



Original article

Urban forest structure and land cover composition effects on land surface temperature in a semi-arid suburban area



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ABSTRACT

Using multispectral imagery and LiDAR data, we developed a high-resolution land cover dataset for a semi-arid, Colorado (USA) suburb. These data were used to evaluate patterns of land cover composition and vertical structure in relation to land use and age of development. Landsat 5 TM thermal band data for six separate dates were used to compare land surface temperature (LST) in urbanized and remnant shortgrass steppe reference areas. We used 2010 census blocks to extract LST and various explanatory variables for use in Random Forest models evaluating the relative importance of land cover composition, LiDAR-derived vertical structure variables, and the Normalized Difference Vegetation Index (NDVI) on LST patterns.

We found that land cover, vertical structure, and LST varied between areas with different land use and neighborhood age. Older neighborhoods supported significantly higher tree cover and mean tree height, but differences in LST were inconsistent between Landsat image dates. NDVI had the highest variable importance in Random Forests models, followed by tree height and the mean height difference between trees and buildings. Models incorporating NDVI, vertical structure, and land cover had the highest predictive accuracy but did not perform significantly better than models using just vertical structure and NDVI. Developed areas were cooler on average than shortgrass steppe reference areas, likely due to the influence of supplemental irrigation in urbanized areas. Patterns of LST were spatially variable, highlighting the complex ways land cover composition and vertical structure can affect urban temperature.

1. Introduction

Dramatic changes in land cover composition and spatial structure accompany urbanization with important consequences for ecohydrological functioning and local climate (McDonnell et al., 1997; Oke, 1989; Walsh et al., 2005). Increases in land surface temperature (LST) commonly occur with urbanization, a phenomenon known as the urban heat island (UHI) effect (Owen et al., 1998; Small, 2006). Changes to LST influence the sustainability of cities, affecting water and energy consumption and public health (Graham et al., 2016; Guhathakurta and Gober, 2007; Wilson, 2013). However, the relative importance of different drivers of LST patterns remain poorly understood outside of a small number of cities (Phelan et al., 2015).

Urbanization affects LST by altering different components of the energy balance of cities (Lemonsu et al., 2004; Phelan et al., 2015; Piringier et al., 2002). Impervious surfaces often have low albedo and can effectively store incident solar radiation, while vegetation can reduce sensible heat through latent heat flux (Phelan et al., 2015; Voogt and Oke, 2003). Urbanization effects on LST are influenced by the

composition and structure of both the pre-development and post-development landscape, as well as human activities such as irrigation. For example, in water-limited areas, high leaf area and latent heat flux made possible by supplemental irrigation and fertilization can create localized areas of cooling (Chow et al., 2011; Declet-Barreto et al., 2013; Georgescu et al., 2011; Taha et al., 1991). Because land cover composition, structure, and management vary with land use (e.g. industrial vs. residential), the resulting LST patterns can be spatially complex.

Vegetation is a key factor shaping urban LST. Proxies of vegetation abundance and condition such as the Normalized Difference Vegetation Index (NDVI) and vegetation fraction are strongly correlated with LST patterns (Gallo et al., 1993; Owen et al., 1998; Rouse et al., 1973; Weng, 2009; Weng et al., 2004; Yuan and Bauer, 2007; Yue et al., 2007), but these fail to account for variability in vegetation composition and vertical structure influencing urban LST. Trees have an especially large effect on local energy balances, carbon and water cycling, and other ecosystem services (Nowak and Crane, 2002; Pataki et al., 2011, 2006; Zheng et al., 2016). While tree canopy cover can be easily

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quantified by analyzing aerial or satellite imagery, such data do not address vertical structure created by trees, an important factor influencing LST (Gage and Cooper, 2017; Kanda et al., 2006; Oke, 1982, 1989).

Geographic variation in daytime heating effects can be explained by differences in the efficiency that heat is transferred to the lower atmosphere, with more heating occurring in aerodynamically smooth areas (Zhao et al., 2014). However, the importance of vertical structure has not been widely examined empirically because comprehensive, landscape-scale data were unavailable. LiDAR remote sensing data, increasingly available for many cities, allows for explicit analysis of vertical structure characteristics affecting turbulent exchanges with the atmosphere (Shugart et al., 2010).

In this study, we evaluated the relationship between land use, land cover composition, vertical structure, and summer daytime LST patterns in a semi-arid suburban city, addressing the following questions:

- (1) How do patterns of land cover composition and vertical structure vary in our study area and in relation to land use and age of development?
- (2) How does LST differ between urbanized areas supporting irrigated vegetation and undeveloped remnant native shortgrass steppe reference areas?
- (3) What land cover composition and vertical structure variables best predict summer daytime LST patterns?

2. Study area

We studied a 287 km² area centered on Aurora, Colorado, a rapidly-growing suburb adjacent to Denver in the Colorado Front Range region (Fig. 1). Most of the area was converted from shortgrass steppe to dryland and irrigated agriculture beginning in the 1850's. The human population has grown rapidly in recent decades, driving urban expansion into former agricultural lands and remnant native grasslands. The study area has a semiarid climate, receiving ~400 mm of precipitation annually, and is dominated by a mix of land uses including single and multi-family residential, retail commercial and light industrial, and parks/open space. The area has modest topographic relief and supports a range of vegetation types including an urban forest of varying composition and structure, irrigated lawns in parks and residential areas, and unirrigated native and ruderal communities.

3. Materials and methods

3.1. Land cover and vertical structure analysis

To evaluate land cover composition and vertical structure

characteristics, we developed a high resolution land cover map using an object-oriented image analysis (OBIA) approach, which often performs better than pixel-based approaches in complex urban areas (Al Fugara et al., 2009; O'Neil-Dunne et al., 2012; Voss and Sugumaran, 2008). The analysis involved the following major steps: (1) data preprocessing; (2) image segmentation; (3) classification; and (4) error analysis. Using LASTools (Rapidlasso, GmbH) and discrete, multiple-return LiDAR data, we created first return, bare Earth, intensity, and normalized digital surface model (nDSM) layers. Four-band (blue, green, red, near infrared) imagery collected concurrently with LiDAR was used to derive Normalized Difference Vegetation Index (NDVI), a Green/NIR ratio layer, and principal components analysis rasters used in image segmentation and classification stages (Table 1; Supplementary Fig. 1).

Data were combined into a single multiband raster in ArcGIS (ESRI, Inc.) and exported into BerkeleyImageSeg (Berkeley Environmental Technology International, LCC) for segmentation using a region merging algorithm (Benz et al., 2004). Pixel mean and standard deviation was calculated for each image segment and data layer in ArcGIS. Data were then exported to the R statistical program (version 3.3.2; R Foundation for Statistical Computing) for classification using a training data set created by manually assigning land cover class to 2100 image segments. The Random Forests algorithm in the “randomForest” R package was used to model land cover class identity and assign classes to image segments (Breiman, 2001; Liaw and Wiener, 2002). A separate validation point data set (n = 767) was created by generating random sample points across the study area and manually assigning class identity by examining high-resolution imagery. The resulting data set was then compared to classification output to calculate overall accuracy, omission error, commission error, and kappa (Congalton and Green, 1999). Masks for each land cover class were used to extract vertical structure variables from LiDAR-derived rasters (Table 2; Supplementary Fig. 1). We used zoning data from the City of Aurora and Arapahoe County governments to evaluate land cover patterns in relation to land use.

3.2. Evaluation of LST

We obtained atmospherically and topographically-corrected surface reflectance, brightness temperature, and NDVI layers from the Landsat 5 satellite as part of the Climate Data Records (CDR) program (<http://glovis.usgs.gov/>) (Masek et al., 2006) and used NDVI and coefficients from Weng et al. (2004) to estimate emissivity. Six late-spring and summer cloud-free scenes for the study area acquired between 2005 and 2011 were chosen to represent temperature patterns at different times during the growing season. Landsat 5 thermal data are collected at 120 m resolution but resampled to 30 m for distribution, the resolution retained in our analyses. We did not address anisotropic effects

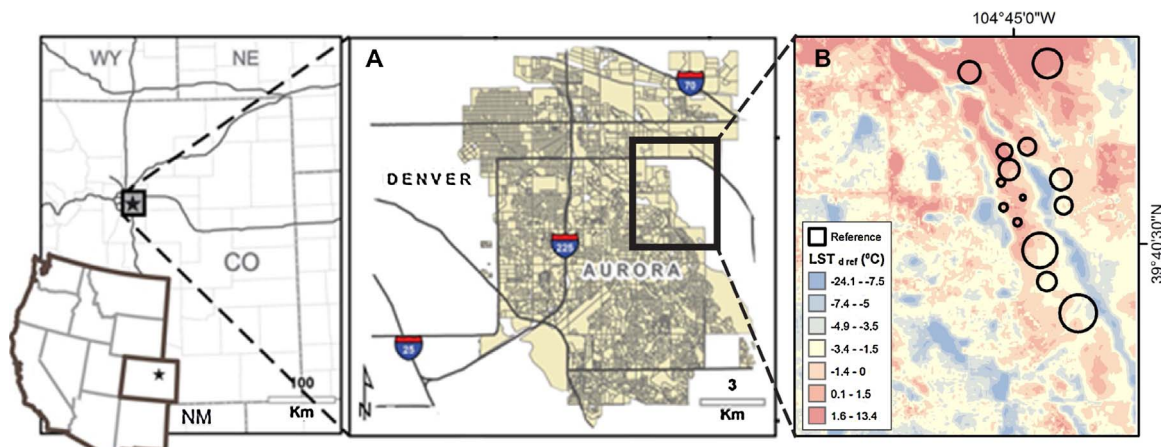


Fig. 1. Aurora-Denver study area in north-central, Colorado, USA (panel A); inset area illustrating reference area polygons and LST_{drer} raster (2008Aug11).

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