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Increases in the climate change adaption effectiveness and availability of vegetation across a coastal to desert climate gradient in metropolitan Los Angeles, CA, USA

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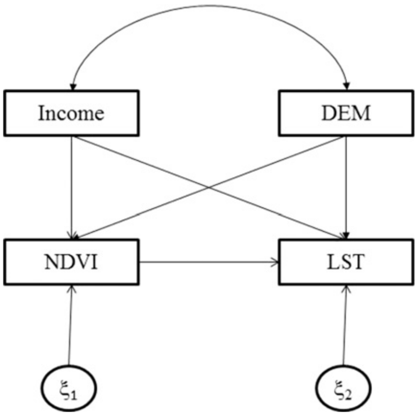
HIGHLIGHTS

- We quantified the relationships between LST, NDVI, elevation and income using structural equation modeling.
- The slope between NDVI and LST increased in cooling effectiveness from −6.06 to −31.77 degrees.
- For increasing $10 K in neighborhood income, NDVI increased from 0.008 to 0.018.
- For increasing $10 K in neighborhood income, LST decreased from −0.05 °C to −0.75 °C.
- In a future warmer climate, vegetation will be more effective at local cooling.

GRAPHICAL ABSTRACT



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ABSTRACT

Urbanization has increased heat in the urban environment, with many consequences for human health and well-being. Managing climate change in part through increasing vegetation is desired by many cities to mitigate current and future heat related issues. However, little information is available on what influences the current effectiveness and availability of vegetation for local cooling. In this study, we identified the variation in the interacting relationships among vegetation (normalized difference vegetation index), socioeconomic status (neighborhood income), elevation and land surface temperature (LST) to identify how vegetation based surface cooling services change throughout the pronounced coastal to desert climate gradient of the Los Angeles, CA metropolitan region, a megacity of > 18 million residents. A key challenge for understanding variation in vegetation as a climate change adaptation tool spanning neighborhood to megacity scales is developing new “big data” analytical tools. We used structural equation modeling (SEM) to quantify the interacting relationships among socio-economic status data obtained from government census data, elevation and new LST and vegetation data obtained from an airborne imaging campaign conducted in 2013 for the urban and suburban areas across a series of fifteen climate zones. Vegetation systematically increased in cooling effectiveness from 6.06 to 31.77 degrees with increasing distance from the coast. Vegetation and neighborhood income were positively correlated throughout all climate zones with a peak in the relationship occurring near 25 km from the coast. Because of the interaction between these two relationships, we also found that higher income neighborhoods were cooler and that this effect peaked at about 30 km from the coast. These results show the availability and effectiveness of vegetation on the local

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climate varies tremendously throughout the Los Angeles, CA metropolitan area. Further, using the more inland climate zones as future analogs for more coastal zones, suggests that in the warmer climate conditions projected for the region the effectiveness of vegetation for regional cooling may increase thus acting as a localized negative feedback mechanism.

1. Introduction

Urbanization has been accelerating across the globe during the previous 30 years (United Nations, 2008; Cohen, 2006; Turner et al., 2004; Tayyebi et al., 2014, 2015; Pijanowski et al., 2010, 2014), which among many impacts has caused increasing heat vulnerabilities in many metropolitan areas (Zhou et al., 2014; Santamouris, 2015). High urban temperatures can impact human health by increasing heat-related illness and mortality (Patz et al., 2005; Jenerette et al., in press), economic costs by increasing energy demand (Grimmond, 2007), and air pollution by increasing greenhouse gas emissions (Crutzen, 2004) and altering air chemistry (Jacob and Winner, 2009). Therefore, reducing heat risks in urban areas is a key challenge for sustainable urban development (Razzaghmanesh et al., 2014). Urban climate adaptation strategies increasingly include recommendations for expanding vegetation cover as a mechanism for urban cooling (WMO, 2007; IPCC. Climate Change, 2007; Luck et al., 2009; Environmental Protection Agency, 2008). However, the effectiveness and current availabilities of any heat adaptation tool varies extensively between cities (Georgescu et al., 2014) and what regulates these differences is still uncertain. At regional scales, potential variation within a city of cooling effectiveness and vegetation availability may also be large (Jonsson, 2004). Identifying the sources of variation in vegetated urban cooling will provide needed information for deploying climate adaptation strategies.

Urban heat distributions depends on a variety of factors such as climate, vegetation, altitude, adjacency to water bodies, and socioeconomic conditions (Grimm et al., 2008). These drivers of LST operate across a variety of spatial–temporal scales are coupled in complex ways (Song et al., 2014), Vegetation is a critical local driver affecting urban heat and the cooling effect of vegetation in urban areas can be extensive (Kalnay and Cai, 2003; Chen et al., 2006; Clarke et al., 2013; Imhoff et al., 2010). The effectiveness of vegetation cooling may depend on multiple factors such as local meteorological conditions, species characteristics, and plant management. Jenerette et al. (2011) found large seasonal variation with the strongest vegetation effects during hot and dry periods (25 °C) and weakest effects during cooler periods. These results suggest similar spatial differences may exist, where in hotter neighborhoods vegetation more effectively cools the local environment. However, almost all previous studies have conducted analyses at the entire metropolitan scale and this prediction has not been tested. We are aware of only one study that has systematically examined the variation of plant cooling effectiveness, which showed large differences among neighborhoods although the causes of this neighborhood variation was unclear (Jenerette et al., in press).

Similarly, the availability of vegetation within neighborhoods is generally associated with neighborhood socioeconomic status, termed a “luxury effect” (Jenerette et al., 2007; Huang et al., 2011; Clarke et al., 2013). This vegetation luxury effect can lead to substantial temperature differences; in Phoenix, AZ, Jenerette et al. (2007) showed that every $10 K increase in neighborhood annual median household income was associated with a 0.28 °C decrease in LST. Notably, the magnitude of this “luxury effect” on vegetation abundance varies by more than a factor of 20 between cities (Jenerette et al., 2013). Likely, within urban variation in the magnitude of the luxury effect is also present and can similarly influence access to vegetation and cooling amenities. We are aware of no study that has examined intra-urban variation in the magnitude of the vegetation or related climate luxury effects. Information on equity in the distribution of vegetation availability can be useful for identifying locations for climate adaptation investments.

Assessing the variation in drivers and the sensitivities to the drivers of vegetation cooling effectiveness and vegetation availability is needed for improving climate adaptation strategies. To fill this research need we evaluated geographic variation in how elevation and neighborhood income affect the extent of vegetation and neighborhood cooling, as quantified through the remotely sensed normalized difference vegetation index (NDVI) and the magnitude of remotely sensed land surface temperature (LST) across the coastal to desert climate gradients throughout the Los Angeles, CA metropolitan area, a megacity of 17.5 million residents. Remote sensing data have commonly been used to quantify heat in urban areas (Chen et al., 2006; Li et al., 2011). However, these studies are still limited by the coarse resolution of existing data (e.g., 120–60 m) or their extent when measured from airborne platforms (Stathopoulou and Cartalis, 2009). To fill this data need for high resolution data at large regional scales, the Hyperspectral Infrared Imager Preparatory (HyspIRI-Prep) mission was conducted in 2013 (Roberts et al., 2015). For these imaging campaigns data with high spectral resolution in both visible and infrared wavelengths were acquired with the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER) instruments flown together over California, USA. One goal of these missions included assessments of urban thermal and land cover relationships.

In this study, we use the HyspIRI-Prep data and additional environmental and social data coupled through advanced analytical tools to answer for greater Los Angeles: 1) How does the effectiveness of vegetation as an LST cooling mechanism vary geographically? 2) How does the socioeconomic luxury effect influence of vegetation availability vary geographically? 3) What influences the variation in the resulting direct, indirect and total effects of neighborhood income on LST throughout the region? We hypothesize that the neighborhood income based luxury effect is more strongly related to vegetation in drier environments as management (i.e. irrigation) can have increasingly larger effects and that vegetation has a greater LST cooling effect in hotter and drier conditions through increased evaporative potentials. Based on these two hypotheses we predict the total cooling effect associated with neighborhood income should be higher in more inland than coastal climate gradient. We used structural equation modeling (SEM) to identify variation in the interactions between LST, NDVI, and income across the coastal to desert climate gradient in the region. SEM, while not frequently used in remote sensing applications, is an advanced analytical tool that provides flexibility for evaluating how variation in drivers influence the availability and cooling effectiveness across large geographic areas. Results from these analyses will have implications for regional scale management within and among cities to maximize effectiveness of climate adaptation implementations.

2. Study area, data sources and data processing

2.1. Study area

Metropolitan Los Angeles is located in the southern portion of the State of California, USA and we evaluated variation in this region at four distinct spatial scales spanning the individual image pixel (Fig. 1A) to the greater Los Angeles metropolitan area (Fig. 1C). The Los Angeles metropolitan area covers five counties (Fig. 1C) and encompasses 88,000 km^2 with over 18 million people. Los Angeles, CA metropolitan area has an expanding heat island due to rapid population growth and experiences heat waves during the summer months (Akbari et al., 2001). This urban area has been shown through field