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Patch size of trees affects its cooling effectiveness: A perspective from shading and transpiration processes

Min Jiao[a,b], Weiqi Zhou[a,b,*], Zhong Zheng[a,b], Jia Wang[a,b], Yuguo Qian[a]

[a] State Key Laboratory Of Urban And Regional Ecology, Research Center For Eco-Environmental Sciences, Chinese Academy Of Sciences, No.18 Shuangqing Road, Beijing 100085, China

[b] University Of Chinese Academy Of Sciences, No.19A Yuquan Road, Beijing 100049, China

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ABSTRACT

Increasing urban greenspace, particularly trees, has been widely recognized as an effective means for urban heat mitigation. Lots of uncertainty, however, occurs on how spatial configuration of trees affects their cooling effectiveness. A frequently asked question from urban planners is that whether a large greenspace patch has better cooling effects than several smaller ones, or vice versa. Here, we attempted to address this question by investigating the effects of patch size of trees on the two key cooling processes: shading and transpiration. We chose two typical tree species, *Ginkgo biloba* and *Populus tomentosa*, with 4 different patch sizes, and conducted the research in Beijing. We integrated field measurements of air temperature, relative humidity and transpiration rate with model simulation, and conducted the analysis at both the patch and within-patch level. We found: (1) Smaller patches had higher temperature, lower humidity and greater within-patch variations in temperature and humidity than larger ones. (2) With a fixed area of tree cover, a number of small patches can provide more shade than a single large patch, suggesting a monotonic increase of shade provision with the division of a large patch into smaller ones. (3) There was a non-linear relationship between patch size and transpiration rate, suggesting a maximum transpiration rate might occur at certain patch size. By considering the joint effects of shading and transpiration, an optimal size of patch might occur, at which the joint effects of shading and transpiration are maximized.

1. Introduction

Urban heat island (UHI) effect refers to the phenomenon that the city center is warmer than the surrounding rural area, first observed by Lake Howard in 1818 (Howard, 1818). The UHI effect tends to be intensified with the accelerated urbanization process (Zhou et al., 2004). Many studies have shown the adverse impacts of UHI effects. For example, it aggravates air pollution (Sun et al., 2015), leads to more extreme heat events (Nasrallah et al., 2004), causes more water and energy consumption (Santamouris et al., 2015), affects the living comfort, and even the health of urban residents (Dung et al., 2016).

There are different ways that can be used to mitigate the urban heat island effect, such as reducing anthropogenic heats, increasing urban green spaces and wetlands, and using high reflectance materials (Avissar, 1996; Fan and Sailor, 2005; Santamouris et al., 2011; Steeneveld et al., 2014). Among these strategies, increasing urban greenspaces has been the most widely advocated approach because not only can urban greenspaces provide cooling effects (Bowler et al., 2010; Chang et al., 2007; Chen et al., 2012), but also provide various other ecosystem services, such as increasing humidity, dust-retention, and noise reduction (Chiesura, 2004).

Considerable amounts of studies have been conducted to investigate the cooling effects of urban greenspace at both the landscape and patch scales. At the landscape scale, studies have mostly focused on the relationships between the composition and configuration (i.e., spatial arrangement) of greenspace and temperatures (both air and land surface temperatures, but land surface temperature more often). Numerous studies have shown that the percent cover of vegetation is negatively correlated with temperatures, suggesting locations with higher proportional cover of greenspace have cooler thermal environments (Adams and Smith, 2014; Guo et al., 2015; Huang and Cadenasso, 2016; Hu and Jia, 2010; Zhou et al., 2014). Spatial configuration also significantly affect temperatures, even after controlling for the effects of percent cover of greenspace (Li et al., 2012; Xie et al., 2013; Zhou et al., 2011; Zhou et al., 2017). For example, mean size of greenspace patches has significantly negative relationship with land surface temperature (LST), suggesting the increase of patch size of greenspace may further lower the temperatures (Kong et al., 2014; Li et al., 2013). In addition,

* Corresponding author at: Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing, 100085, China.
E-mail addresses: jiaomin@scib.ac.cn (M. Jiao), wzhou@rcees.ac.cn (W. Zhou), szzings@163.com (Z. Zheng), ecowangjia@163.com (J. Wang), guozigu1015@163.com (Y. Qian).

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patch density is negatively correlated to LST, indicating more patches of greenspace may lead to cooler thermal environments (Li et al., 2011).

Fewer studies have been conducted at the patch level. Most of these studies have focused on how the effects of patch characteristics of greenspace, such as size, shape and species composition affect their cooling effects (Bowler et al., 2010). These studies find that greenspace patches with larger sizes generally have lower air and surface temperatures than smaller ones (Chang et al., 2007; Gioia et al., 2014). In addition, greenspace can also lower the temperature in its surrounding areas to a certain distance range. This range is affected by the patch size of the greenspace, with larger patches tending to have cooling effect for greater extent (Chang et al., 2007; Chen et al., 2012; Gioia et al., 2014). Few studies, however, have investigated the cooling effects of a large patch, compared to several small ones whose total areas equals to the large one. In other words, the research question that whether a large greenspace patch has better cooling effects than several smaller ones remain largely unaddressed. Additionally, previous studies on cooling effects of greenspace mostly focused on the statistical relationships between patterns of greenspace and temperatures. Only a very few studies have been conducted from the perspective of the two major cooling mechanisms, that is, shading and transpiration (Armson et al., 2012; Rahman et al., 2015; Shashua-Bar and Hoffman, 2000; Wang et al., 2016). While there is an increasing interest in the cooling mechanisms of greenspace, previous studies have mostly focused on one of the two cooling processes, either the role of shading of trees in affecting local and regional thermal environment (Armson et al., 2012; Wang et al., 2016), or the evapotranspirational cooling effectiveness of different tree species (Rahman et al., 2015). Few studies have investigated both cooling processes.

The overall objective of this study is to investigate how the patch sizes of trees affect the two key cooling processes, shading and transpiration, and thus their cooling effects. Specifically, we attempt to address two questions: (1) how do the air temperature and humidity of greenspaces vary by patch sizes at both the patch level and within-patch level (i.e., the internal distributions within a patch)? (2) How does the patch size of trees affect its effects on shading and transpiration? In other words, how do the shading and transpiration change as one single large patch of greenspace becomes several scattered small ones whose total areas equals to the large one? The results from this study can enhance our understanding on how patch size of greenspace affect the two key cooling processes of shading and transpiration, and thus their cooling effects. These results will also provide important insights for urban greenspace planning and management.

2. Methods

2.1. Study area

This study was carried out at the Beijing city (39°28′ − 41°25′N, 115°25′ − 117°30′E). Beijing is the capital of China, with a total area of 16,410 km^2 and total population of more than 22 million. Beijing lies in the northeast of the North China Plain, and belongs to the Haihe River watershed. Beijing city has the monsoon-influenced humid continental climate, with an annual average temperature of 12.3 °C and annual precipitation of 572 mm. Its coldest month is January (around 1 °C) and warmest month is July (above 30 °C). Since the implementation of the Reform and Open Policy in 1978, Beijing experienced rapid urbanization and followed by intensification of urban heat island effects (Liu et al., 2007).

2.2. Selection of greenspace patches

In this study, we selected five patches of trees with different sizes (Fig. 1). These included two patches of *Ginkgo biloba* with sizes of 77165 m^2 (G1) and 11648 m^2 (G2), and three patches of *Populus tomentosa* with sizes of 12272 m^2 (P3), 4561 m^2 (P4) and 672m^2 (P5), respectively. We chose *Ginkgo biloba* and *Populus tomentosa* because these are the two most widely used greening species in Beijing. We selected the four types of patch sizes based on the size distribution of patches of greenspace in the Beijing City (Qian et al., 2015a). Approximately 90% of the greenspace patches were smaller than 5000 m^2, among which 50% were smaller or equaled to 500 m^2. In addition, patches with size greater than 5000 but smaller than 10,000 m^2 accounted for approximately 5%, the same as that of patches with size greater than 10,000 but smaller than 80,000 m^2. Consequently, we focused on patches with sizes of 80,000 m^2, 10,000 m^2, 5000 m^2, and 500 m^2.

Ideally, we would select patches of both tree species for each type of sizes. However, after considering the main factors that may affect the cooling effect of vegetation, such as age of trees, distance between trees, type of ground surface, surrounding environments and maintenance conditions (Hagishima et al., 2007), it is difficult to find such four patches for each tree species in our study area. Consequently, we selected two patches of *Ginkgo biloba* and three patches of *Populus tomentosa*. The two patches of *Ginkgo biloba* were both pure forests that were planted at the same time and maintained in the same way, and thus were similar in diameter at breast height (12.1 ∼ 14.6 cm and 11.1 ∼ 14.9 cm), in distance between trees (2 ∼ 3 m), in ground surfaces (soils) and surrounding surfaces (impervious surfaces). The three patches of *Populus tomentosa* were also pure forests that were planted at the same time and maintained in the same way, with similar diameter at breast height (18.5 ∼ 23.8 cm, 18.2 ∼ 25.5 cm and 17.2 ∼ 25.2 cm), similar distance between trees (3 ∼ 4 m), and similar ground surfaces (soils) and surrounding surfaces (impervious surfaces).

2.3. Field measurements and model simulation

We measured air temperature, relative humidity and transpiration rate of each patch in August 25–28, 2015, and simulated the areas shaded by green patches (Table 1). The weather conditions during these days were similar. Air temperature and relative humidity at the height of 1.5 m were measured with MI-6401 at 09:00, 12:00 and 15:00. For each patch, we set four transects from the center to the edge, and collected five measurements with equal intervals along each transect. Green patches were divided into five zones accordingly, and the within-patch variations of temperature and humidity were described as the changes of temperature and humidity per unit distance of each zone. We also measured the temperature and relative humidity of surrounding environments simultaneously. Measurements were obtained at every 20 m along 2 or 3 streets extended from the edges of the patch until the temperature and relative humidity remained relative stable. The cooling and humidification effect of a green patch was evaluated by the difference between the mean value of air temperature and relative humidity measured at the green patch and the surroundings.

We only considered transpiration of trees, but not soil evaporation in this research. This is because the five patches are all mature forest with relative dry soil surface and dense canopy which intercepts most of the incident radiation. Previous studies have shown that the soil evaporation is probably insignificant when the tree canopy intercepts most of the incident radiation and the soil surface is dry (Lambers et al., 2008a). Transpiration rate of trees was measured by using LI-6400XT. We measured the transpiration rate of the sun leaves at upper parts of trees (Hileman et al., 1994; Premachandra et al., 1994). We used the same sampling strategy to measure the within-patch transpiration rates as that of the temperature and humidity.

Areas shaded by greenspace patch were simulated and estimated using the Solar Radiation tool embedded in ArcGIS™. For each patch, a 12-h simulation starting at 06:00 local time in 25-July 2015 was conducted. We calculated the cumulative values of solar radiation received by each patch for the whole day, based on which the shaded area of each green patch was measured. We ran the simulations for patches with 4 different sizes, 80,000 m^2, 10,000 m^2, 5000 m^2 and 500 m^2,