Applied Energy 161 (2016) 437–444

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Cooling and energy saving potentials of shade trees and urban lawns in a desert city

Zhi-Hua Wang *, Xiaoxi Zhao, Jiachuan Yang, Jiyun Song

School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, USA

HIGHLIGHTS

- We developed a numerical framework incorporating trees in an urban canopy model.
- Shade trees have more prominent energy saving potential than urban lawns.
- The trade-off between water-energy is a key for urban landscape management.
- Urban vegetation can significantly alleviate outdoor thermal stress.

ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form 17 September 2015
Accepted 7 October 2015
Available online 22 October 2015

Keywords:
Building energy efficiency
Human thermal comfort
Hydrological processes
Monte Carlo simulation
Radiative heat exchange
Urban vegetation

ABSTRACT

The use of urban vegetation in cities is a common landscape planning strategy to alleviate the heat island effect as well as to enhance building energy efficiency. The presence of trees in street canyons can effectively reduce environmental temperature via radiative shading. However, resolving shade trees in urban land surface models presents a major challenge in numerical models, especially in predicting the radiative heat exchange in canyons. In this paper, we develop a new numerical framework by incorporating shade trees into an advanced single-layer urban canopy model. This novel numerical framework is applied to Phoenix metropolitan area to investigate the cooling effect of different urban vegetation types and their potentials in saving building energy. It is found that the cooling effect by shading from trees is more significant than that by evapotranspiration from lawns, leading to a considerable saving of cooling load. In addition, analysis of human thermal comfort shows that urban vegetation plays a crucial role in creating a comfortable living environment, especially for cities located in arid or semi-arid region.

1. Introduction

In the United States, building consumes nearly half (47.6%) of the energy produced every year [1,2]. The enormous building energy consumption in growing urban areas, together with the associated excessive waste heat release, have given rise or contributed adversely to a number of environmental issues, such as the urban heat island (UHI) effect, air quality degradation, human thermal discomfort, and microclimate modification via urban land–atmosphere interactions [3–7]. In order to alleviate urban thermal stress as well as to improve building energy efficiency, the use of urban vegetation (or more generally known as the urban "green infrastructure") is becoming an important landscape management strategy for homeowners, including, e.g. lawns, green roofs/walls, domestic gardens, and urban forest/agriculture [8–14]. In particular, for cities in arid or semi-arid environment, shade trees and urban lawns are the two popular forms of urban vegetation: shade trees are usually presented in xeric landscape with parsimonious irrigation requirement, while urban lawns are commonly found as mesic landscape (Fig. 1).

In last decades, mesic green roofs and urban lawns, and their effect on environmental cooling and energy saving potentials, have received increasing research effort. Rather sophisticated numerical and experimental techniques have been developed with applications ranging from building-resolving to city scales [9,10,15]. Mesic vegetation cools the environment primarily via evapotranspiration (ET) by redistributing available energy incident on a land surface for latent heat of vaporization. On the other hand, it requires constant irrigation in order to maintain the biophysical function of plants and the net effect on building energy efficiency involves an intricate trade-off between energy and water consumption [16]. For instance, irrigation for private gardens consumes 16–34% of the total water supplied to a city, letting alone

* Corresponding author. Tel.: +1 480 727 2933; fax: +1 480 965 0577.
E-mail address: zhwang@asu.edu (Z.-H. Wang).

http://dx.doi.org/10.1016/j.apenergy.2015.10.047

(a) (b)

Fig. 1. Typical urban vegetation types in Phoenix, Arizona: (a) a shade tree on xeric (desert) landscape and (b) mesic urban lawn (with xeric trees in the background).

the water used for irrigating large open spaces such as public parks and golf courses [17]. Thus for cities in arid environment, it essentially boils down to the fundamental question that "how much water it takes to cool the city?" [18].

In contrast to mesic urban vegetation, the cooling effect of xeric landscapes (usually shade trees) is mainly due to the direct blockage of solar radiation (radiative shading) effect. As ET from a xeric landscape is insignificant as compared to that of a mesic one, it presents an attractive alternative to city planners [19,20]. Previous studies have shown that homes with shade trees in cooling dominant cities can save over 30% of residential peak cooling demand [13]. However, studies on energy savings by urban trees remain scarce up to date due to practical difficulties: Experimental investigations were usually conducted at a single building scale, whereas numerical simulations assumed simplified and inadequate representation of trees. Furthermore, it was found that the actual energy savings by shade trees depend heavily on the local climate, with large seasonal and geographic variabilities [13,21–23]. Despite the continuous advance in numerical techniques for modeling urban climate (at macroscale) and building energy operation (at microscale), as well as the effort of bridging the scale gap [23,24], it remains an open challenge to realistically represent the dynamics of urban vegetation (especially trees) in urban land surface models.

Among the available urban land surface models, the family of urban canopy models (UCMs) have been demonstrated as a useful tool for capturing the physics of the coupled energy and water transport over built terrains [25,26]. In particular, recent development of the single-layer UCM has significantly enhanced the integrated urban energy balance and hydrological modeling [27,28], which has lately been implemented into widely used Weather Research and Forecasting (WRF) platform and coupled with mesoscale atmospheric dynamics [15]. This latest WRF–UCM framework features the resolution of urban facet heterogeneity ("patchiness" of vegetated and paved surfaces in a built environment), physical parameterization of urban lawns with subsurface soil water dynamics, urban oasis effect, green roof systems, and anthropogenic sources of water and energy [15]. Nevertheless, complex geometry and spatial locations of shade trees in urban areas present an outstanding challenge in accurate simulation of radiative heat exchange in the built environment. The presence of trees in a street canyon, for example, completely modifies the radiative view factors between a pair of canyon facets (i.e. sky, walls, and ground) by intercepting radiative rays transmitted in between. Only until recently, researchers have successfully formulated these view factors with trees participating in the radiative exchange in street canyons, based on stochastic "ray-tracing" methods [29,30].

In this study, we developed a new modeling framework by explicitly integrating urban trees into the latest single-layer UCM, enabled by the recent stochastic formulation of radiative heat exchange among trees and urban facets. This allows us to conduct macroscale (neighborhood to city scales) urban climate modeling incorporating shade trees and urban lawns with different cooling mechanisms and to compare their energy saving potentials. Unlike previous studies that were mostly focused on modeling at single-building scale with limited simulation time, this new modeling framework is driven by the annual climatology of a prototypical desert city, viz. Phoenix Arizona, and realistically resolves building-environment interactions in terms of energy and water exchange in urban canopy layers.

We selected Phoenix as our study area mainly due to two major concerns. First, this area is undergoing extensive urban expansion in last few decades and emerged as a hub of UHI and urban environmental study [31]. Secondly, as a prototypical arid city located in the Sonoran Desert, sustainable development of Phoenix, especially for strategic planning for urban mitigation and energy savings has been facing the practical concern of the trade-off between energy and water use [18,32]; the latter is a particularly scarce and precious resource in the desert city, making the alternative urban greening by trees instead of mesic urban lawns extremely attractive. Despite the extensive research effort on urban environmental issues received in this area, hitherto there is a lack of comparative study on the different cooling and energy saving potentials by xeric and mesic urban vegetation. In this study, we will conduct a case study with various scenarios of urban vegetation covers (fraction of urban lawns and size of trees). Results of simulations by the new numerical framework proposed in this study are expected to give us valuable guidance on future landscape planning strategies to alleviate thermal stress, to improve building energy efficiency, as well as to promote environmental sustainability.

2. Methodology

2.1. Single-layer urban canopy model

Single layer UCM is an urban land surface model with a "big canyon" representation of the urban geometry. Fig. 2 presents a schematic of the energy transport inside the urban canopy, including the representation of radiative shading by shade trees and ET cooling by urban lawns. The longitudinal dimension along the street is assumed to be much longer than the cross sectional dimensions (building height and street width), such that building arrays can be represented as a two-dimensional (2D) canyon. The use of big canyon geometry captures the essence of land surface processes in a built environment, such as modified hydrothermal properties of engineering materials, modified flow patterns by manmade structures, radiative trapping, and capability of explicit incorporation of anthropogenic sources of energy/water/pollutants and interior building operation. In this study, we adopt the latest single-layer UCM recently developed and implemented in the WRF platform by Yang et al. [15], featuring the resolution of urban facet heterogeneity, realistic urban hydrology (for both urban vegetation and paved surfaces), urban oasis effect, green roof systems, and anthropogenic water and energy input.

In this model, ET from vegetated surfaces is explicitly correlated with the subsurface soil water dynamics. The prognostic equation for soil water content is given by the Richards equation as,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial \theta}{\partial z} + K + F_\theta\right), \tag{1}$$

where θ is the volumetric soil water content, D is the soil–water diffusivity, K is the hydraulic conductivity, and $F_\theta = P + Q_F - \mathrm{Ro} - \mathrm{ET}$ is the surface forcing for soil water transport, with P the precipitation, Q_F the anthropogenic water input, and Ro the surface runoff.

The rate of ET from urban lawns is jointly controlled by the atmospheric demand and the soil water supply. Here we use the formula given by Brutsaert [33] for calculating the latent heat LE from urban lawns as

$$\mathrm{LE}_{\mathrm{lawn}} = L_v \beta_e E_p, \tag{2}$$

where L_v is the latent heat of vaporization, β_e is a reduction factor as a function of soil water content (supply control) determined in Eq. (1), and E_p the potential evaporation rate (demand control). For well irrigated urban lawns where soil water content does not impose a constraint on water stress, $\beta_e = 1$. The aerodynamic resistance method [28] is used to compute the potential evaporation rate as,

$$E_p = \frac{\rho_a (q_G^* - q_{can})}{r_a + r_s}, \tag{3}$$

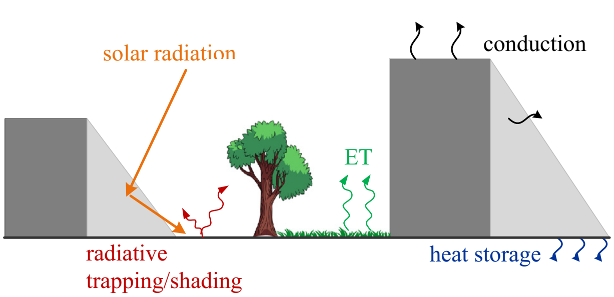

Fig. 2. Schematic of thermal energy transport inside an urban canopy, with radiative shading by shade trees and ET cooling by urban lawns.

where ρ_a is the density of air, r_a is aerodynamic resistance for turbulent heat transfer between urban surface and the above-lying atmospheric layer, and r_s is the stomatal resistance of plants. Inside an urban canyon, the aerodynamic resistance is formulated based on *in situ* measurements of horizontal and vertical wind speed U_{can} and W_{can} respectively [34], as

$$r_a = \left(11.8 + 4.2\sqrt{U_{can}^2 + W_{can}^2}\right)^{-1}. \tag{4}$$

The estimate of vegetation stomatal resistance is based on the meteorological approach [35,36], by correlating r_s to meteorological variables, that is,

$$r_s = r_{s,\min} \frac{F_{SR} F_\theta F_e F_T}{\mathrm{LAI}}, \tag{5}$$

where $r_{s,\min}$ is the minimum stomatal resistance depending on different plant types, LAI is the leaf area index, and F_{SR}, F_θ, F_e and F_T are the adjusting factors for meteorological conditions, namely the solar radiation, soil–water content, vapor pressure deficit, and atmospheric temperature, respectively. Based on previous studies, it is suggested that $r_{s,\min} = 40\ \mathrm{s\ m^{-1}}$ can be used for typical plants of urban lawns (e.g. short grasses).

2.2. Representation of trees in street canyons

With urban areas represented as "big canyons" (see Fig. 2) in the single-layer UCM, radiative heat exchange is typically captured using view factors between urban facets (sky, ground, and walls) [28,34]. Formulation of radiative view factors is analytically tractable, given the geometry of street canyons are regular (usually rectangular) without obstacles presented. On the other hand, if shade trees are to be introduced inside street canyons for more realistic representation of urban vegetation, analytical solutions of view factors between trees and urban facets become formidable, if not impossible. Instead, stochastic "ray-tracing" methods based on Monte Carlo techniques have been developed [29,30] to tackle the challenge by quantizing radiation (short- and long-wave) inside a street canyon using bundles of equal energy intensity ("rays"). The trajectory of each radiative ray is separately generated and traced using random numbers. Specifically, the direction of an emitted ray from a surface (designated as surface "1") is determined by the polar angle θ_1, and the azimuthal angle η_1, each associated with a random number R_θ and R_η, as

$$R_\theta = \frac{\theta_1}{2\pi}, \tag{6}$$

$$\sqrt{R_\eta} = \sin \eta_1. \tag{7}$$

The trajectory of this emitted ray is then traced according to the randomly generated direction: if it is intercepted by a surface 2 in the street canyon, it then contributes to the view factor F_{12}. Since a canyon is completely enclosed by the sky, ground, and two-opposite facing walls, the emitted ray must be incident on one of these facets, thus the unity property of view factors will be observed, i.e. $\sum_{j=1}^{N} F_{ij} = 1$, where N is the total number of canyon facets. In the presence of shade trees in the canyon, chances arise that a ray emitted from a canyon facet can be intercepted by a tree crown. Thus the introduction of trees effectively reduces view factors between all canyon facets, and helps to cool these surfaces with shading. It is also noteworthy that using Monte Carlo method for tracing rays, the numerical expense only increases linearly (by introducing shade trees as additional surfaces in the canyon), while that of analytical methods involving mathematical integration of the radiative transport equation increases exponentially.

Once the view factor matrix F_{ij} between urban surfaces is determined, the net radiative flux on each surface Q_i can be computed analytically using the matrix method [37],

$$Q_i = \begin{cases} \sum_{j=1}^{N} F_{ji}M_j - M_i & \text{if } \varepsilon_i = 1 \\ \frac{\varepsilon_i \sum_{j=1}^{N} \psi_{ji}M_j - M_i}{1-\varepsilon_i} & \text{if } \varepsilon_i \neq 1 \end{cases}, \tag{8}$$

where subscripts 'i' and 'j' are facet indices, ε is the emissivity, I_i is the irradiance (total incoming radiation), M_i is the emittance (total emitted), $[\psi_{ij}] = [\Gamma_{ij}]^{-1}$ is the inverse of the matrix Γ_{ij} defined as

$$\Gamma_{ij} = \delta_{ij} - (1 - \varepsilon_i)F_{ij}. \tag{9}$$

Here δ_{ij} is the Kronecker delta matrix. Note the matrix solution in Eq. (8) analytically resolves infinite number of reflections between canyon facets and trees through matric inversion for diffusive radiation exchange. The "emissivity" ε is used in the case of diffuse longwave radiation, while in the case of diffuse shortwave (solar) radiation, $(1 - a)$ will be used in the place of ε, with a the surface albedo (solar reflectivity).

By combining the Monte Carlo method for estimating view factors and the matric method for solving the net radiation, the numerical framework can therefore readily capture the effect of shade trees in the radiative energy exchange in a street canyon. Thus in this study, urban trees are explicitly incorporated into the single-layer UCM *for the first time*, which enables direct comparison of cooling effect and energy savings between trees and lawns. To our best knowledge, the comparative study between the two commonly found vegetation types has hitherto been missing, despite their potential in energy savings and important implications to sustainable urban development in arid environments.

3. Numerical simulations

3.1. Model evaluation

Both the UCM and the Monte Carlo method have been evaluated as "stand-alone" models separately [15,30], with relatively short simulation periods ranging from 24 h to one week. In this study, we aim to use newly coupled numerical framework to investigate the energy saving potentials of urban vegetation specifically in the arid city of Phoenix, Arizona. The coupled model is calibrated and tested against field measurements recorded by a flux tower located at Maryvale, West Phoenix, Arizona. The tower measured the local urban meteorology at the frequency of 10 Hz, and eddy covariance data were sampled using an integral time of 30 min. The model was initialized using surface states such as skin temperatures of each urban facet, while the initial conductive heat fluxes were set to zero. Tower measurements (30-min) of atmospheric variables, including air temperature/humidity, wind speed, pressure, and precipitation, and record of lumped (monthly) irrigation water usage from the City of Phoenix were used to drive the model over the entire calendar year of 2012.

Comparisons of model predictions and measurements of the annual surface temperature T_s, the sensible heat flux H, and the latent heat flux LE are shown in Fig. 3. The statistical goodness-of-fit coefficients (R^2) are 0.991, 0.874, and 0.691, while root mean square errors (RMSEs) are 1.39 °C, 12.51 W m^{-2}, and 7.36 W m^{-2} for T_s, H, and LE respectively. It is apparent that the model is robust in capturing the surface temperature, whereas its capacity in predicting sensible and latent heat fluxes is slightly weaker. This is inherent in all numerical weather predictions due to the predictive skill of turbulent transport of thermal energy and humidity. Nevertheless, the model performance of the new modeling framework is significantly improved as compared to the results of a synthetical study reported by Grimmond et al. [25,26]. In their study, the best median RMSE values of a group 31 urban land surface models, with most detailed information of urban landscape and vegetation, were reported as 22 W m^{-2} and 43 W m^{-2} for predicted H and LE, respectively.

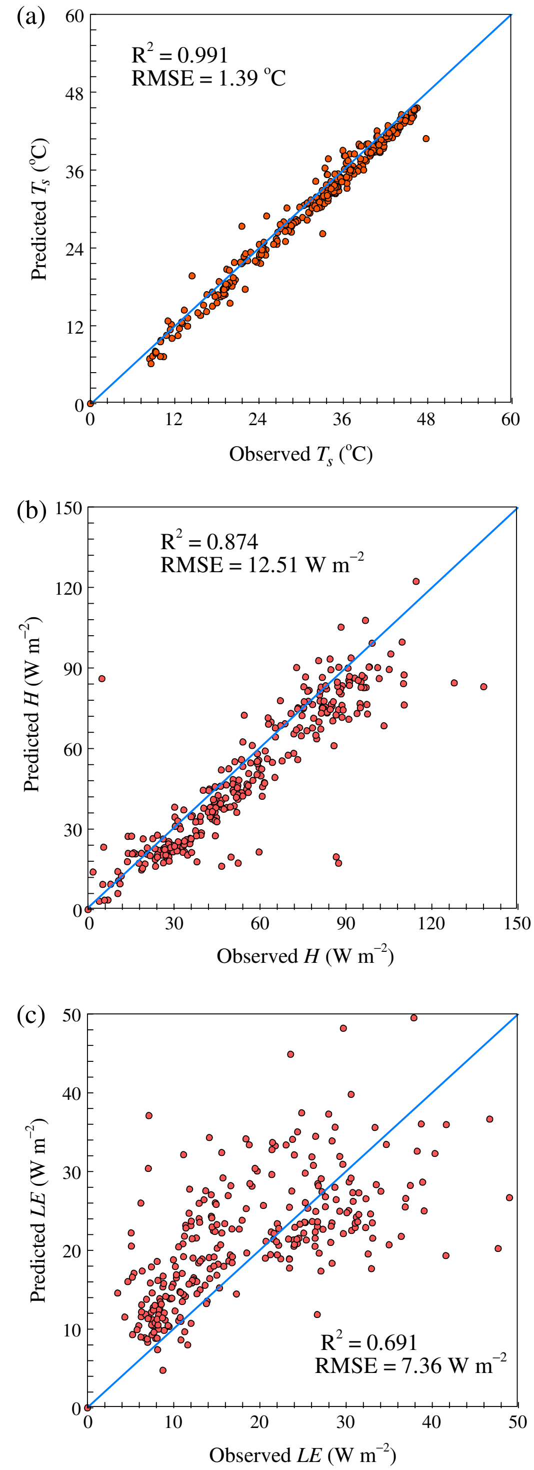

Fig. 3. Comparison of measured and predicted (a) T_s, (b) H, and (c) LE in Phoenix during the calendar year 2012.

3.2. Case study

Next we carry out a set of case studies using the validated modeling framework. The model is driven using measured meteorological forcing in Phoenix in 2012, with input parameters calibrated in Section 3.1 from model evaluation. To better assess the cooling effect of urban vegetation inside the street canyon, we focus on the ground (street) level, while keeping the hydrothermal properties of roofs and walls constant. The two controlling parameters for representing shade trees and urban lawns are the normalized tree crown radius r_t, and the areal vegetation (lawn) fraction f_v, defined as

$$r_t = \frac{R_t}{R+W}, \tag{10}$$

$$f_v = \frac{A_{\text{lawn}}}{A_{\text{ground}}}, \tag{11}$$

where R_t is the physical dimension of the tree crown radius (in m), R and W are the physical dimension of roof and street widths respectively, and A is the surface area. Notice that we assume the shading effect of tree trunks is relatively small and negligible as compared to that of the crown. Based on a previous survey of urban trees [38], the physical range of r_t is set to be from 0 to 0.1, with an interval of 0.02; and the lawn fraction is chosen as $0 \leqslant f_v \leqslant 1$, with an interval of 0.1 in subsequent simulations.

For mesic urban lawns, the daily irrigation rate used in this study is estimated based on the current irrigation water use data provided by the city from the in-situ (monthly) measurement. To quantify the savings of cooling load of urban vegetation during hot seasons, the electricity consumption by the air-conditioning system is set to exactly offset the thermal energy entering into buildings via walls to maintain a constant interior temperature of 25 °C. Note that here we neglect: (1) thermal energy entering buildings via roofs, and (2) the efficiency of air conditioning system and the variation of the building interior temperature. Due to these simplifications, results based on model simulations are not considered as quantitative, but rather qualitative, measures of saving of building energy. Nevertheless, given that the actual cooling load in buildings is closely related to the ambient thermal environment in the street canyon and heat flux conducted through walls, the results presented hereafter provides useful information on quantifying energy saving potentials of urban vegetation, though precise quantification requires more detailed information and further modeling efforts, e.g. combining the UCM framework with an operational building energy model. More details for quantification of energy savings based on the UCM predictions and the justification of the assumptions can be found in [16].

4. Results

Out of the series of the case study, we selected four representative cases for illustration, including: (1) the base scenario: urban canyon without vegetation ($r_t = 0$, $f_v = 0$), (2) ET cooling by lawns ($r_t = 0$, $f_v = 0.6$), (3) shading by trees ($r_t = 0.06$, $f_v = 0$), and (4) the combined cooling effect ($r_t = 0.06$, $f_v = 0.6$). Specifically, two model outputs, viz. the canyon air temperature (representing the human thermal comfort) and the heat conducted into buildings via walls (directly related to building cooling demand) are chosen as indicators. In addition, as our focus in this study is to estimate energy saving potential of urban vegetation in a cooling dominant desert city, we will focus on the summer months, viz. June, July and August, in subsequent sections.

Fig. 4 presents the results of model predictions of these outputs for a continuous 6-day period (01–07 June, 2012) for all four cases. The ET cooling by lawns decreases the maximum daytime temperature during the simulation period from 45.7 °C to 43.3 °C (f_v from 0 to 0.6) while shading reduces the peak temperature from 45.7 °C to 40.2 °C (r_t from 0 to 0.06). It is noticeable that the reduction of nocturnal temperatures by urban vegetation is comparatively more significant than that of daily peak temperatures. This is consistent to our field observation of surface temperatures over different urban land cover types. Given that UHI is more prominent in nighttime, the cooling effect by urban vegetation provides an effective means for UHI mitigation in the desert city. Model predictions of conductive heat flux through building walls follow the similar trend of the air temperature, with the cooling effect by shading manifested in Fig. 4b. This is primarily because that the impact of urban lawns via ET cooling has an indirect effect on heat conduction through walls via reduction of canyon air temperature and reflection of radiation from ground, while trees can provide direct shading on walls thus its effect is more significant.

In addition, model predicted monthly-averaged diurnal profiles of canyon air temperature and the conductive heat flux are shown in Fig. 5, for the aforementioned four cases driven by June 2012 meteorological forcing. The monthly average profiles represent the model estimates under a variety of weather conditions in the month. It is apparent that shading by trees (with $r_t = 0.06$, roughly 60% of the maximum possible tree crown size in a street canyon) exhibits a greater cooling effect than that of urban lawns (with 60% vegetation fraction). The difference is more manifested in the predicted conductive heat flux with the aforementioned reason, signaling that a larger potential saving of cooling load by shade trees in the study area.

Fig. 6 shows the estimated monthly-averaged energy consumption in June, July and August in residential districts of Phoenix for a variety of shade tree sizes and urban lawn fractions. It is clear that increasing sizes of both lawns and shade trees reduce the cooling load, while the improvement by shading is more prominent. Furthermore, we convert the reduction of energy consumption into monetary saving, using the electricity price provided by one of the local providers, viz. the Salt River Project (SRP). The local utility company provides different plans for electricity prices based on

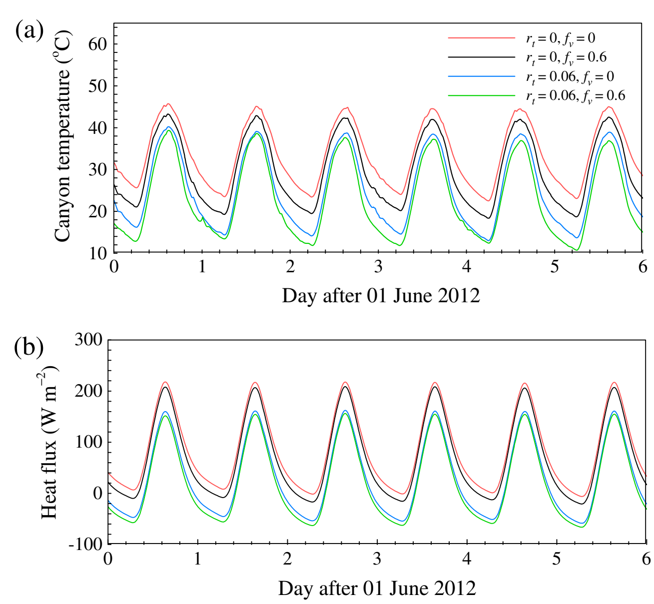

Fig. 4. Comparison of predicted (a) canyon air temperature, and (b) conductive heat flux into buildings with different urban lawn fractions f_v and normalized shade tree radius r_t. The meteorological forcing of Phoenix during 01–07 June, 2012 is used to drive the numerical simulations.

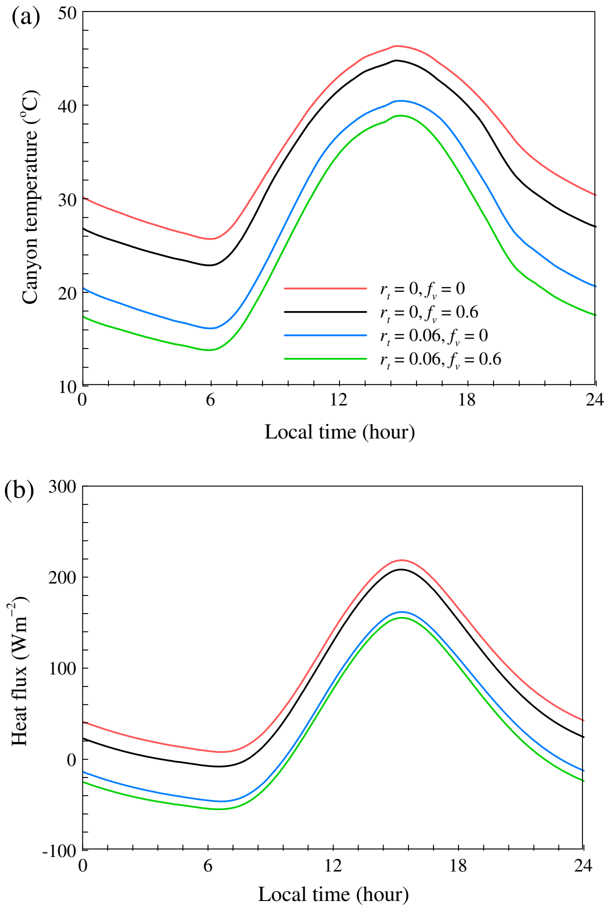

Fig. 5. Comparison of predicted monthly-averaged diurnal cycles of (a) canyon air temperature, and (b) conductive heat flux into buildings, with different urban lawn fractions f_v and normalized shade tree radius r_t over June, 2012.

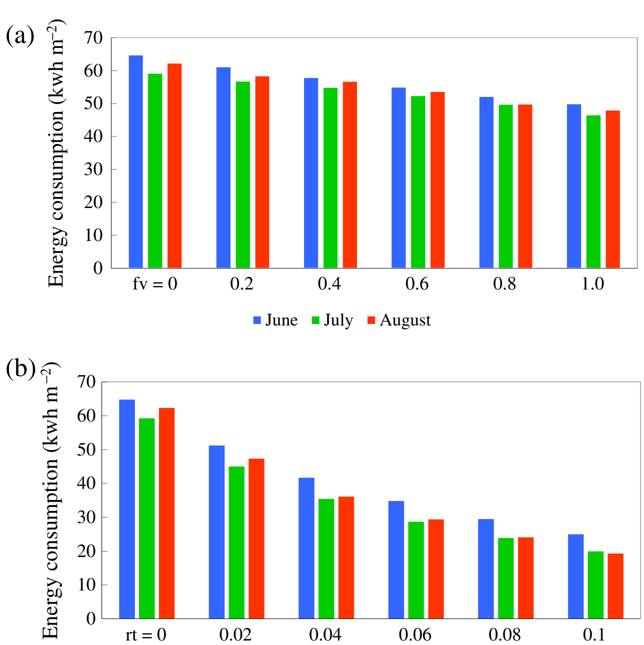

Fig. 6. Comparison of monthly-averaged energy consumption for various (a) fractions of vegetation on ground, and (b) normalized tree crown radius, for June, July, and August respectively.

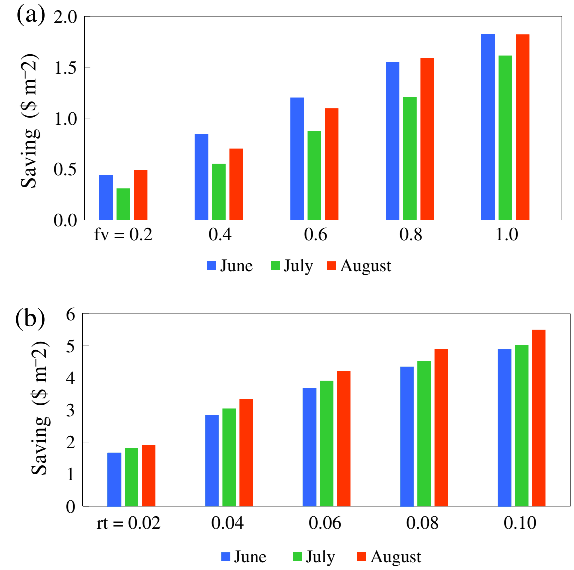

Fig. 7. Comparison of monthly-averaged monetary saving as compared to the "non-vegetation" case ($r_t = 0, f_v = 0$) for various (a) fractions of vegetation on ground, and (b) normalized tree crown radius, for June, July, and August respectively.

various peak and off-peak usage. For consistency, here we use the basic plan (http://www.srpnet.com/prices/home/basicfaq.aspx#2) provided by SRP, with the electricity prices 12.31, 12.83 and 12.83 ¢ kW h^{-1} for June, July and August, respectively. The results are shown in Fig. 7, with the savings vary from month to month subject to the variability of local climate and environmental temperatures. For the simulated summer of 2012, the maximum savings are found in August, namely \$1.82 m^{-2} with 100% lawn coverage, and \$5.50 m^{-2} with the maximum tree crown size ($r_t = 0.1$).

5. Discussion

5.1. Cooling and energy savings

Energy saving potentials of urban vegetation is directly related to their cooling effect on the environmental temperature. Simulation results clearly indicate that both urban lawns and shade trees are effective in cooling an urban environment and energy saving. The main differences between the two urban vegetation types include: (1) the cooling effect of lawns is mainly induced by redistributing available energy for latent heat of vaporization via ET, while trees cools the environment mainly by radiative shading (reduction of direct solar radiation on urban facets); (2) shade trees in xeric landscapes requires less irrigation than lawns (e.g. drip versus sprinkler irrigation) to sustain their biological function as well as the cooling effect; and (3) morphologically, urban lawns cover roughly 2D surface whereas trees occupy three-dimensional volumes. Different cooling mechanisms of lawns and trees trigger different irrigation requirement, which imposes important constraints on water resource planning. The first two aspects make shade trees a particularly attractive option in terms of energy-water trade-off, especially for cities in arid or semiarid regions. In addition to the potential of energy savings, savings of irrigation water by shade trees should be taken into account. Further comparative quantification of the environmental co-benefit of trees and lawns necessarily calls for more complete analysis such as life cycle assessment [39].

Furthermore, results of simulations show that despite the additional cost of water resource consumption, lawns are not as effective as trees in cooling and energy saving potentials (Figs. 4–7). This is closely related to the morphological differences of the two types of vegetation. Covering a 2D surface, the effect of ET cooling by lawns on building energy savings though the vertical facets (walls) is indirect. The cooling effect is transmitted to buildings first by direct cooling of the canyon air, and then by reducing the reflected thermal radiation (diffuse) from ground to walls. In contrast, by intercepting radiative energy, shade trees directly lower the skin temperatures of both vertical and horizontal urban facets, and yield more significant cooling effect and energy saving potentials. The relative cooling efficiency of trees and lawns is also shown in Fig. 8 for all simulated cases, where monthly-averaged (June 2012) canyon air temperatures are plotted in isotherms as a function of r_t and f_v. The observation is consistent to the results presented in the previous section. It is also noteworthy that when both shade trees and urban lawns are presented and the vegetation cover is abundant, the added cooling effect and energy savings, as compared to those due to single vegetation, are limited.

5.2. Outdoor thermal comfort

In addition to building energy savings, cooling by urban vegetation directly influences the human thermal comfort, especially in outdoor environment, which, in turn, has significant impact on energy consumption, one example being the use of air-conditioning system in vehicles. In this study, we adopted a widely used temperature humidity index (THI), defined as [40]

$$\mathrm{THI} = 0.8T_a + \frac{\mathrm{RH} \times T_a}{500}, \tag{12}$$

where T_a is the air temperature in °C and RH is the relative humidity in %.

Based on tests on human subjects, it is suggested as when THI > 29, work should be suspended in mid-latitudes and warm-humid regions [41]. Using this criterion, the predicted percentage of work-suspended time, measured in a 30-min interval based on model outputs, is shown in Fig. 9. It is clear that the introduction of larger fractions of urban vegetation can effectively abate the suspended working time in all summer months. In particular, comparing the two cases of "cooling by lawns" ($r_t = 0$, $f_v = 0.6$) and "shading by trees" ($r_t = 0.06$, $f_v = 0$), it is found that despite that shading induces more significant cooling effect than ET (c.f. Fig. 5a), both cases yield comparable work suspension rate over the entire summer. This is because the increase of air humidity from urban lawns via ET plays a significant role in affecting the human thermal comfort. The desert climate of Phoenix features very dry and hot summers, whereas a small increment in relative humidity helps to compensate the evaporative loss from human skin, hence improves THI.

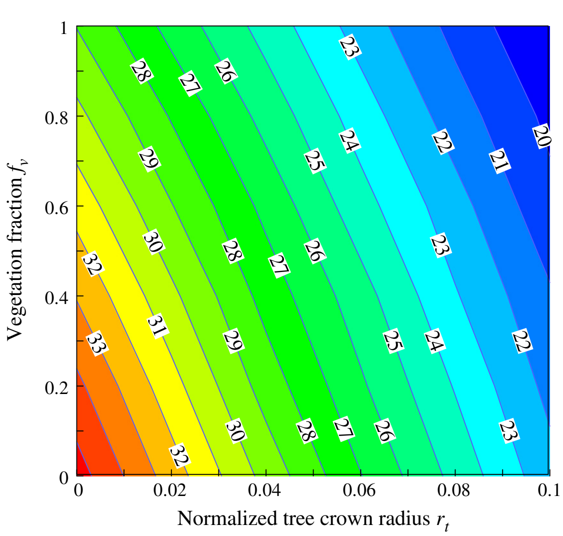

Fig. 8. Isotherms of canyon air temperature as a function of normalized tree crown radius and vegetation fraction.

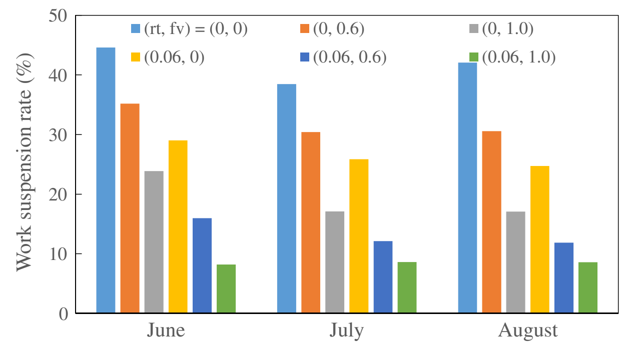

Fig. 9. Estimated work suspension rate (with THI > 29) with different urban lawn and shade tree covers for June, July, and August respectively.

6. Concluding remarks

In this paper, we developed a novel numerical framework by integrating shade trees into the latest single-layer WRF–UCM with enhanced urban hydrological processes. The proposed framework was applied to investigate the effect of urban vegetation on urban cooling and potential savings of building energy, using the desert city Phoenix as a testbed. It was found that trees have an overall more significant cooling effect due to shading than the ET cooling of lawns, which is more manifest in potential building energy savings. In addition, shade trees in semiarid and arid cities are usually presented as xeric landscape with parsimonious irrigation requirement. This further adds to the total saving potentials of urban trees by imposing less constraint on water resource management.

We reiterate here that due to the assumptions and simplifications, the results presented here based on numerical case study may not precisely represent the real scenarios due to a number of assumptions used in simulations. In addition, results of simulations are expected to be site-specific, as they depend largely on climatic, geographic, demographic, and socioeconomic conditions of different cities worldwide. Nevertheless, this paper presents a pioneering effort in quantifying the use of urban vegetation as a landscape planning strategy with a novel modeling framework. The results are instructive in demonstrating the effectiveness and potential of shade trees and urban lawns in mitigating adverse environmental effect (such as UHI), saving building energy, and enhancing human thermal comfort in built environments, particularly in arid and semi-arid regions. It is also recommended that in future studies, the life cycle analysis of cost-benefit of urban vegetation, the constraint of water usage (e.g. for irrigation), and the trade-off between energy and water resources should be thoroughly investigated.

Acknowledgements

This work is supported by the US National Science Foundation (NSF) under grant number CBET-1435881. Field measurement by the eddy-covariance tower at Maryvale, West Phoenix sponsored by NSF under grant EF-1049251 is acknowledged.

References

[1] Flinn J, Satyanarayanan M. Powerscope: a tool for profiling the energy usage of mobile applications. In: Mobile computing systems and applications, 1999 proceedings WMCSA'99 second IEEE workshop on: IEEE; 1999. p. 2–10.
[2] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8.
[3] Salamanca F, Georgescu M, Mahalov A, Moustaoui M, Wang M, Svoma BM. Assessing summertime urban air conditioning consumption in a semiarid environment. Environ Res Lett 2013;8(3):034022.
[4] Oke TR. The energetic basis of the urban heat island. Quart J Roy Meteorol Soc 1982;108(455):1–24.
[5] Santamouris M. Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol Energy 2014;103:682–703.
[6] Nazaroff WW. Exploring the consequences of climate change for indoor air quality. Environ Res Lett 2013;8:015022.
[7] Song J, Wang ZH. Interfacing the urban land–atmosphere system through coupled urban canopy and atmospheric models. Boundary-Layer Meteorol 2015;154:427–48.
[8] Cameron RWF, Blanusa T, Taylor JE, Salisbury A, Halstead AJ, Henricot B, et al. The domestic garden – its contribution to urban green infrastructure. Urban For Urban Green 2012;11:129–37.
[9] Berardi U, GhaffarianHoseini A, GhaffarianHoseini A. State-of-the-art analysis of the environmental benefits of green roofs. Appl Energy 2014;115:411–28.
[10] Ouldboukhitine S-E, Belarbi R, Sailor DJ. Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings. Appl Energy 2014;114:273–82.
[11] Feng H, Hewage K. Energy saving performance of green vegetation on LEED certified buildings. Energy Build 2014;75:281–9.
[12] Perez G, Rincon L, Vila A, Gonzalez JM, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. Appl Energy 2011;88:4854–9.
[13] Akbari H, Kurn DM, Bretz SE, Hanford JW. Peak power and cooling energy savings of shade trees. Energy Build 1997;25:139–48.
[14] Huang Y, Akbari H, Taha H, Rosenfeld AH. The potential of vegetation in reducing summer cooling loads in residential buildings. J Clim Appl Meteorol 1987;26:1103–16.
[15] Yang J, Wang ZH, Chen F, Miao S, Tewari M, Voogt J, Myint S. Enhancing hydrologic modeling in the coupled Weather Research and Forecasting – urban modeling system. Boundary-Layer Meteorol 2015;155:87–109.
[16] Yang J, Wang ZH. Optimizing urban irrigation schemes for the trade-off between energy and water consumption. Energy Build 2015;107:335–44.
[17] Mitchell V, Mein RG, McMahon TA. Modelling the urban water cycle. Environ Model Softw 2001;16:615–29.
[18] Gober P, Brazel A, Quay R, Myint S, Grossman-Clarke S, Miller A, et al. Using watered landscapes to manipulate urban heat island effects: how much water will it take to cool Phoenix? J Am Plan Assoc 2010;76:109–21.
[19] Volo TJ, Vivoni ER, Martin CA, Earl S, Ruddell BL. Modelling soil moisture, water partitioning, and plant water stress under irrigated conditions in desert urban areas. Ecohydrology 2014;7:1297–313.
[20] Litvak E, Bijoor NS, Pataki DE. Adding trees to irrigated turfgrass lawns may be a water-saving measure in semi-arid environments. Ecohydrology 2014;7:1314–30.
[21] Heisler GM. Energy savings with trees. J Arboricul 1986:113–25.
[22] Akbari H, Taha H. The impact of trees and white surfaces on residential heating and cooling energy use in 4 Canadian cities. Energy 1992;17:141–9.
[23] Loughner CP, Allen DJ, Zhang D-L, Pickering KE, Dickerson RR, Landry L. Roles of urban tree canopy and buildings in urban heat island effects: parameterization and preliminary results. J Appl Meteorol Climatol 2012;51:1775–93.
[24] Kikegawa Y, Genchi Y, Yoshikado H, Kondo H. Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. Appl Energy 2003;76:449–66.
[25] Grimmond CSB, Blackett M, Best MJ, Barlow J, Baik JJ, Belcher SE, et al. The international urban energy balance models comparison project: first results from Phase 1. J Appl Meteorol Climatol 2010;49:1268–92.
[26] Grimmond CSB, Blackett M, Best MJ, Baik JJ, Belcher SE, Beringer J, et al. Initial results from Phase 2 of the international urban energy balance model comparison. Int J Climatol 2011;31:244–72.
[27] Wang ZH, Bou-Zeid E, Smith JA. A spatially-analytical scheme for surface temperatures and conductive heat fluxes in urban canopy models. Boundary-Layer Meteorol 2011;138:171–93.
[28] Wang Z-H, Bou-Zeid E, Smith JA. A coupled energy transport and hydrological model for urban canopies evaluated using a wireless sensor network. Quart J Roy Meteorol Soc 2013;139:1643–57.
[29] Krayenhoff E, Christen A, Martilli A, Oke T. A multi-layer radiation model for urban neighbourhoods with trees. Boundary-Layer Meteorol 2014;151:139–78.
[30] Wang Z-H. Monte Carlo simulations of radiative heat exchange in a street canyon with trees. Sol Energy 2014;110:704–13.
[31] Chow WTL, Brennan D, Brazel AJ. Urban heat island research in Phoenix, Arizona: theoretical contributions and policy applications. Bull Am Meteorol Soc 2012;93:517–30.
[32] Ruddell BL, Salamanca F, Mahalov A. Reducing a semiarid city's peak electrical demand using distributed cold thermal energy storage. Appl Energy 2014;134:35–44.
[33] Brutsaert W. Hydrology: an introduction. Cambridge: Cambridge University Press; 2005.
[34] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. Boundary-Layer Meteorol 2000;94:357–97.
[35] Noilhan J, Planton S. A simple parameterization of land surface processes for meteorological models. Mon Weather Rev 1989;117:536–49.
[36] Niyogi DS, Raman S. Comparison of four different stomatal resistance schemes using FIFE observations. J Appl Meteorol 1997;36:903–17.
[37] Wang ZH. Geometric effect of radiative heat exchange in concave structure with application to heating of steel I-sections in fire. Int J Heat Mass Transf 2010;53:997–1003.
[38] Dwyer JF, Nowak DJ, Noble MH, Sisinni SM. Connecting people with ecosystems in the 21st century: an assessment of our nation's urban forests. General Technical Report-Pacific Northwest Research Station, USDA Forest Service; 2000.
[39] Spatari S, Yu ZW, Montalto FA. Life cycle implications of urban green infrastructure. Environ Pollut 2011;159:2174–9.
[40] Nieuwolt S. Tropical climatology. An introduction to the climates of the low latitudes. Chichester: John Wiley and Sons; 1977.
[41] Auliciems A, Szokolay SV. Thermal comfort. Australia: The University of Queensland; 2007.