Applied Geography 95 (2018) 45–53

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Beyond fractional coverage: A multilevel approach to analyzing the impact of urban tree canopy structure on surface urban heat islands

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1. Introduction

The United Nations (2016) estimates that people living in urban areas now account for 54.5% of the global population, a number expected to reach 60% by 2030. As cities continue to expand in size and density, residents may be exposed to a range of environmental stressors such as increased ambient air pollution (Dockery et al., 1993), water pollution (Satterthwaite, 1997), and increases in surface and air temperatures when compared to their rural surroundings known as the Urban Heat Island (UHI) effect (Oke & Maxwell, 1975). Beyond the direct impacts of observed higher mortality rates during extreme heat waves (Laaidi et al., 2012), urban heat islands have also been linked to increased residential water and energy use (Akbari, Pomerantz, & Taha, 2001; Guhathakurta & Gober, 2007), and can create more favorable conditions for the formation of some deleterious air pollutants such as photochemical smog (Akbari, 2002; Akbari et al., 2001).

Aware of these impacts, city managers are now making it a priority to reduce UHI intensity. A cornerstone of those mitigation efforts is expanding vegetative coverage in the form of the urban forest. Though there are a growing number of descriptions of the urban forest, for this research we adopt the definition of Konijnendijk, Ricard, Kenney, and Randrup (2006, p. 472) "all tree-dominated green areas in and around urban areas". While all urban vegetation generates some level of ecosystem services, including air pollution reduction (Escobedo & Nowak, 2009; McPherson, Scott, & Simpson, 1998) and carbon sequestration (Nowak & Crane, 2002; Rowntree & Nowak, 1991), many of these ecosystem services tend to be directly correlated with leaf area (Peper & McPherson, 2003), where urban trees dominate other forms of vegetation. As a result, urban trees also play a more significant role in temperature mitigation (Federer, 1976; Taha, Akbari, & Rosenfeld, 1991) by intercepting incoming solar radiation, directly shading surfaces, and reducing ambient temperatures through evapotranspiration (Arnfield, 2003; Federer, 1976).

Despite the acknowledged connections between urban forests, heat islands, and residential well-being, we still have only a partial understanding of how urban tree canopy impacts heat islands because research remains focused on two different spatial scales. Studies concentrate on either the city-scale, treating the urban forest as a single unit of analysis that is contrasted with surrounding rural areas (Imhoff, Zhang, Wolfe, & Bounoua, 2010; Oke, 1973; Zhang, Imhoff, Wolfe, & Bounoua, 2010), or focus on the local-scale to examine microclimatic variation within cities (Buyantuyev & Wu, 2010; Connors, Galletti, & Chow, 2013; Davis, Jung, Pijanowski, & Minor, 2016; Jenerette et al., 2016). City-scale examinations of surface urban heat islands collectively establish that cities with lower aggregate tree canopy cover tend to have increased urban-rural temperature differences. Many of these studies apply correlation or regression methods to quantify the strength of the relationship between average vegetation indices (i.e., spectral band ratios derived from remote sensing imagery that highlight the wavelengths chlorophyll absorb and reflect in healthy vegetation) such as the normalized difference vegetation index (NDVI) or enhanced vegetation index (EVI), and average temperature differences as a measure of surface heat island intensity. Examining a suite of US cities using regression, Gallo et al. (1993) demonstrate a significant negative relationship between average NDVI derived from NOAA AVHRR satellite imagery, and average minimum surface temperatures. Aggregating pixel level NDVI values derived from Landsat imagery to the city level, Zhang et al. (2010) demonstrate a negative relationship between the average differences in NDVI and differences in surface temperature between urban and rural locations. Comparing 419 large cities around the world, Peng et al. (2012) found both the average vegetation continuous field (VCF) values and average EVI values derived from MODIS satellite imagery to be moderately to strongly correlated with surface heat island intensity. Relating these city-scale results with their regional surroundings, Imhoff et al. (2010) demonstrate that a city's ecological setting contributes to the relative intensity of the heat island effect. Specifically, the authors show that cities situated in forested areas have more intense urban heat islands when compared to those in more arid ecoregions.

In contrast to research conducted at the city-scale, a suite of local-scale studies establish the impacts individual or small stands of trees have on microclimates located within individual cities. While a few local-scale studies have completed direct measurements over transects (e.g., Hart & Sailor, 2009), more commonly the relationship between

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https://doi.org/10.1016/j.apgeog.2018.04.004
Received 21 February 2017; Received in revised form 2 April 2018; Accepted 9 April 2018

vegetation abundance and microclimatic variation in the surface heat island is examined using secondary data collected on either small sample plots (e.g., Connors et al., 2013), at the parcel level (e.g., Jenerette et al., 2016; Stone & Rodgers, 2001; Wang, Berardi, & Akbari, 2015), or aggregated to sub-city census units such as U.S. census block groups (e.g., Buyantuyev & Wu, 2010; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006) or Canadian census tracts (e.g., Greene & Millward, 2017). Beyond confirming the surface and ambient temperature mitigating impacts of vegetation observed at the city-scale, this local-scale research has also collectively established that increases in vegetated area translate to cooler surface and ambient temperatures at the local scale, though the strength of this relationship is constrained by factors such as the type of vegetation (Givoni, 1991), leaf area index (Kenney, 2008), and the position of a tree in relation to a structure (Akbari, 2002; Sawka, Millward, Mckay, & Sarkovich, 2013). Examining block groups in the United States, Buyantuyev and Wu (2010) observed moderately strong explanatory power in both ordinary least squares regression and geographically weighted regression models that used NDVI as predictor of daytime surface temperature. Using similar regression methods, Jenerette et al. (2016) observed moderate correlation between NDVI and daytime land surface temperature at the parcel level. When those authors shifted their unit of analysis to the larger neighborhood level, they found stronger explanatory power suggesting the possible presence of larger scale effects unaccounted for in their original statistical model.

Taken together, city- and local-scale studies suggest that either a single process operating at different scales or multiple interacting processes affects the relationship between urban forests and urban heat islands. First, the removal of individual trees and associated loss of shade and evapotranspiration generates incremental increases in surface temperatures at the local-scale. Second, the collective removal of trees has aggregate effects observed as an increase in city-scale temperature relative to surrounding rural areas. However, what factors shape how local-scale canopy coverage influences city-scale temperature mitigation remains uncertain. A handful of recent studies by Connors et al. (2013), Zheng, Myint, and Fan (2014), and Greene and Millward (2017) analyzing fragmentation statistics (e.g., patch and edge density) or alternative land-cover measures (e.g., vegetation, impervious surface, tree canopy closure) as predictors of surface temperature, suggest the spatial arrangement of canopy at a neighborhood-scale, above the local-scale but below the city-scale, may shape within-city variation in urban surface temperature.

In other words, urban forest configurations that have larger edges with non-forested land-uses are likely to have decreased effects on temperature mitigation because those edge areas lack the additional shading provided by neighboring trees (Delgado, Arroyo, Arevalo, & Fernandezpalacios, 2007). Conversely densely forested areas, where trees are in close proximity to other trees and limbs intermingle, should have higher temperature mitigating effects than at the edge of a forest patch. Literature focusing on the fragmentation of native forests have demonstrated the presence of temperature gradients moving perpendicularly from the edge to the interior of a forest patch. These gradients vary depending on geographic context. Delgado et al. (2007) observed that temperature gradients stabilized within 3 m of moving from the edge towards the middle of a forest patch. A longer gradient was observed by Davies-Colley, Payne, and Van Elswijk (2000) before temperature stabilized for New Zealand broadleaf forests. If this gradient is as little as 3 m, the smaller forest patches of the urban forest are still likely to exhibit the consequences of this edge to center gradient. Holding area constant, the higher the edge to area ratio for a patch, the greater the area of gradient, and the more likely the patch will have higher fringe temperatures. While in a single patch this increased area may appear marginal, when looking at the collective of patches the sum of the temperatures tied to this gradient area becomes significant.

To our knowledge what remains missing from the literature is an explicit recognition and analysis of how the spatial arrangement of the urban forest, at scales between the local and the city, may impact temperature mitigation and the provision of ecosystem services across scales. Using the city of Toronto as our empirical foundation, this article analyzes the effect neighborhood- and local-scale forest canopy characteristics have on urban surface temperatures. We first establish a baseline OLS regression model that adopts the typical approach to examining the relationship between fractional coverage of tree canopy, canopy configuration (e.g., canopy area, edge), and surface temperature at the local or dissemination area (DA) level. In addition to direct measures of tree canopy, we also account for each DA's distance to Lake Ontario. This large body of water, on which Toronto's downtown core is located, is likely to reduce local surface temperatures (Bosselmann, Arens, Dunker, & Wright, 1995; Changnon & Jones, 1972). Extending this model, we use multilevel regression to then examine two related effects. First, we examine the effect canopy configuration measured at the neighborhood-scale has on surface temperature at the local-scale. Second, we analyze whether neighborhood-scale canopy configuration impacts the effect that nested local-scale canopy coverage has on local-scale surface temperature. By doing so, this article addresses a missing segment in current urban forestry research: the need to examine the impact of canopy characteristics on the provision of ecosystem services like temperature mitigation at scales between local microclimates and the entire city. Policy makers and forest managers will be interested in the impact neighborhood-scale forest configuration has on surface temperature mitigation as they work to identify planting and management practices suitable for their specific urban context.

2. Materials and methods

2.1. Study area

This paper examines relationships between temperature and urban canopy cover in the city of Toronto Ontario Canada. Toronto is the most populous city in Canada and covers approximately 641 km^2 along the northern edge of Lake Ontario. Fig. 1 shows the city's division into neighborhood-scale administrative wards, which can be further subdivided into local-scale dissemination areas (DA). The number of DAs per Ward ranges from a minimum of 48 to a maximum of 99, with a mean of 81.

We examine Toronto's urban forest for several reasons. First, Toronto exhibits considerable aggregate canopy cover, with approximately 10.2 million trees providing 28 percent areal coverage and numerous ecological services to residents (Nowak et al., 2013). Second, within the city, tree canopy coverage is geographically varied. Ward canopy coverage ranges from a low of 6.7 percent to a maximum of 55.6 percent. Finally, differences in ward canopy coverage are the result of a diversity of landscape features (e.g., parks, ravines) whose different natural structures produce spatial variation in neighborhood-level canopy configuration (City of Toronto: Parks, Forestry & Recreation, Urban Forestry, 2013). Studies of urban heat islands (Fan et al., 2015, 2017) suggest that these ward-level differences in canopy configuration are likely to contribute DA-level variations in surface temperature. However, a direct and simultaneous examination of these effects remains largely absent from the literature.

2.2. Data sources and variable definition

We collected the data used in our analysis from two different sources. First, high resolution land cover data derived from 0.6 × 0.6 m classified QuickBird imagery captured during the summer of 2007 were obtained from the City of Toronto Open Data Catalogue (City of Toronto: Parks, Forestry & Recreation, Urban Forestry, 2009). Second, we estimated surface temperature data from the Landsat 5 Thematic Mapper Channel 6 (thermal infrared sensor) radiance collected from Path 18 Row 30 on 29 June 2007 (ID: LT50180302007180GNC01) as outlined by the U.S. Geological Survey (2016). Digital numbers were