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Variation in the urban vegetation, surface temperature, air temperature nexus

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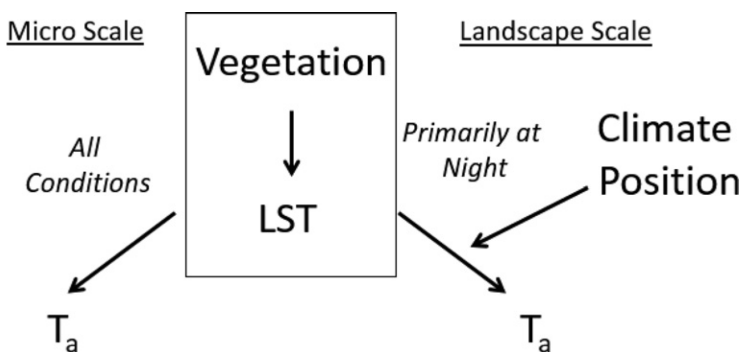
HIGHLIGHTS

- We investigated the vegetation – air temperature – land surface temperature nexus in southern California.
- We coupled 300 in-situ air temperature sensors with airborne measurements of a vegetation index and surface temperature.
- Vegetation was associated with cooler land surface temperature during the day and air temperature at night.
- Vegetation provides cooling benefits although the effects on microclimate vary by temperature, vegetation, and time of day.

GRAPHICAL ABSTRACT



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ABSTRACT

Our study examines the urban vegetation – air temperature (T_a) – land surface temperature (LST) nexus at micro- and regional-scales to better understand urban climate dynamics and the uncertainty in using satellite-based LST for characterizing T_a. While vegetated cooling has been repeatedly linked to reductions in urban LST, the effects of vegetation on T_a, the quantity often used to characterize urban heat islands and global warming, and on the interactions between LST and T_a are less well characterized. To address this need we quantified summer temporal and spatial variation in T_a through a network of 300 air temperature sensors in three sub-regions of greater Los Angeles, CA, which spans a coastal to desert climate gradient. Additional sensors were placed within the inland sub-region at two heights (0.1 m and 2 m) within three groundcover types: bare soil, irrigated grass, and underneath citrus canopy. For the entire study region, we acquired new imagery data, which allowed calculation of the normalized difference vegetation index (NDVI) and LST. At the microscale, daytime T_a measured along a vertical gradient, ranged from 6 to 3 °C cooler at 0.1 and 2 m, underneath tall canopy compared to bare ground respectively. At the regional scale NDVI and LST were negatively correlated ($p < 0.001$). Relationships between diel variation in T_a and daytime LST at the regional scale were progressively weaker moving away from the coast and were generally limited to evening and nighttime hours. Relationships between NDVI and T_a were stronger during nighttime hours, yet effectiveness of mid-day vegetated cooling increased substantially at the most arid region. The effectiveness of vegetated T_a cooling increased during heat waves throughout the region. Our

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findings suggest an important but complex role of vegetation on LST and T_a and that vegetation may provide a negative feedback to urban climate warming.

1. Introduction

Urbanization is characterized by extensive land use transformation and altered surface thermal characteristics (Kalnay and Cai, 2003). Increased heat capacity associated with built environments leads to warmer nighttime urban air temperatures (T_a), commonly described as the urban heat island (Oke, 1973; Santamouris, 2015). During the day, limited evaporation and low albedos of built surfaces are associated with greater daytime urban radiant temperatures observed from remote sensors, commonly referred as land surface temperature (LST; Jenerette et al., 2007). Notably, urbanization is associated with a high degree of spatial heterogeneity in thermal characteristics and as a result, there are large differences in intra-urban land surface and air temperatures (Upmanis et al., 1998; Svensson and Eliasson, 2002; Huang et al., 2011; Hall et al. 2016; Jenerette et al., 2016) that change substantially at daily and seasonal scales (Jenerette et al., 2013; Coseo and Larsen, 2014). Both components of urban temperature variation have important implications for the well-being of urban residents. T_a has been repeatedly found to influence energy demand through its relation to air conditioning habits and human health through heat-related illness (Kalkstein, 1991; Santamouris et al., 2001; Hondula and Barnett, 2014). LST is also an important variable in the study of urban climates (Voogt and Oke, 2003) and has been shown to directly correlate with heat-related health incidents (Laaidi et al., 2012; Vanos, 2015; Jenerette et al., 2016). Uncertainties in understanding spatial and temporal variation in both T_a and LST in urban environments undermine a robust understanding of the drivers of urban microclimates and relationships between LST and more widely characterized T_a. Resolving the uncertainties at the vegetation-LST-T_a nexus is essential for designing urban landscapes that minimize the many negative consequences of high urban temperatures.

LST modulates T_a of the lower layer of the urban atmosphere and is a primary factor in determining surface radiation and energy exchange, the internal climate of buildings, and human comfort in cities (Voogt and Oke, 2003). Intra-urban T_a differences of >8 °C have been reported (Upmanis et al., 1998; Svensson and Eliasson, 2002; Stabler et al., 2005). LST variation within a city can be larger, spanning >20 °C (Jenerette et al., 2007). Reconciling causes and correlations in variation between these two urban temperature components remains a persistent challenge (Hartz et al., 2006). The few studies of the relationships between LST and T_a have had mixed results with some studies showing strong correlations and others not identifying relationships (Hartz et al., 2006; Cheng et al., 2008; Schwarz et al., 2012). When T_a - LST linkages are observed they show diel variation; with some evidence of correlations at night but less so during the day (Kawashima et al., 2000). The diel variation may be in response to the effects of increased atmospheric mixing during the day compared to night and also thermal properties of different surfaces. While distinct indicators of urban microclimates, both daytime increases in LST and nighttime increases in T_a represent risks to human health in urban environments (Kalkstein, 1991; Harlan et al., 2014).

Increasing urban vegetation is becoming a widely used tool for reducing both urban T_a and LST (Kurn et al., 1994; Weng and Yang, 2004; McPherson et al., 2011; Gillner et al., 2015; Larsen, 2015). Urban vegetation has a particularly important role in cooling surface temperatures during the day via evapotranspiration, physical shading, and also by increased albedo and reflected radiation relative to paved surfaces (Imhoff et al., 2010; Jenerette et al., 2016). For instance, the albedo of green roofs, which ranges from 0.7 to 0.85, is much higher than the 0.1 to 0.2 albedo range of typical roofing surfaces such as bitumen, tar, and gravel, and enables green roofs to reflect 20–30% of solar radiation (Berardi, 2014). Georgescu et al. (2014) suggested in a modeling study that urban adaptation strategies such as green roofing (i.e., highly transpiring), or cool roofing (i.e., highly reflective) can offset urban-induced air temperature warming in cities across the United States and also offset a significant percentage of future greenhouse gas-induced warming over large scales. Similarly, many empirical studies have shown that increasing vegetation and specifically, canopy cover can substantially reduce LST (Declet-Barreto et al., 2016).

The magnitude of vegetated LST cooling depends on multiple factors including local meteorological conditions and extent of vegetation cover. Different forms of vegetation, for example grass versus trees, may have different influences on local microclimate. Tree-shading of built surfaces can provide comparable surface cooling as transpiring grass and additional cooling benefits relative to grass (Armson et al., 2012; Vanos et al., 2016). For instance, Armson et al. (2012) showed tree shade reduced surface temperatures by up to 19 °C, compared to a 24 °C reduction in maximum surface temperature related to grass cover. Yet, grass cover had little effect on globe temperature, a metric incorporating the effects of radiation, T_a, and wind on human comfort, while shading reduced globe temperature by 5–7 °C. Diel and seasonal variation in correlations between vegetation and LST suggest much stronger coupling during midday and in warmer seasons, than at night and in cooler seasons (Buyantuyev and Wu, 2010; Jenerette and Potere, 2011; Myint et al., 2013; Jenerette et al., 2016). Similarly, spatial variation across a climate gradient of the correlation between vegetation and LST also suggest more effective cooling in hot, arid locations compared to milder, coastal locations (Tayyebi and Jenerette, 2016).

In contrast, the role of vegetation in reducing T_a is less well understood and linkages between vegetation cover and T_a are more variable than vegetation – LST relationships. Sampling campaigns directed toward evaluating the effects of individual trees, green spaces, green roofs, or the urban tree canopy have shown localized air cooling associated with vegetation (Hart and Sailor, 2009; Feyisa et al., 2014; Petralli et al., 2014; Santamouris, 2014; Yan et al., 2014; Coseo and Larsen, 2014; Gillner et al., 2015; Wang et al., 2015). However, other studies have found no detectable effects of vegetation on T_a (Grundström and Pleijel, 2014; Klemm et al., 2015) or only limited effects when comparing the endpoints between bare to vegetated land covers (Skelhorn et al., 2014). Where vegetation effects on urban T_a have been found, they vary in diel magnitudes and in response to differing weather conditions (Coseo and Larsen, 2014; Wang et al., 2015). Further, climate context may have large influences on connections between land surface and local T_a patterns (Hall et al., 2016).

To address the uncertainties in the vegetation-LST-T_a nexus, we investigated their relationships at micro- and regional-scales across the Greater Los Angeles region spanning a coastal to desert gradient. First, we asked how different dominant vegetation functional types affected microscale T_a patterns at an intermediate climate location. At microscales, we hypothesized that vegetation would decrease near-surface temperatures, with increased cooling associated with taller canopies. We further predicted the land cover effect would be greater at near surface than at 2 m above ground because of increased air mixing at higher locations. Second, we asked how the relationships between urban vegetation, LST, and T_a vary across a regional-scale coastal to desert climate gradient. We hypothesized that increased vegetation cover will reduce T_a and LST-T_a differences, regardless of micro- or regional-scale, due to increased surface shading and evapotranspiration associated with increasing vegetation cover. We predicted that microclimate and vegetation relationships would increase in magnitude with increasing distance