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Combined vegetation volume and “greenness” affect urban air temperature

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ABSTRACT

Cities are often substantially warmer than their surrounding rural areas. This ‘urban heat island effect’ can negatively affect the health of urban residents, increase energy usage, and alter ecological processes. While the effect of land use and land cover on urban heat islands has been extensively studied, little is known about the role of vegetation volume or built-area volume about this phenomenon. We ask whether the 3-dimensional structure of urban landscapes influences variations in temperature across a city. Using heights-above-ground information derived from LiDAR data and the Normalized Difference Vegetation Index (NDVI) calculated from multispectral (4 band: Blue, Green, Red, and Near Infrared) aerial images, we estimated vegetation volume and built-area volume (non-vegetated) in Chicago, Illinois (USA). Daily minimum temperature data were obtained from 36 weather stations for summer 2011. The differences in urban air temperature across the study area were as large as 3 °C. Maximum likelihood models indicated that a combination of NDVI and vegetation volume best predicted nighttime temperature in Chicago, and that vegetation growing within 250–500 m of the weather station was most influential. Our results indicate that vegetation in “the matrix”, i.e. the area outside parks and preserves, is important in temperature mitigation since the majority of the vegetation volume in the study area occurs within residential, commercial/industrial, and institutional land uses. However, open space, which covers only 15% of the study area, has nearly as much total vegetation volume as residential land, which covers 61% of the study area. Clearly, both large wooded parks within a city and large trees scattered across residential areas are needed to best mitigate the urban heat island effect.

1. Introduction

Urban heat islands affect urban settlements worldwide. The degree to which the temperature in the city is augmented compared to its rural surroundings depends on regional context, such as the biome wherein the city is located and the city's size (Imhoff, Zhang, Wolfe, & Bounoua, 2010). Other factors, such as impervious surface extent, vegetation cover, and anthropogenic activities, are important too (Peng et al. 2012). In a study of 38 U.S. cities, yearly urban temperatures were on average 2.9 °C warmer than surrounding areas in all biomes except those with arid and semiarid climates (Imhoff et al. 2010). The effect is most pronounced on clear, still nights in the summer and has been detected both in surface and air temperatures (Voogt & Oke, 2003).

Urban heat islands can intensify summer heat waves, cause heat stress, and worsen air pollution (Loughner et al., 2012). Chicago, in particular, has suffered from heat waves, with the 1995 heat wave being responsible for over 700 deaths, mostly among low-income elderly individuals who did not have a strong social support system (Klinenberg, 2002). Other studies have shown that the most vulnerable members of society are also those most affected by extreme heat events (Buyantuyev & Wu, 2010; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Jenerette et al. 2007; Jenerette, Harlan, Stefanov, & Martin, 2011).

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At the regional scale, it is well accepted that urban centers tend to be warmer than rural areas, especially in summer (U.S. EPA, 2015). More fine-scaled investigations, however, have found that land cover configuration and composition affect temperature, especially surface temperatures compared to air temperatures (Buyantuyev & Wu, 2010; Connors, Galletti, & Chow, 2013; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Song, Du, Feng, & Guo, 2014; Myint, Wentz, Brazel, & Quattrochi, 2013). This effect depends partially on air flow through the urban area, which is a function of the spatial arrangement, size, and density of objects (buildings, trees, streets) in the city (Voogt & Oke, 2003). At the parcel scale, large deciduous trees planted on the eastern, southern, or western sides of homes decrease summer electricity use (Ko & Radke, 2013). One study (Ko & Radke, 2013), showed that the sum of tree height within 18.3 m of the western side of a property (as measured by LiDAR) decreased energy use the most, although occupant behavior most affected home energy consumption.

Mitigating urban heat island effects, especially in the face of climate change, is a goal for many municipalities (Akbari et al. 2008). Much research has focused on ascertaining the effect of vegetation cover or impervious surface cover on temperature in cities. Increased low albedo surfaces and impervious surfaces have been linked to elevated surface (Buyantuyev & Wu, 2010; Imhoff et al. 2010; Jenerette et al. 2007; Myint et al., 2013; Roth, Oke, & Emery, 1989; Weng, Lu, & Schubring, 2004; Yuan & Bauer, 2007) and air temperatures (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Coseo & Larsen, 2014; Harlan et al. 2006) in urban areas.

Maps of vegetation cover or impervious surface area are usually derived from satellite imagery. Green space in particular is often estimated by calculating Normalized Difference Vegetation Index (NDVI) or Soil Adjusted Vegetation Index (SAVI). Since vegetation provides evaporative surfaces, heat storage capacity (Gallo et al. 1993) and shading, it can influence temperatures. Skelhorn et al. (2014) modeled surface and air temperature fluctuations in suburban areas of Manchester UK according to various greening scenarios. They found that a 5% increase in mature tree cover, versus hedges and young trees, decreased surface temperature by 1 °C and 0.5 °C respectively, while a 5% increase in grass cover increased surface temperature by 0.6 °C. No changes in air temperature were noted.

We estimated vegetation volume and built-area volume using LiDAR and multispectral (Red, Green, Blue, and Near Infrared bands) aerial images, and used weather station data from across Cook County, Illinois (USA), to determine whether built-area volume, vegetation volume (as a proxy for vegetation biomass), or NDVI is a stronger predictor of summer air temperature. Finally, we examined these relationships at 5 different scales (with buffers around the weather station ranging from 100 m to 1000 m) to determine the extent of any effects of our response variables on temperature.

2. Methods

2.1. Study area

In 2010, Cook County, Illinois (USA) had just over 5 million inhabitants (2010 U.S. Census). The county covers almost 2448 km^2 and borders Lake Michigan. Its climate is classified as humid continental, with four distinct seasons throughout the year. Cook County is home to Chicago, the third largest city in the United States in terms of population. In the Chicago region in 2010, there were an estimated 157 million trees that accounted for 15.5% of the total land cover, and 73.5% of these trees were less than 6 inches in diameter (Nowak et al. 2013).

2.2. Sample locations

Within Cook County, we located thirty-nine weather stations with nearly continuous data during our study period (Fig. 1). The three weather stations associated with the region's airports (O'Hare International Airport, Chicago Midway International Airport, and the Chicago Executive Airport) were removed from subsequent analyses because of the unusually large amount of impervious surface near the stations. Six weather stations were within 2 km of each other, so we randomly removed three of them from subsequent analyses to prevent overlap of the buffers. Our final data set comprises 33 weather stations, which serve as the center point for the ensuing landscape analyses. The mean (standard deviation), minimum, and maximum distance between nearest neighbor sites, i.e. nearest pairs of weather stations, are 4.9 (3.0), 2.1, and 13.5 km, respectively.

2.3. Temperature data

Minimum, maximum, and average daily temperatures for 2011 were downloaded from wunderground.com for the 33 Cook County weather stations. We used data from summer months (June 21 to September 21), as urban heat island effects are more pronounced in the summer (Imhoff et al. 2010; Myint et al. 2013; Yuan & Bauer, 2007). We used the daily minimum temperature as a proxy for nighttime temperature. We calculated an average of the daily minimum temperature over the three summer months. The mean daily minimum temperature at each weather station for summer 2011 was used as the response variable in our models, and is hereafter referred to as mean nighttime temperature.

We compared summer temperatures in 2011 to twenty year normal temperatures to summarily examine whether summer 2011 was a “typical summer” for our study region. The mean (low – high) normal (1981–2010) temperatures from O'Hare Airport's weather station (main airport situated at the North end of Cook County, Illinois) for June, July, August, and September are 20.5 (14.5–26.5), 23.3 (17.7–28.9), 22.4 (17.2–27.2), and 18.1 (12.4–23.8° Celsius), respectively (http://www.sws.uiuc.edu/atmos/statecli/General/chicago-climate-narrative.htm). Comparatively, the mean (low – high) temperature at the same weather station for June, July, August, and September 2011 were 21.1 (15.6–26.7), 26.1 (21.1–31.7), 23.3 (17.8–28.3), and 16.7 (12.2–20.6° Celsius; wunderground.com/history/airport/KORD), indicating that the summer of 2011 might have been slightly warmer than the average summer.

2.4. Estimation of vegetation volume, built-area volume, and NDVI

LiDAR data over Cook County were downloaded from the Illinois Height Modernization Program (ILHMP) web site. The LiDAR data acquisition occurred in November 2008 and April 2009. While that time of year is considered “leaf-off” in Cook County, LiDAR has been shown to reliably detect tree tops (maximum height) in leaf-off conditions, even for deciduous trees (Wasser, Day, Chasmer, & Taylor, 2013). The average density of the point cloud data was 5.05 point/m^2.

We adopted a 2D grid structure with 5 ft (1.5 m) spatial resolution for LiDAR data processing, so that each pixel had an average point density of 11.8 points/pixel. First, the point cloud data were classified into ground and non-ground points using LasTools (http://www.cs.unc.edu/~isenburg/lastools/). Then, a Digital Terrain Model (DTM) was generated by applying natural neighbor interpolation to ground points only. We chose a natural neighbor interpolation algorithm for DTM generation since it is