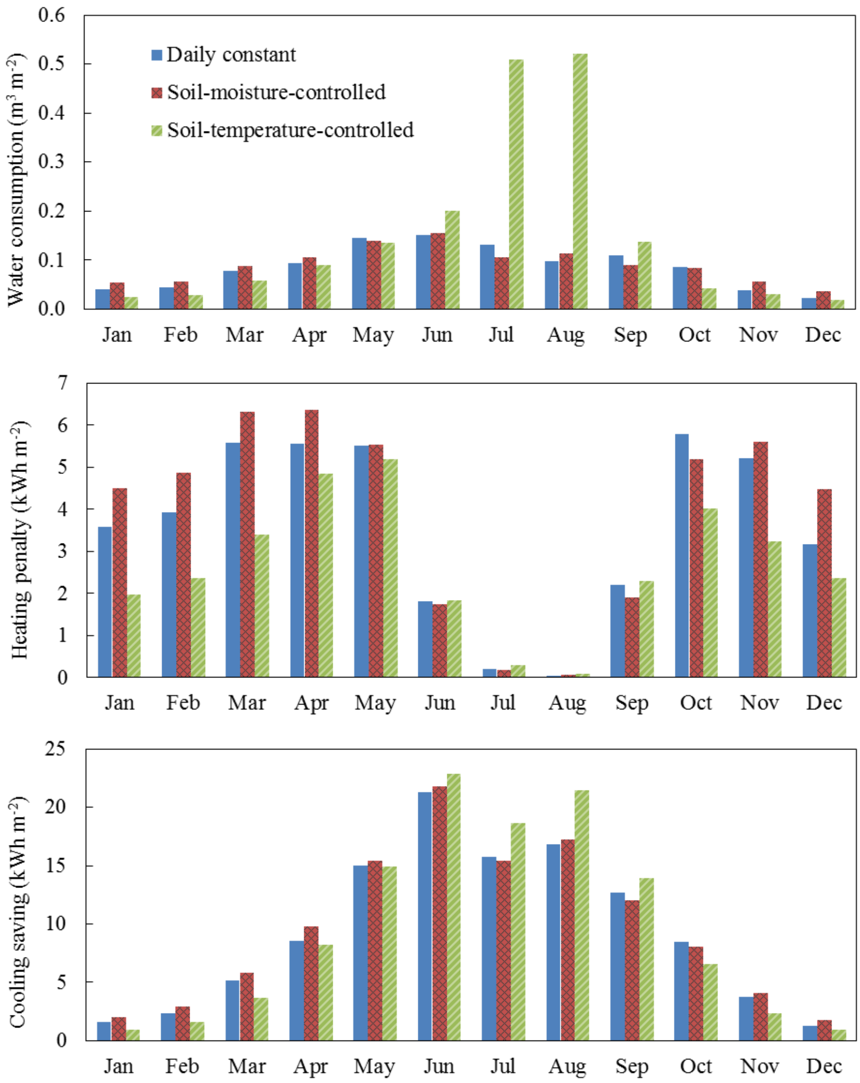

Fig. 4. Monthly (top) water consumption, (middle) heating penalty, and (bottom) cooling saving by various irrigation schemes as compared to the no-irrigation case.

$$\text{cost}_{\text{total}} = P_{\text{water}} \left(\frac{w}{h} \right) f_{veg} \sum_t W + P_{\text{electricity}} \sum_t |Q_{in}|,$$

where P_{water} and $P_{\text{electricity}}$ are the unit prices of water and electricity usage respectively, w/h is ration between ground and wall areas, f_{veg} is the areal fraction of vegetation over ground surface, W is the water consumption rate, t is the time, and Q_{in} is the heat flux entering the building via walls. The resulted total cost is in dollar per square meter wall area. Monthly saving in total cost of different irrigation schemes as compared to the no-irrigation case is shown in Fig. 5. Results show that during hot seasons, irrigating more water leads to more total saving. Maximum monthly saving can be up to about \$2.5 m^{-2} in the soil-temperature-controlled scheme for June and August. In cool to cold months when heating demand dominates, additional moisture from irrigation results in increased total cost (negative values in Fig. 5). Monthly cost of the soil-moisture-controlled scheme is about \$0.13 m^{-2} higher than that of the soil-temperature-controlled scheme throughout the winter. Table 1 summarizes the annual water use, electricity consumption, and total cost of all schemes. Among investigated schemes, the soil-moisture-controlled scheme has the largest total cost. Compared to daily constant irrigation, it consumes more water and has higher total cost, primarily due to the increased heating penalty during cool seasons. The soil-temperature-controlled scheme has a significantly larger annual water usage, which is 60% more than that of other two schemes. However, the cost of water can be offset by the saving in cooling energy. Overall, the soil-temperature-controlled irrigation scheme is the most efficient in reducing annual total cost of mesic neighborhoods. Besides, it is more effective in reducing urban temperatures during the summer than the current irrigation scheme, thus providing benefits of a better living environment to residents.

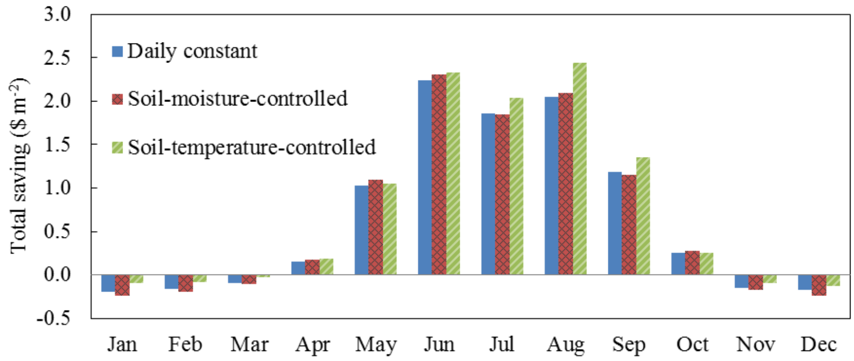

Fig. 5. Monthly total saving by various irrigation schemes as compared to the no-irrigation case.

Table 1. Summary of annual water usage, energy consumption, and total cost of all study irrigation schemes.

	No-irrigation	Daily constant	Soil-moisture-controlled	Soil-temperature-controlled
Water usage (m^3 m^{-2})	0	1.04	1.09	1.79
Energy consumption (kWh m^{-2})	1405.8	1335.7	1336.3	1321.6
Annual total cost ($ m^{-2})	151.29	143.28	143.32	142.44

In addition to alleviating environmental temperature and building energy demand, urban irrigation has important implications for thermal comfort of pedestrians in outdoor urban environment. With a large city size, warm and dry climate, and significant amount of clear days, Phoenix is among the hubs of urban heat islands in the United States where people experience intense thermal discomfort during hot days in outdoor or non-air-conditioned indoor environments (Brazel et al., 2000). In this study, we selected the Index of Thermal Stress (ITS) developed by Givoni (1963) to identify the impact of urban irrigation on outdoor thermal comfort for Phoenix. ITS is a measure of the rate at which the human body must give up moisture to the environment in order to maintain thermal equilibrium. Here the ITS for pedestrians doing gentle outdoor activities (e.g. walking) in the street canyon is calculated. Reduction of ITS by different irrigation schemes as compared to the no-irrigation case is shown in Fig. 6. By reducing environmental temperature and increasing humidity, urban irrigation leads to reduction in ITS throughout the year except for September. Due to four major rainfall events, September has a significantly higher relative humidity than other months. Further moisture brought by irrigation under the humid condition thus results in degradation of outdoor thermal comfort. In hot summer, reduction of ITS by the soil-temperature-controlled scheme is more significant than that of other two schemes. Maximum reduction is about 35 W m^{-2} in June.

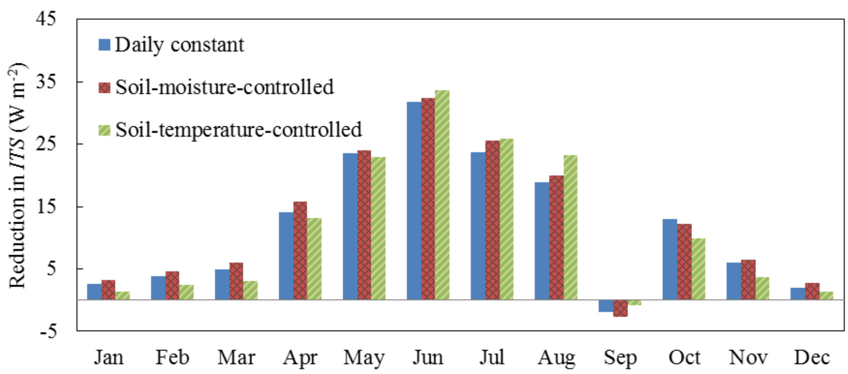

Fig. 6. Monthly reduction of ITS by various irrigation schemes as compared to the no-irrigation case.

The comparative analysis indicates that the soil-temperature-controlled irrigation is the best scheme in terms of annual total saving. The use of water to cool a city necessarily points to the intricate balance of water-energy nexus. Is there an optimal temperature regulating the soil-temperature-controlled irrigation that can maximize the combined saving of energy and water resources? To address this question, a set of simulations with six other controlling top-soil temperatures is carried out. Figure 7 demonstrates the annual saving in energy, water and the combined cost by different soil-temperature-controlled irrigation schemes as compared to the no-irrigation case. Positive values in the graph denote net saving. At a lower activating temperature, the soil-temperature-controlled scheme consumes more water during hot periods. Due to the nonlinear distribution of temperature, cost of water decreases more rapidly at a lower soil temperature. The combined annual saving exhibits a nonlinear trend as a function of activating soil temperature. Water usage with an activating temperature of 26 ^{o}C is only about 18% of that with an activating temperature of 20 ^{o}C. The latter consumes 17.1 kWh m^{-2} less energy than the former. Maximum annual saving is about $9.20 per square meter wall area at 23 ^{o}C, while minimum saving of $6.47 per square meter wall area is found with an activating temperature of 20 ^{o}C. Comparing with the annual saving of $8.01 m^{-2} by daily constant scheme, the activating top-soil temperature needs to be carefully determined in order to yield the optimal irrigation scheme using temperature control in terms of the trade-off between water and energy. It is worth to mention that optimal activating soil temperature depends on meteorological conditions and thus can vary vastly for different seasons or different climatic zones. Analysis here using a yearly constant activating temperature serves as a first step towards optimizing irrigation schemes for building energy efficiency. Further studies on a temporally varying activating soil temperature are needed.

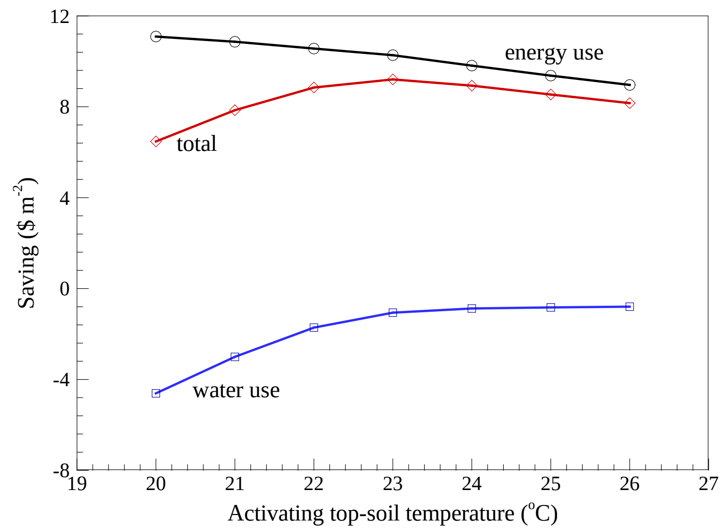

Fig. 7. Annual saving in cost of water consumption, energy cost and total cost by soil-temperature-controlled irrigation scheme with various activating soil temperatures as compared to the no-irrigation case.

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