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

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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.

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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

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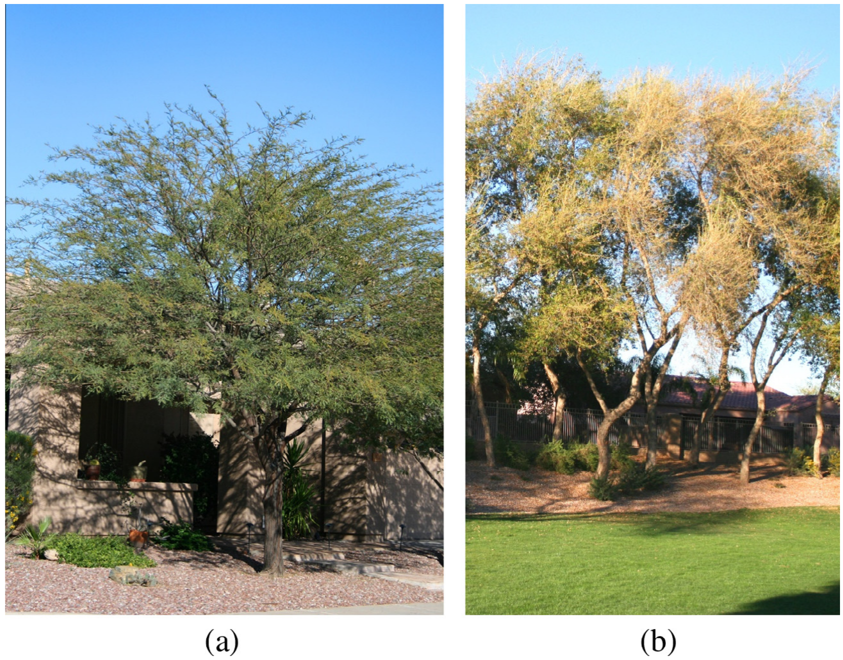

Fig. 1. Typical urban vegetation types in Phoenix, Arizona: (a) a shade tree on xeric (desert) landscape and (b) mesic urban lawn (with xeric trees in the background).

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