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

ARTICLE INFO

Keywords:

Greenspace patch size
Cooling effect
Humidification effect
Edge effect
Shading
Transpiration

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 (Avisar, 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).

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 km² 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 m² (G1) and 11648 m² (G2), and three patches of *Populus tomentosa* with sizes of 12272 m² (P3), 4561 m² (P4) and 672m² (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 m², among which 50% were smaller or equaled to 500 m². In addition, patches with size greater than 5000 but smaller than 10,000 m² accounted for approximately 5%, the same as that of patches with size greater than 10,000 but smaller than 80,000 m². Consequently, we focused on patches with sizes of 80,000 m², 10,000 m², 5000 m², and 500 m².

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 m², 10,000 m², 5000 m² and 500 m²,

Fig. 1. The sampling location for five green patches in Beijing city. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

corresponding to the sizes of the sampled patches. The height of the trees for the patch of *Ginkgo biloba* was set as 7 m, the height of trees of the sampling patches, while the height for the other three patches of *Populus tomentosa* was 14 m.

3. Results

3.1. Temperature and humidity of woodland patches with different sizes

We found that the smaller the patch, the higher the temperature and the lower the relative humidity of the *Ginkgo biloba* and *Populus tomentosa* forest (Fig. 2). Average air temperature throughout the day of G1 (the patch of *Ginkgo biloba* with size of 80,000 m²) was 0.5 °C lower than G2 (the patch of *Ginkgo biloba* with size of 10,000 m²), while the average relative humidity of G1 was 2.1% higher than G2. The largest differences of air temperature and relative humidity between G1 and G2 occurred at 15:00, and were − 1.6 °C and 7.1%, respectively. Similarly, the patch of *Populus tomentosa* with size of 10,000 m², P3, had the lowest average air temperature and highest relative humidity (29.5 °C, 47.7%), followed by the patch of *Populus tomentosa* with size of 5000 m², P4 (30.9 °C, 42.3%), and the patch of *Populus tomentosa* with size of 500 m², P5 (31.4 °C, 41.0%). The maximum differences of air temperature and relative humidity between P3 and P5 also occurred

at 15:00 (− 4.2 °C and 16.9%).

3.2. Within-patch variations of temperature and humidity

The results showed that there were larger within-patch variations in temperature and humidity in smaller patches. Temperature and humidity changed dramatically from the center to the edge for small forest patches. For example, for the patch of *Populus tomentosa* with size of 500 m², temperatures changed from 33.6 °C in the center to 35.1 °C in the edge at 15:00. In contrast, changes in temperature and humidity were relatively small in large patches. Temperature only gradually increased from the patch center to edges, while relative humidity slightly decreased (Fig. 3). These patterns occurred for all the hours we sampled. As for different hours, the variations in temperature for each zone increased from morning to afternoon, reaching the maximum variation of air temperature at 15:00, while the change of relative humidity did not clearly show such a trend.

3.3. Cooling and humidification effects of greenspaces with different sizes

All the woodland patches had 0.7–5.7 °C lower air temperatures and 1.3–15.8% higher relative humidity than their surrounding environments, indicating clear cooling and humidification effects throughout

Table 1
Observational items, locations and equipment.

Observational items	Locations	Observational Equipment (accuracy or measured band)
Air temperature, relative humidity	Patch inside, four transects from the center to the edge of each patch, five measurements were made with equal intervals along each transect Surrounding, measurements were made spaced at about 20 m from patch edge to outside, along 2 or 3 streets	Portable environmental quality integrated tester (Poly MI 6401, METREL) (± 0.2 °C, 0.1 °C and ± 2%, 0.1%)
Transpiration rate	Patch inside, the same with air temperature and relative humidity	Portable photosynthesis system (LI-6400XT, USA LI-COR) (± 1.0 mmol H ₂ O m ^{−2} s ^{−1})
Shade area	The areas shaded by patches	Simulation with Solar Radiation tool embedded in ArcGIS™

Fig. 2. (a) Air temperature of green patches with different size. (b) Relative humidity of green patches with different size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the day. The magnitudes of cooling and humidifying, however, varied by patch size (Fig. 4). Larger greenspace patches tended to have stronger cooling and humidification effects. G1 had stronger cooling and humidification effects than G2 at all the hours throughout the day. Similarly, larger patches of *Populus tomentosa* had stronger cooling and humidification effects, but there were some variations at different hours during the day.

3.4. Shading and transpiration rates and their relationships to patch size

The larger the patch, the more shading area was provided to its peripheral region (Fig. 5a). With the same patch size, P3 provided a shading area of 2134.5 m², greater than that of 1335.5 m² provided by G2. This was because trees of P3 (*Populus tomentosa*) were higher than those of G2 (*Ginkgo biloba*). The simulation results showed that with a fixed area of tree cover, a number of small patches could provide more shade than a single large patch, suggesting a monotonic increase of shade provision with the division of a large patch into several smaller ones (Fig. 5b). Shade provision increased by 5383 m² as 1 G1 patch was divided into 8 patches with the size of G2. And the shade area increased nearly four-folds when 8 patches of the size of P3 were divided into 160

patches of the size of P5.

For the same tree species, vegetation transpiration rates varied by patch size (Fig. 6). The transpiration rate of G1 with a patch size of 80,000 m² was lower than that of G2 with a patch size of 10,000 m² throughout the day, suggesting for *Ginkgo biloba*, the transpiration rate increased with the decrease of the size of the patch. However, *Populus tomentosa* showed totally opposite trend. The transpiration rate of *Populus tomentosa* decreased with the decrease of the patch size. As expected, the transpiration rate of P3 was higher than G2. In fact, the difference in transpiration rate between the two different tree species was greater than that among the same species with different patch sizes.

4. Discussion

4.1. Effects of patch size on the air temperature, relative humidity, cooling and humidifying effect of greenspaces

The cooling and humidifying effect is a phenomenon that the temperature of greenspace is lower, and the humidity is higher, than its peripheral region, which leads to the reduction of temperature and increase of humidity in the peripheral region by horizontal transport of

Fig. 3. Temperature and humidity change per unit distance for each zone of greenspace with different size.

Fig. 4. (a) The relative difference of air temperature between each green patch and its surrounding environment. (b) The relative difference of relative humidity between each green patch and its surrounding environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cool air mass and evapotranspirative air-parcels from trees (Chang and Li, 2014). All the greenspace patches in our research clearly showed a cooling and humidifying effect, consistent with many previous research results (Cao et al., 2010; Feyisa et al., 2014; Oliveira et al., 2011; Qin et al., 2014). Furthermore, our results showed that patch size had a significant effect on the cooling and humidifying effect of greenspace, and the larger patches tended to have greater cooling and humidifying effect. Such findings have also been reported in a number of previous studies. For example, Gioia et al. (2014) found that the patch size of vegetation largely explained the variation in temperature in three urban areas of northwestern Argentina. Chang et al. (2007) found that large parks were cooler than small ones on average based on the analysis of 61 city parks in Taipei.

We found that the changes in temperature and humidity from the patch center to the edge of were greater for smaller patches. This may be due to the smaller greenspace patches tend to be hyper-disturbed because of the edge effects (Laurance et al., 1997; Malcolm, 1994; Malcolm, 1998). According to the edge effect, a greenspace patch can be divided into interior area that is relatively stable and the edge area that is easily affected by the surrounding. The edge effect is closely related to the size of a patch, the adjacent patches and the matrix (Laurance and Yensen, 1991). With the increase of the patch size, the interior area increases faster than the edge area, and vice versa (Didham et al., 1998; Laurance and Yensen, 1991; Wu and Vankat, 1991).

Consequently, a larger greenspace patch could have more interior areas which are less affected by the ambient environment, while a smaller one tends to have a greater proportion of edge areas (Ries et al., 2004), which are vulnerable to the disturbance from the peripheral

Fig. 6. Transpiration rates of trees in green patches with different size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

region (Wu and Vankat, 1991). In fact, when the patch size is smaller than some threshold level, the entire patch becomes edge area (Wu and Vankat, 1991). This edge effect may also explain the observed results that the temperature of smaller patches was higher, and the humidity was lower than the larger ones (Moreno et al., 2014), as small patches have greater proportions of edge areas, hotter and drier than interior area (Laurance, 2004).

Fig. 5. (a) Shading area of green patches with different size. (b) Shade provision with the division of a large patch into several smaller ones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Effects of patch size on shading and transpiration

Patch size plays an important role in shade provision by greenspace. With a fixed total area, multiple small patches can provide more total area of shade than a single large one, with a greater number of small patches, the more shade provision. In other words, the shade provision per unit area of green patch was negatively related to patch size. This is because when a single large one is divided into a number of smaller ones, more edges are created (Laurance and Yensen, 1991). As the shade provision by trees increases with solar angle getting smaller, the negative relationship between patch size and shade provision per unit area is strengthened near sunrise or sunset. These results indicated that in terms of shade provision, given a fixed amount of green cover, a larger number of smaller patches of greenspace are better.

Results showed that the transpiration rate changed by patch size. It was a non-linear relationship between the transpiration rate and patch size. When the patch is big enough, the transpiration rate decreases with the increase of patch size. As shown in our study, G2, the smaller patch of *Ginkgo biloba* had larger transpiration rate than G1. This may be related to the edge effect. Due to the lack of obstacles to both solar radiation and winds resulting in large inputs of radiation and sensible heat, the transpiration rate of edge was higher than that of the central part (Hagishima et al., 2007). When the patch is relatively small, the result can be reversed, as indicated by the patches of *Populus tomentosa*. This is because too much input of radiation and sensible heat may lead to leaf rolling or wilting to avoid excessive water loss, resulted in decreased transpiration rate (Lambers et al., 2008b).

In addition, different tree species composition with varied height will affect the amount of shade provision, and higher trees can provide more shading area to its peripheral region. Our results also showed that the difference in transpiration rate among greenspace patches with different sizes was smaller than that between tree species, suggesting that the selection of suitable tree species may be more important than changing the size of greenspace to improve the effect of transpiration cooling. Pataki et al. (2011) also reported that species composition was the major driver for transpiration differences among various urban forests. Therefore, selecting appropriate tree species is also an important way to improve the cooling effect.

4.3. Dose an optimal patch size of woodland occur for most efficient cooling effects?

The cooling effects of urban greenspace are mostly determined by the two key processes, shading and transpiration (Bowler et al., 2010). Our results showed that both processes were affected by patch size. While the shade provided by trees increased substantially when woodland became more fragmented, there was a non-linear relationship between patch size and transpiration rate. Therefore, we could expect that an optimal patch size of woodland may occur at which the woodland provides the most efficient cooling effects. This optimal size would be determined by the trade-off between shading and transpiration. Identifying such optimal patch size can have significant practical implications for urban greenspace management and design. This is because land in cities that can be used for greening is very limited (Qian et al., 2015b), and therefore knowledge on enhancing the cooling effects of greenspace by for example, optimizing their spatial configuration in addition to adding more greenspace is highly desirable. Unfortunately, we could not identify this optimal size in this study because we were not able to choose adequate number of patches of woodland with various sizes that met the experimental conditions. Future research that aims to identify such threshold is highly desirable, and results from this study can provide important insights on how to design such studies. With the advances in Light Detecting and Ranging (LiDAR) and unmanned aerial vehicle technology, greenspace patches can be accurately mapped, as well as their vertical dimension (Zhou, 2013). In addition, the two key cooling processes, shading and

evapotranspiration, can be measured based on simulation with recent advances in modeling (e.g., Ryu et al., 2016; Song and Wang, 2016; Wang et al., 2016). These advances facilitate future studies that aims to identify such optimal threshold of patch area at which maximum cooling efficiency might occur.

5. Conclusions

Our study examined how the sizes of greenspaces affect the two key cooling processes, shading and transpiration, and thus their cooling and humidification effects. We found that the size of tree patch affected trees' effects on air temperature reduction and relative humidity enhancement at both the patch and within-patch level. Smaller patches tend to have higher temperature, lower humidity and greater within-patch variations in temperature and humidity than larger ones. It might be due to the fact that smaller greenspace patches tend to be hyper-disturbed because of the edge effects. Trees' patch size also affected the shading and transpiration processes. A large tree patch provides more shade than a smaller one, but a number of small patches can provide more shade area than a single large one with the same total area of tree cover. We found a non-linear relationship between patch size and transpiration rate. By considering the joint effects of patch size on shading and transpiration, an optimal size of patch might occur, at which the joint effects of shading and transpiration are maximized and thus the most efficient cooling effects occur. We also found shade provision by trees and transpiration rates of trees varied greatly by different tree species, suggesting the choice of tree species should be considered for better cooling and humidification of trees. But the adaptability of the tree species to the local climate and the vegetation water consumption shall be considered when selecting the suitable tree species for urban greening. These findings can provide important insights to urban greenspace managers and planners as the land in the city that can be used for greening is limited.

Acknowledgement

The support of the National Natural Science Foundation of China (41422104 and 41371197) is gratefully acknowledged.

References

- Adams, M.P., Smith, P.L., 2014. A systematic approach to model the influence of the type and density of vegetation cover on urban heat using remote sensing. *Landscape Urban Plann.* 132, 47–54. <http://dx.doi.org/10.1016/j.landurbplan.2014.08.008>.
- Armson, D., Stringer, P., Ennos, A.R., 2012. The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban For. Urban Greening* 11, 245–255. <http://dx.doi.org/10.1016/j.ufug.2012.05.002>.
- Avisar, R., 1996. Potential effects of vegetation on the urban thermal environment. *Atmos. Environ.* 30, 437–448. [http://dx.doi.org/10.1016/1352-2310\(95\)00013-5](http://dx.doi.org/10.1016/1352-2310(95)00013-5).
- Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape Urban Plann.* 97, 147–155. <http://dx.doi.org/10.1016/j.landurbplan.2010.05.006>.
- Cao, X., Onishi, A., Chen, J., Imura, H., 2010. Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. *Landscape Urban Plann.* 96, 224–231. <http://dx.doi.org/10.1016/j.landurbplan.2010.03.008>.
- Chang, C.R., Li, M.H., 2014. Effects of urban parks on the local urban thermal environment. *Urban For. Urban Greening* 13, 672–681. <http://dx.doi.org/10.1016/j.ufug.2014.08.001>.
- Chang, C.R., Li, M.H., & Chang, S.D., 2007. A preliminary study on the local cool-island intensity of Taipei city parks. *Landscape Urban Plann.* 80, 386–395. <http://dx.doi.org/10.1016/j.landurbplan.2006.09.005>.
- Chen, X., Su, Y., Li, D., Huang, G., Chen, W., & Chen, S., 2012. Study on the cooling effects of urban parks on surrounding environments using Landsat TM data: a case study in Guangzhou, southern China. *Int. J. Remote Sens.* 33, 5889–5914. <http://dx.doi.org/10.1080/01431161.2012.676743>.
- Chiesura, A., 2004. The role of urban parks for the sustainable city. *Landscape Urban Plann.* 68, 129–138. <http://dx.doi.org/10.1016/j.landurbplan.2003.08.003>.
- Didham, R.K., Hammond, P.M., Lawton, J.H., Eggleton, P., Stork, N.E., 1998. Beetle species responses to tropical forest fragmentation. *Ecol. Monogr.* 68, 295–323. [http://dx.doi.org/10.1890/0012-9615\(1998\)068\[0295:bsrttf\]2.0.co;2](http://dx.doi.org/10.1890/0012-9615(1998)068[0295:bsrttf]2.0.co;2).
- Dung, P., Guo, Y., Phong, T., Rutherford, S., Wang, X., Minh, N., Cuong, M.D., Nga, H.N., Norre, A., Chu, C., 2016. The effects of high temperature on cardiovascular admissions in the most populous tropical city in Vietnam. *Environ. Pollut.* 208, 33–39.

- <http://dx.doi.org/10.1016/j.envpol.2015.06.004>.
- Fan, H.L., Sailor, D.J., 2005. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. *Atmos. Environ.* 39, 73–84. <http://dx.doi.org/10.1016/j.atmosenv.2004.09.031>.
- Feyisa, G.L., Dons, K., & Meilby, H., 2014. Efficiency of parks in mitigating urban heat island effect: an example from Addis Ababa. *Landscape Urban Plann.* 123, 87–95. <http://dx.doi.org/10.1016/j.landurbplan.2013.12.008>.
- Gioia, A., Paolini, L., Malizia, A., Oltra-Carrio, R., Antonio Sobrino, J., 2014. Size matters: vegetation patch size and surface temperature relationship in foothills cities of northwestern Argentina. *Urban Ecosyst.* 17, 1161–1174. <http://dx.doi.org/10.1007/s11252-014-0372-1>.
- Guo, G., Wu, Z., Xiao, R., Chen, Y., Liu, X., Zhang, X., 2015. Impacts of urban biophysical composition on land surface temperature in urban heat island clusters. *Landscape Urban Plann.* 135, 1–10. <http://dx.doi.org/10.1016/j.landurbplan.2014.11.007>.
- Hagishima, A., Narita, K.I., Tanimoto, J., 2007. Field experiment on transpiration from isolated urban plants. *Hydrol. Process.* 21, 1217–1222. <http://dx.doi.org/10.1002/hyp.6681>.
- Hileman, D.R., Huluka, G., Kenjige, P.K., Sinha, N., Bhattacharya, N.C., Biswas, P.K., Lewin, K.F., Nagy, J., & Hendrey, G.R., 1994. Canopy photosynthesis and transpiration of field-grown cotton exposed to free-air CO₂ enrichment (face) and differential irrigation. *Agric. For. Meteorol.* 70, 189–207. [http://dx.doi.org/10.1016/0168-1923\(94\)90058-2](http://dx.doi.org/10.1016/0168-1923(94)90058-2).
- Howard, L., 1818. *The Climate of London*. W. Phillips, London.
- Hu, Y., Jia, G., 2010. Influence of land use change on urban heat island derived from multi-sensor data. *Int. J. Climatol.* 30, 1382–1395. <http://dx.doi.org/10.1002/joc.1984>.
- Huang, G., Cadenasso, M.L., 2016. People, landscape, and urban heat island: dynamics among neighborhood social conditions, land cover and surface temperatures. *Landscape Ecol.* 31, 2507–2515.
- Kong, F., Yin, H., James, P., Huttyra, L.R., He, H.S., 2014. Effects of spatial pattern of greenspace on urban cooling in a large metropolitan area of eastern China. *Landscape Urban Plann.* 128, 35–47.
- Lambers, H., Chapin III, F.S., Pons, T.L., 2008a. *Plant Physiological Ecology. Scaling-Up Gas Exchange and Energy Balance from the Leaf to the Canopy Level*. Springer, New York, pp. 247–253.
- Lambers, H., Chapin III, F.S., Pons, T.L., 2008b. *Plant Physiological Ecology. Plant Water Relations*. Springer, New York, pp. 163–217.
- Laurance, W.F., Yensen, E., 1991. Predicting the impacts of edge effects in fragmented habitats. *Biol. Conserv.* 55, 77–92. [http://dx.doi.org/10.1016/0006-3207\(91\)90006-u](http://dx.doi.org/10.1016/0006-3207(91)90006-u).
- Laurance, W.F., Laurance, S.G., Ferreira, L.V., Rankin de Merona, J.M., Gascon, C., Lovejoy, T.E., 1997. Biomass collapse in Amazonian forest fragments. *Science* 278, 1117–1118. <http://dx.doi.org/10.1126/science.278.5340.1117>.
- Laurance, W.F., 2004. Forest-climate interactions in fragmented tropical landscapes. *Philos. Trans. R. Soc. Lond. Ser. B-Biol. Sci.* 359, 345–352. <http://dx.doi.org/10.1098/rstb.2003.1430>.
- Li, J., Song, C., Cao, L., Zhu, F., Meng, X., Wu, J., 2011. Impacts of landscape structure on surface urban heat islands: a case study of Shanghai, China. *Remote Sens. Environ.* 115, 3249–3263. <http://dx.doi.org/10.1016/j.rse.2011.07.008>.
- Li, X., Zhou, W., Ouyang, Z., Xu, W., & Zheng, H., 2012. Spatial pattern of greenspace affects land surface temperature: evidence from the heavily urbanized Beijing metropolitan area, China. *Landscape Ecol.* 27, 887–898. <http://dx.doi.org/10.1007/s10980-012-9731-6>.
- Li, X., Zhou, W., Ouyang, Z., 2013. Relationship between land surface temperature and spatial pattern of greenspace: what are the effects of spatial resolution? *Landscape Urban Plann.* 114, 1–8. <http://dx.doi.org/10.1016/j.landurbplan.2013.02.005>.
- Liu, W., Ji, C., Zhong, J., Jiang, X., Zheng, Z., 2007. Temporal characteristics of the Beijing urban heat island. *Theor. Appl. Climatol.* 87, 213–221. <http://dx.doi.org/10.1007/s00704-005-0192-6>.
- Malcolm, J.R., 1994. Edge effects in central amazonian forest fragments. *Ecology* 75, 2438–2445. <http://dx.doi.org/10.2307/1940897>.
- Malcolm, J.R., 1998. A model of conductive heat flow in forest edges and fragmented landscapes. *Clim. Change* 39, 487–502. <http://dx.doi.org/10.1023/a:1005376603186>.
- Moreno, M.L., Bernaschini, M.L., Perez-Harguindeguy, N., Valladares, G., 2014. Area and edge effects on leaf-litter decomposition in a fragmented subtropical dry forest. *N.A. Oecol. Int. J. Ecol.* 602, 6–29. <http://dx.doi.org/10.1016/j.actao.2014.07.002>.
- Nasrallah, H.A., Nieplova, E., Ramadan, E., 2004. Warm season extreme temperature events in Kuwait. *J. Arid. Environ.* 56, 357–371. [http://dx.doi.org/10.1016/s0140-1963\(03\)00007-7](http://dx.doi.org/10.1016/s0140-1963(03)00007-7).
- Oliveira, S., Andrade, H., Vaz, T., 2011. The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. *Build. Environ.* 46, 2186–2194. <http://dx.doi.org/10.1016/j.buildenv.2011.04.034>.
- Pataki, D.E., McCarthy, H.R., Litvak, E., Pincetl, S., 2011. Transpiration of urban forests in the Los Angeles metropolitan area. *Ecol. Appl.* 21, 661–677. <http://dx.doi.org/10.1890/09-1717.1>.
- Premachandra, G.S., Hahn, D.T., Axtell, J.D., Joly, R.J., 1994. Epicuticular wax load and water-use efficiency in bloomless and sparse-bloom mutants of sorghum-bicolor 1. *Environ. Exp. Bot.* 34, 293–301. [http://dx.doi.org/10.1016/0098-8472\(94\)90050-7](http://dx.doi.org/10.1016/0098-8472(94)90050-7).
- Qian, Y., Zhou, W., Li, W., Han, L., 2015a. Understanding the dynamic of greenspace in the urbanized area of Beijing based on high resolution satellite images. *Urban For. Urban Greening* 14, 39–47. <http://dx.doi.org/10.1016/j.ufug.2014.11.006>.
- Qian, Y., Zhou, W., Yu, W., Pickett, S.T.A., 2015b. Quantifying spatiotemporal pattern of urban greenspace: new insights from high resolution data. *Landscape Ecol.* 30, 1165–1173. <http://dx.doi.org/10.1007/s10980-015-0195-3>.
- Qin, Z., Li, Z., Cheng, F., Chen, J., Liang, B., 2014. Influence of canopy structural characteristics on cooling and humidifying effects of *Populus tomentosa* community on calm sunny summer days. *Landscape Urban Plann.* 127, 75–82. <http://dx.doi.org/10.1016/j.landurbplan.2014.04.006>.
- Rahman, M.A., Armonson, D., Ennos, A.R., 2015. A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. *Urban Ecosyst.* 8, 371–389. <http://dx.doi.org/10.1007/s11252-014-0407-7>.
- Ries, L., Fletcher, R.J., Battin, J., Sisk, T.D., 2004. Ecological responses to habitat edges: mechanisms, models, and variability explained. *Annu. Rev. Ecol. Evol. Syst.* 35, 91–522. <http://dx.doi.org/10.1146/annurev.ecolsys.35.112202.130148>.
- Ryu, Y.H., Bou-Zeid, E., Wang, Z.H., Smith, J.A., 2016. Realistic representation of trees in an urban canopy model. *Boundary Layer Meteorol.* 159, 193–220. <http://dx.doi.org/10.1007/s10546-015-0120-y>.
- Santamouris, M., Synnefa, A., Karlessi, T., 2011. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Sol. Energy* 85, 3085–3102. <http://dx.doi.org/10.1016/j.solener.2010.12.023>.
- Santamouris, M., Cartalis, C., Synnefa, A., Kolokotsa, D., 2015. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings-A review. *Energy Build.* 98, 119–124. <http://dx.doi.org/10.1016/j.enbuild.2014.09.052>.
- Shashua-Bar, L., Hoffman, M.E., 2000. Vegetation as a climatic component in the design of an urban street – An empirical model for predicting the cooling effect of urban green areas with trees. *Energy Build.* 31, 221–235. [http://dx.doi.org/10.1016/s0378-7788\(99\)00018-3](http://dx.doi.org/10.1016/s0378-7788(99)00018-3).
- Song, J., Wang, Z.H., 2016. Diurnal changes in urban boundary layer environment induced by urban greening. *Environ. Res. Lett.* 11, 114018. <http://dx.doi.org/10.1088/1748-9326/11/11/114018>.
- Steenekveld, G.J., Koopmans, S., Heusinkveld, B.G., Theeuwes, N.E., 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. *Landscape Urban Plann.* 121, 92–96. <http://dx.doi.org/10.1016/j.landurbplan.2013.09.001>.
- Sun, S., Cao, P., Chan, K.P., Tsang, H., Wong, C.M., Thach, T.Q., 2015. Temperature as a modifier of the effects of fine particulate matter on acute mortality in Hong Kong. *Environ. Pollut.* 205, 357–364. <http://dx.doi.org/10.1016/j.envpol.2015.06.007>.
- Wang, Z.H., Zhao, X., Yang, J., Song, J., 2016. Cooling and energy saving potentials of shade trees and urban lawns in a desert city. *Appl. Energy* 161, 437–444. <http://dx.doi.org/10.1016/j.apenergy.2015.10.047>.
- Wu, J.G., Vankat, J.L., 1991. An area-based model of species richness dynamics of forest islands. *Ecol. Modell.* 58, 249–271. [http://dx.doi.org/10.1016/0304-3800\(91\)90039-4](http://dx.doi.org/10.1016/0304-3800(91)90039-4).
- Xie, M., Wang, Y., Chang, Q., Fu, M., Ye, M., 2013. Assessment of landscape patterns affecting land surface temperature in different biophysical gradients in Shenzhen, China. *Urban Ecosyst.* 16, 871–886. <http://dx.doi.org/10.1007/s11252-013-0325-0>.
- Zhou, L.M., Dickinson, R.E., Tian, Y.H., Fang, J.Y., Li, Q.X., Kaufmann, R.K., Tucker, C.J., Myneni, R.B., 2004. Evidence for a significant urbanization effect on climate in China. *Proc. Natl. Acad. Sci. U. S. A.* 101, 9540–9544. <http://dx.doi.org/10.1073/pnas.0400357101>.
- Zhou, W., Huang, G., Cadenasso, M.L., 2011. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. *Landscape Urban Plann.* 102, 54–63. <http://dx.doi.org/10.1016/j.landurbplan.2011.03.009>.
- Zhou, W., Qian, Y., Li, X., Li, W., Han, L., 2014. Relationships between land cover and the surface urban heat island: seasonal variability and effects of spatial and thematic resolution of land cover data on predicting land surface temperatures. *Landscape Ecol.* 29, 153–167. <http://dx.doi.org/10.1007/s10980-013-9950-5>.
- Zhou, W., Wang, J., Cadenasso, M.L., 2017. Remote Sensing of Environment Effects of the spatial configuration of trees on urban heat mitigation: a comparative study. *Remote Sens. Environ.* 195, 1–12. <http://dx.doi.org/10.1016/j.rse.2017.03.043>.
- Zhou, W., 2013. An object-based approach for urban land cover classification: integrating LiDAR height and intensity data. *IEEE Geosci. Remote Sens. Lett.* 10, 928–931. <http://dx.doi.org/10.1109/lgrs.2013.2251453>.