

Research paper

Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: Integrating modeling with in-situ measurements

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ARTICLE INFO

Keywords:

Urban green space
Spatial configuration
Urban heat island
Solar radiation
High-rise building area
Numerical modeling

ABSTRACT

Trees have long been recognized as effective for mitigating urban heat islands by reducing air temperature through evapotranspiration and intercepting shortwave radiation that heat up land surfaces. Many studies have shown that both the composition and configuration of vegetation can contribute to heat reduction at the city scale. Fewer studies, however, have focused on cooling mechanisms at the neighborhood scale. Here, we integrate modeling with in situ measurements to investigate how different spatial arrangements of trees in residential neighborhoods affect their cooling effects. We conducted the research in a residential neighborhood with high-rise apartment buildings in Beijing. We tested four scenarios with different spatial arrangements of trees, and quantified their effects on cooling. We used the high spatial and temporal resolution microclimate model ENVI-met and validated the model with in situ measurements. We found: (1) Different spatial arrangements had differentiated effects on intercepting shortwave radiation, which led to variations in air temperature. For example, new trees that were completely exposed to solar radiation had stronger cooling effects (air temperature was 0.22 °C lower) than new trees that were located in the shadow of surrounding buildings. (2) Different spatial arrangements led to obviously different effects of sensible heat reduction, with a maximum difference of 14.84×10^8 J/ha. Our results underscore the importance of the spatial arrangement of trees on cooling in residential neighborhoods. These results have important implications in urban planning and design at the neighborhood scale.

1. Introduction

Urbanization leads to radical changes in land surfaces and the atmosphere, which involves the transformation of radiation, heat and moisture, and consequently produces energy exchanges that are distinctly different from rural areas (Oke, 1987). Natural landscapes are massively replaced by complex impervious alternatives that not only absorb large amounts of solar radiation but also trap both incident shortwave and outgoing long-wave radiation from escaping to the atmosphere (Oke, 1982). Moreover, impervious surfaces prevent the infiltration of water into the soil, which reduces evapotranspiration and increases sensible heating of the local ambient air (Coutts, Beringer, & Tapper, 2007). Such modifications of land surfaces and energy exchanges from urbanization give rise to the urban heat island (UHI), which is a phenomenon in which cities are on average warmer than the surrounding rural areas. The UHI is among the most evident aspects of human impacts on the earth system, and it has been documented in large and small urban areas worldwide (Peng et al., 2012). Urban warming can have substantial impacts on energy consumption,

air and water quality and human health, particularly considering climate change, and more frequent and longer lasting heat waves (Meehl & Tebaldi, 2004). Therefore, it is of critical importance to improve the urban environment by managing and planning its land use pattern.

Strategies commonly applied to existing urban areas often focus on ameliorating deleterious effects of UHI, such as by using cool pavement/high albedo pavement, permeable concrete or asphalt, and increasing greenspace. Increasing vegetation, especially trees, is particularly favored by urban planners and designers because vegetation can simultaneously lower sensible heat and increase latent heat flux into the atmosphere (Georgescu et al., 2015). In addition, vegetation can provide important ecosystem services, such as regulating urban stormwater, sequestering carbon, and improving health and aesthetics (de Sousa, Montalto, & Palmer, 2016). Previous studies have shown that both the composition and configuration of vegetation affect its cooling effects (Connors, Galletti, & Chow, 2013; Du, Xiong, Wang, & Guo, 2016; Li, Zhou, & Ouyang, 2013; Li, Zhou, Ouyang, Xu, & Zheng, 2012; Zhou, Huang, & Cadenasso, 2011). With limited space available in

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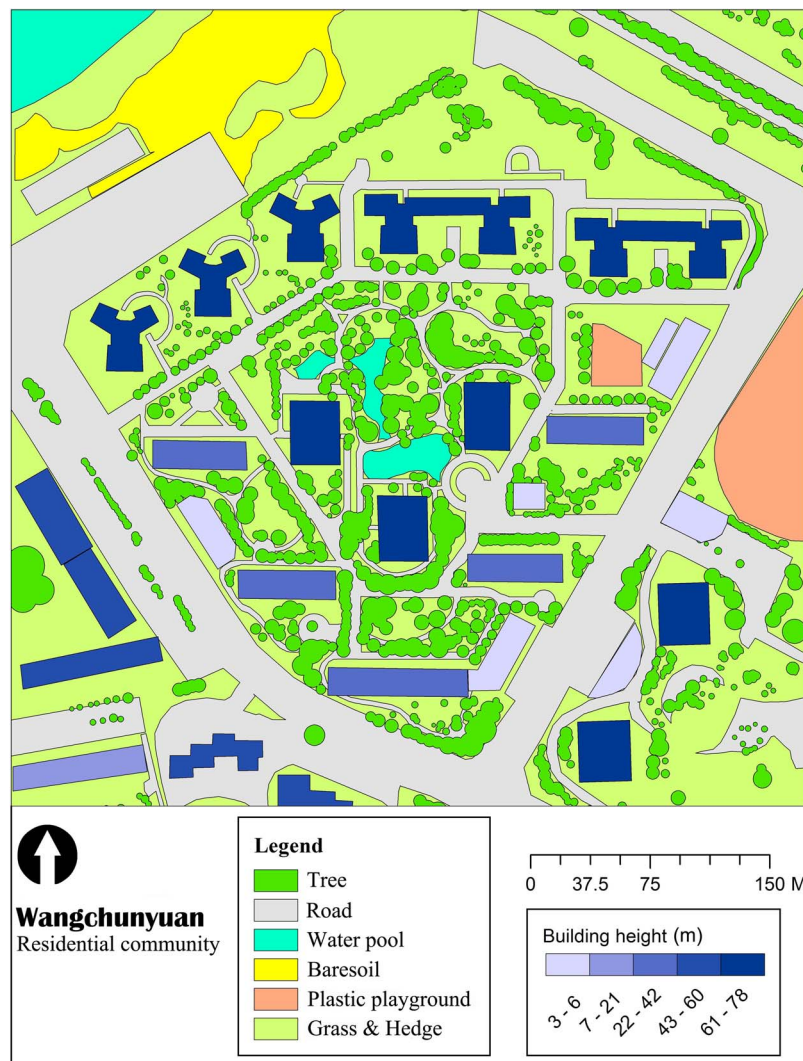


Fig. 1. Land cover types of WCY and its surrounding area.

developed urban areas for greening, a frequently asked question is how to optimize the spatial arrangement of vegetation for improved cooling effects.

Previous studies have shown that the spatial configuration of greenspaces affects the UHI magnitude (Li et al., 2011; Liu & Weng, 2008; Zhou et al., 2011). Indices derived from landscape ecology, such as patch density and edge density, were usually used to represent the cooling effect of different spatial configurations of greenspaces. Specifically, patch density of greenspaces has a significant positive relationship with surface temperature, meaning that an increase in patch density will lead to higher UHI magnitude (Li et al., 2013). Kong, Yin, James, Hutya, and He (2014) indicated that a large greenspace patch may enhance the cooling effects of nearby smaller greenspaces. They suggested using multiple small greenspaces in urban planning to improve the urban thermal environment. In contrast, an increase of edge density would help to lower the UHI magnitude (Zhou et al., 2011). These studies were generally based on land surface temperature derived from remote sensing data, such as Landsat-7 ETM+ (Enhanced Thematic Mapper Plus) images, which has a spatial resolution (60 m for thermal infrared band) that is still too coarse for detailed description of landscape configuration at a neighborhood scale. At the neighborhood or block scale, more attention was given to air temperature variation obtained from field measurements or numerical simulations. However, there is no consistent relationship between land surface temperature and ambient air temperature, which limits the scaling-down of these findings from city to neighborhood scale. These findings may support

better decisions on spatial arrangement of greenspaces at the city scale. On the neighborhood scale, however, urban planners and designers need more specific principles to arrange the greenspaces. As a main living space, the thermal environment of the residential community has drawn increasing interest from multiple disciplines (Wang, 2006; Wang, Zhang, Zhao, He, & Li, 2011; Yang, Lau, & Qian, 2010; Yang, Yan, Xu, & Lam, 2013). However, the thermal condition of the residential community in Beijing remains largely unexamined.

Here, we investigate how different spatial arrangements of trees affect their cooling effects in residential neighborhood by integrating modeling with in situ measurements. We conducted the research in a residential neighborhood with high-rise apartment buildings in Beijing. We tested four scenarios with different spatial arrangements of trees and quantified their effects on cooling. We used the high spatial and temporal resolution microclimate model ENVI-met, and validated the model with in situ measurements. The results from this study have important implications in urban planning and designing at the neighborhood scale.

2. Material and methods

2.1. Study area

Beijing has undergone rapid urbanization over the last 30 years, with the urban area expanding from 801 km² in 1980–2,452 km² in 2010 (Wu, Zhao, Zhu, & Jiang, 2015), and the population increasing

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