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Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation

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ABSTRACT

Urban warming has become a serious problem due to global warming and rapid urbanization. One important phenomenon is the increasing urban heat island (UHI) effect, which has a serious negative impact on energy consumption, environmental pollution, and human well-being. Trees lower land surface and air temperatures by providing shade and through the process of evapotranspiration and therefore are useful in effectively mitigating the UHI effect. The cooling effects of trees vary depending on the tree crown size and density and the optical properties of their leaves. Selection of the best species to plant is important in achieving effective mitigation of the UHI effect. In this research, we examined four woodlands. Three of these woodlands are dominated by species (*Cinnamomum camphora, Metasequoia glyptostroboides, Magnolia grandiflora*) that are frequently planted in Nanjing, China and one is a mixed woodland. Terrestrial laser scanning (TLS) was employed to detail the vegetation canopy structure and capture the volume of three-dimensional point clouds of the leaves (L_V_{3DPC}), as well as the shade at each case study site. Meteorological parameters were measured at each site. Statistical analysis was used to assess the cooling effects of the different woodlands and their impacts. This research revealed that trees can influence the microclimate beneath their canopies and that the degree of the impact is different for different tree species. Statistical analyses showed that the woodlands studied exhibit obvious temperature reductions during the daytime (05:00–19:30) and weaker temperature reductions during the nighttime (19:30–05:00). The temperature reduction was greatest for *M. glyptostroboides*, followed by *C. camphora*, *M. grandiflora*, and the trees in the mixed broad-leaved woodland. These results indicate that small-leaved species tend to be more effective at cooling than large-leaved species. Comparisons of the Leaf Area Index (LAI) and Sky View Factor (SVF) with L_V_{3DPC} and shade, respectively, show that L_V_{3DPC} and shade better reflect the impact of the vegetation canopy on the cooling effect. Multiple linear regression analyses showed that shading by trees is of prime importance in cooling the thermal environment. The high significance of L_V_{3DPC} and shade indicate that the tree canopy is a major component of the contribution of trees to microclimatic environments, particularly the cooling effect under the tree canopy. This paper presents an innovative technique for determining tree canopy shade using TLS data for the purpose of analyzing the cooling effect of trees. The findings can be used as a guide to aid in the selection of the best species for urban greenspace planning and design to cool the thermal environment and enhance energy savings in urban environments.

1. Introduction

Strategies for mitigating the intensity of urban heat islands are becoming important in terms of energy savings and human thermal comfort (Akbari et al., 2001; Patz et al., 2005; Donovan and Butry, 2009; Pandit and Laband, 2010; Cohen et al., 2012). One

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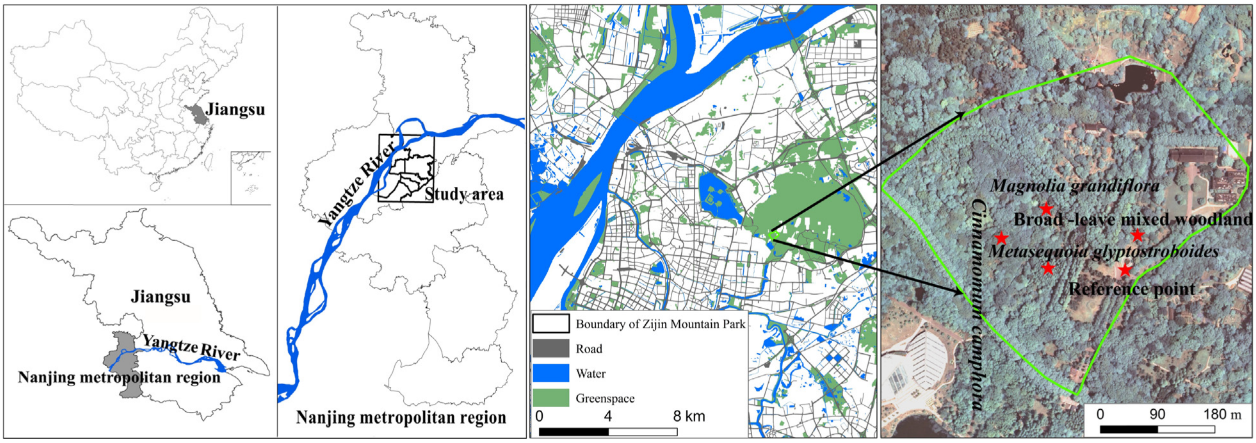

Fig. 1. Study area and observation sites.

adaptation strategy to address these issues is to increase the amount of urban vegetation (Gill et al., 2007; Oliveira et al., 2011). The cooling effect of vegetation has been widely documented (Dimoudi and Nikolopoulou, 2003; Chen and Wong, 2006; Giridharan et al., 2008; Fahmy et al., 2010). Vegetation cools the urban environment through moderation of the land surface temperature by shading it from direct sunlight, intercepting solar radiation, and consequently altering heat fluxes (Simpson, 2002; Tsiros, 2010; Lindberg and Grimmond, 2011). Vegetation also cools the air through the process of evapotranspiration (Akbari and Konopacki, 2004; Shashua-Bar et al., 2009; Zhao et al., 2014). The vegetation canopy is a major contributor to cooling and moderating microclimatic environments. The development of new methods of canopy access has enabled researchers to conduct more quantitative analysis of vegetation canopies (Lowman and Wittman, 1996; Jupp et al., 2009). However, detailed and accurate quantification of vegetation canopy structures (particularly the shading resulting from the canopy) and the effect on cooling is still challenging, even when combined with micro-meteorological observations (Tooke et al., 2011).

The cooling effects of different vegetation species are likely to differ (Leuzinger et al., 2010; Shahidan et al., 2010; Rahman et al., 2014). Previous studies have found that the characteristics of tree species, including the tree shape, the canopy size, the canopy density, and the features of the tree leaves, can influence the resulting cooling effect (Bueno-Bartholomei and Labaki, 2003; Georgi and Dimitriou, 2010; Shahidan et al., 2010). Heisler (1986) found that maple trees reduced the amount of radiation reaching surfaces below the canopy more than other tree species, as they had the largest leaves and intercepted the greatest amount of solar radiation. Conversely, Leuzinger et al. (2010) demonstrated that small-leaved tree species tended to be more effective at cooling because they maintained lower crown temperatures than those of larger-leaved species (Doick and Hutchings, 2013). Lin and Lin (2010) found that, of the variables they considered, foliage density contributed most to cooling of the soil surface, followed by leaf thickness, leaf texture, and leaf color lightness. Shahidan et al. (2010) compared two tree species (*Mesua ferrea L. and Hura crepitans L.*) and found that foliage density and branching patterns caused differences in the resulting cooling effects.

Tree canopy shading is determined by the canopy shape and depth, leaf area distribution, the characteristics of the individual tree within the species, the amount of leaf cover, and the sun angle (Shashua-Bar and Hoffman, 2000; Kotzen, 2003; Shahidan et al., 2010). Different levels of shading will produce different cooling effects by blocking the penetration of solar radiation (Shashua-Bar and Hoffman, 2000; Kotzen, 2003). Previous studies have quantified tree shade in different ways, including computer simulations, use of the sky view factor (SVF), and mathematical models (Tooke et al., 2009; Shahidan et al., 2010; Hämmerle et al., 2011; An et al., 2014; Gal and Unger, 2014). Computer simulations, such as the shadow pattern simulator, have been used to calculate the potential of tree shade to reduce energy use in residential buildings (McPherson et al., 1985; Simpson, 2002). With respect to the tree size, canopy density, and solar angle, simulating the shading effect accurately remains complicated. The SVF has been employed in the measurement of shading effects in urban environments and specifically in the determination of the impact of tree shading on microclimates (Grimmond et al., 2001; Holmer et al., 2001; Ng et al., 2012). Methods for determining the value of the SVF include fish-eye photography, the use of global positioning system (GPS) signals, the use of LiDAR data, and the use of vector/raster three-dimensional (3-D) geospatial data (Chapman and Thornes, 2004; Ali-Toudert and Mayer, 2007; Shaker and Drezner, 2010; Chen et al., 2012; Kidd and Chapman, 2012). The SVF at a particular spatial location is commonly given as a constant value for a day, irrespective of the method used to obtain the data. However, this is not a true representation of the shade in a vegetation canopy, because of the anisotropy of tree structures and the variation in the solar angle throughout the day. The SVF is therefore limited in its ability to represent the transient characteristics of shade produced by vegetation.

Mathematical models have also been widely used to evaluate tree shade. For example, Shashua-Bar and Hoffman (2000) used a statistical method to calculate the shaded area under a tree canopy at predetermined times and were able to explain over 70% of the air temperature variance within the studied green space. The precision and completeness of mathematical modeling-based and photography-based estimates have been examined by several researchers (e.g., Simpson, 2002; Gómez-Muñoz et al., 2010; Berry et al., 2013). Georgi and Dimitriou (2010) proposed the concept of solar radiation transmittance, L (with values ranging from 0 to 100 and 0 representing total shade) and found that there was an exponential relationship between the rate of decrease in the air temperature and L. The ability of quantitative analysis to describe the influence of shade on cooling effects is therefore expected to improve with increasing precision in the characterization of shade. However, little previous research has been undertaken to compare the amount of shade cast by different tree species and in particular to investigate the influence of changes in shade on cooling effects within a single day (Armson et al., 2012).

The leaf area index (LAI), defined as "half the total intercepting area per unit ground surface area" (Chen and Black, 1992) is another