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Megacity-scale analysis of urban vegetation temperatures

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ABSTRACT

In cities, vegetation temperature is important for quantifying water use, microclimates, and water and energy fluxes, as demonstrated by urban climate models and in situ studies. Remote sensing is capable of observing land surface temperatures (LST) across a city; however, its ability to quantify vegetation canopy temperatures is limited because of LST variability resulting from urban surface heterogeneity, differences in vegetation fraction and non-vegetated material, and the coarse resolution of available thermal imagery. This study is a large-scale analysis of urban surface composition and temperature variability across the Los Angeles, USA, metropolitan area (4466 km^2). Sub-pixel fractions of two plant functional types (tree and turfgrass) and four urban materials (impervious surface, commercial roof, non-photosynthetic vegetation, and soil) were quantified using hyperspectral imagery (Airborne Visible/Infrared Imaging Spectrometer). Fractional cover gradients of plant types and non-vegetated materials were developed using 1.7 million pixels, from which we modeled LST changes using simultaneously collected thermal imagery (MODIS-ASTER Airborne Simulator). Vegetation LST variability was mapped by subtracting modeled LST from observed LST and investigated relative to building density and vegetation management. Overall, LST varied significantly among plant functional types and urban material types. Across heterogeneous mixtures, LST and vegetation fraction exhibited a negative, linear relationship, with the slopes of LST change showing significant differences between trees and turfgrass. The map of vegetation LST variability had a standard deviation of 3.5 °C, indicating significant variability across Los Angeles independent of vegetation type or fractional cover. Building density was observed to affect tree and turfgrass LST differently, while a negative relationship was observed between vegetation LST and irrigation (R^2 = 0.55). Our results show that an LST signal of vegetation function, distinct from that of vegetation fractional cover, can be observed and modeled at city-scales in fractional mixture analysis, indicating potential for improved understanding of urban microclimates.

1. Introduction

Vegetation canopy temperature is an indicator of vegetation stress, evapotranspiration (ET) rate, and plant carbon uptake (Moran, 2004; Duursma et al., 2014; Grigsby et al., 2015). Observing vegetation temperature variability across a city is therefore critical for quantifying urban water use, energy budgets, and microclimate variability (Akbari et al., 2001; Ali-Toudert and Mayer, 2005; Moonen et al., 2012). Remote sensing can observe spatial patterns in land surface temperature (LST) across large urban spatial domains; however, the coarse spatial resolution of most remotely sensed imagery, combined with LST variability related to urban materials, tends to obscure thermal signals of vegetation stress or function (Weng, 2009).

Canopy LST can indicate vegetation stress and ET because well-watered vegetation efficiently sheds energy via latent heat flux, lowering LST (Soer, 1980). A water-stressed plant will conserve water by closing its leaf stomata, reducing latent energy exchange (transpiration) and therefore increasing canopy LST. In situ and flux tower studies can observe the physical mechanisms underlying this process, but they operate at the neighborhood rather than the city scale (Voogt and Oke, 1998; Grimmond and Oke, 1999; Arnfield, 2003; Peters et al., 2011; Stewart and Oke, 2012). Remote sensing can measure city-wide negative correlations between LST and vegetation abundance, measured as a fraction or an index value such as Normalized Difference Vegetation Index (NDVI), because areas with greater leaf area and irrigation have greater latent heat exchange (Dousset and Gourmelon, 2003; Amiri et al., 2009; Yuan and Bauer, 2007; Zhang et al., 2009; Liu et al., 2016; Zhou et al., 2017). However, remote sensing cannot observe the underlying functional mechanisms, and because vegetation fraction is a primary driver of LST variability in thermal imagery, other drivers of vegetation LST are obscured (Weng et al., 2004).

Direct observation of city-scale vegetation LST without the effect of vegetation fraction requires thermal imagery with high spatial resolution. However, thermal infrared wavelengths have lower energy than

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visible, near-infrared, or short-wave infrared (VSWIR) wavelengths, and therefore require a larger ground instantaneous field of view, referred to as a pixel throughout the remainder of this manuscript. The typical spatial resolution of spaceborne thermal imagery ranges from 90 m (Advanced Spaceborne Thermal Emission and Reflection Radiometer: ASTER) and 100 m (Landsat Operational Land Imager: Landsat OLI) to 1 km (Moderate Resolution Imaging Spectrometer: MODIS) (Mushore et al., 2017). These resolutions will record a single LST value for areas larger than many common urban vegetation patches, including small residential yards or street trees, thus capturing pixels with a range of vegetation cover. Mounting thermal imagers on lower, slower airborne platforms can improve spatial resolution; however, imaging a large urban footprint would require collection over multiple days with varying conditions, and would likely preclude comparative studies between different cities (Zhao and Wentz, 2016). Therefore, quantifying urban vegetation LST variability using coarser resolution thermal imagery remains a priority.

Using coarse resolution thermal imagery to assess urban vegetation LST will require controlling for LST effects of vegetation cover, as well as other surface drivers of LST variability. One such driver is plant functional type, which in most North American cities largely consists of trees and turfgrass (Nowak et al., 2001; Milesi et al., 2005). Tree and turfgrass LST can differ for several reasons. Tree shadows cool nearby surfaces and inhibit soil water evaporation, while turfgrass has far less capacity to cast shadows (Litvak et al., 2014; Gillner et al., 2015). Trees and turfgrass also access water differently because their root systems are at different depths, although variation in built infrastructure and management practices can increase rooting depth variability in urban trees (Grabosky and Gilman, 2004; Bijoor et al., 2012). From the point of view of a thermal imager, another difference between tree and turfgrass LST is that the LST of tree-covered patches can be affected by the diversity of materials beneath the canopy, such as other vegetation, pavement, or roofs, whereas turfgrass LST does not include effects of dissimilar materials because it does not have an understory (Friedl, 2002). Assessing LST solely in relationship to green vegetation fraction or NDVI ignores these and other sources of LST variability related to vegetation type.

The diversity of abiotic materials found in a city is also a key source of LST variability, due to material properties such as albedo, thermal conductivity, moisture content, and structure (Oke, 1988). Pixels with low vegetation fraction will have LST that is dominated by that of the non-vegetated material, making it especially important to control for this variable when using coarse spatial resolution imagery (Sandholt et al., 2002; Weng, 2009). Furthermore, non-vegetated surfaces can affect nearby vegetation, sometimes in contradictory ways. For example, asphalt can increase ET by advection of warm air over well-watered vegetation, but it can also decrease ET by inducing stomatal closure in overhanging tree canopies (Oke, 1979; Oke, 1988; Kjelgren and Montague, 1998).

Explicit categorization and quantification of surface heterogeneity is the first step for evaluating vegetation LST variability in a thermal image. This must be accomplished over a large urban extent in order to observe a wide range of possible vegetation thermal responses across percent cover gradients of plant functional type and material composition. Surface heterogeneity is generally quantified using optical imagery and, if acquired across a large city, will likely be at spatial resolutions typical of spaceborne sensors such as Landsat OLI (30 m). At these scales, sub-pixel analysis is necessary to quantify vegetation fractional cover and material mixtures. Sub-pixel composition and fractions are typically estimated using some form of linear spectral mixture analysis (SMA) (Settle and Drake, 1993). SMA assumes that reflectance measured in each pixel is the linear combination of the reflectances from all sub-pixel materials, weighted by their relative fraction within the pixel. For urban environments, Multiple Endmember Spectral Mixture Analysis (MESMA) is particularly well-suited because it allows different cover classes to be represented by multiple endmembers (EM) (Roberts et al., 1998). For example, with MESMA a green vegetation class can be represented by spectra from multiple species of tree and turfgrass, while an impervious surface class can include spectra from concrete, asphalt, metal, or any other material of interest. Incorporating multiple EMs makes MESMA a robust method for unmixing scenes with extreme material diversity, and it has therefore been used to unmix urban scenes across the globe (Rashed et al., 2003; Powell et al., 2007; Franke et al., 2009; Roberts et al., 2012; Wu et al., 2014).

Typically, urban sub-pixel analysis is used to estimate fractions of vegetation, impervious surfaces, and soil (VIS) because these groups tend to be spectrally distinct and therefore easier to discriminate using SMA (Ridd, 1995; Wu, 2004). However, teasing out LST differences between plant functional types and urban materials requires more functionally uniform class definitions than the VIS model provides. A limited number of studies have assessed city-scale temperatures of urban trees and/or turfgrass separately across changing cover fractions, but they have not accounted for the effects of variability in the non-vegetated fraction (Myint et al., 2013; Myint et al., 2015; Jenerette et al., 2016; Zhou et al., 2017). Another group of studies has investigated the role of impervious surface fraction; however, they have not accounted for differences in plant functional types and other variability related to the non-impervious fraction (Yuan and Bauer, 2007; Zhang et al., 2009; Buyantuyev and Wu, 2010; Morabito et al., 2016). More recently, studies have used the spectral resolution of hyperspectral imagery as well as the EM diversity allowed by methods such as MESMA to expand the VIS model to include tree, turfgrass, roof, impervious surface, non-photosynthetic vegetation (NPV), and soil (Okujeni et al., 2013; Okujeni et al., 2015; Roberts et al., 2017; Wetherley et al., 2017). This creates an opportunity to assess urban LST across both vegetated and abiotic sub-pixel fractions that have unique effects on water and energy fluxes.

In this study, we leveraged these recent advances in our ability to define more functionally uniform sub-pixel classes to quantify material and plant type heterogeneity across the megacity of Los Angeles, California, USA. A megacity is a large urban area with a population in excess of 10 million people (United Nations, 2016). Conducting a study across a megacity allows for a sufficient sample size of pixels with varying surface heterogeneity and associated LST measurements. We extracted 1.7 million pixels to construct plant functional type and urban material fractional gradients and evaluate changing LST. We then derived an expected temperature response based on sub-pixel composition in order to assess deviations from measured temperatures across the study area. We produced a map of vegetation LST variability and investigated additional drivers of vegetation LST that are difficult to observe at city-scales. Specifically, we asked the following questions:

1. What is the urban plant and material variability of Los Angeles?
2. How do plant and material type affect measured LST?
3. How does vegetation LST vary across a megacity?

2. Methods

2.1. Study area

The study area included 4466 km^2 of urbanized land within the Los Angeles metropolitan area (Los Angeles) (Fig. 1). Los Angeles is situated in southern California along the Pacific coast, and includes parts of Los Angeles, Orange, Riverside, San Bernardino, and Ventura Counties (average elevation of 161.8 m and standard deviation of 137.3 m; USGS National Elevation Dataset). It is composed of a range of residential, commercial, industrial, and agricultural areas, with a primary downtown in the city of Los Angeles along with several other urbanized centers located throughout. Urban materials are typical of North American cities, with large expanses of asphalt, concrete, and roofing materials. Area vegetation consists of ~200 urban tree species as well