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Measuring urban tree loss dynamics across residential landscapes

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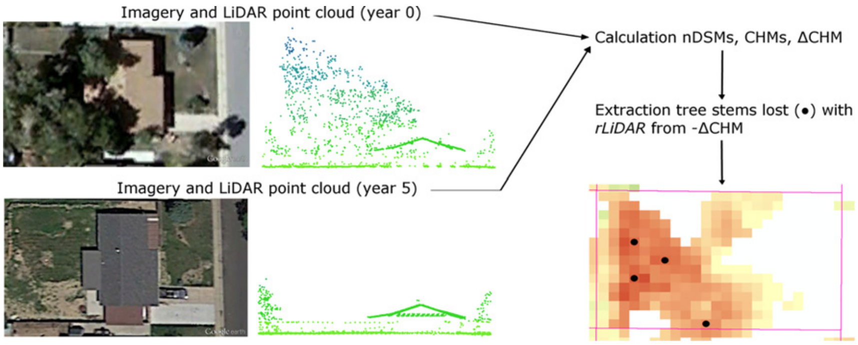
HIGHLIGHTS

- Combined LiDAR and multi-spectral imagery to measure residential tree loss dynamics
- Method averaged 95% accuracy in tree stem loss identification.
- Denver and Milwaukee lost 13,427 and 15,000 residential tree stems in 5 years.
- Canopy cover and urban development age were related to number of tree stems lost.
- Socio-economic settings had little or no effect on residential tree loss dynamics.

GRAPHICAL ABSTRACT



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ABSTRACT

The spatial arrangement of urban vegetation depends on urban morphology and socio-economic settings. Urban vegetation changes over time because of human management. Urban trees are removed due to hazard prevention or aesthetic preferences. Previous research attributed tree loss to decreases in canopy cover. However, this provides little information about location and structural characteristics of trees lost, as well as environmental and social factors affecting tree loss dynamics. This is particularly relevant in residential landscapes where access to residential parcels for field surveys is limited. We tested whether multi-temporal airborne LiDAR and multi-spectral imagery collected at a 5-year interval can be used to investigate urban tree loss dynamics across residential landscapes in Denver, CO and Milwaukee, WI, covering 400,705 residential parcels in 444 census tracts. Position and stem height of trees lost were extracted from canopy height models calculated as the difference between final (year 5) and initial (year 0) vegetation height derived from LiDAR. Multivariate regression models were used to predict number and height of tree stems lost in residential parcels in each census tract based on urban morphological and socio-economic variables. A total of 28,427 stems were lost from residential parcels in Denver and Milwaukee over 5 years. Overall, 7% of residential parcels lost one stem, averaging 90.87 stems per km^2. Average stem height was 10.16 m, though trees lost in Denver were taller compared to Milwaukee. The number of stems lost was higher in neighborhoods with higher canopy cover and developed before the 1970s. However, socio-economic characteristics had little effect on tree loss dynamics. The study provides a simple method for measuring urban tree loss dynamics within and across entire cities, and represents a further step toward high resolution assessments of the three-dimensional change of urban vegetation at large spatial scales.

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1. Introduction

When viewed from above, most urban landscapes contain trees and vegetation. These can provide humans a number of important ecosystem

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services ranging from stormwater runoff and pollution reduction to urban heat island mitigation and psychological wellbeing (Dobbs et al., 2011; Livesley et al., 2016). As such, it is not surprising that over the last two decades the increased availability of remotely sensed imagery has fueled research on urban tree canopy cover (Iverson and Cook, 2000; Mennis, 2006; Jiang et al., 2017). These investigations have largely focused on the assessment of factors regulating canopy cover, such as the morphological characteristics of urban landscapes (e.g., land use, parcel size, age of development) (Luck et al., 2009; Lowry et al., 2012; Bigsby et al., 2014) and socio-economic characteristics of neighborhoods (e.g., education, income) (Grove et al., 2006, 2014; Schwarz et al., 2015).

Advancements in data collection, storage, and processing have made LiDAR (*Light Detection And Ranging*) technology much more efficient for accurate assessments of the three-dimensional structure of urban trees and vegetation (Alonzo et al., 2014; Raciti et al., 2014; Mitchell et al., 2016). These investigations are important because the structure of vegetation, rather than its cover per se, can significantly affect the biophysical and micro-climatic characteristics of urban greenspace (McPherson et al., 1997; Davis et al., 2016), ecological and hydrological processes (Ossola et al., 2015a; Ossola et al., 2016), and the provision of habitat for biodiversity (Stagoll et al., 2012; Le Roux et al., 2014; Ossola et al., 2015b).

However, the structure of urban vegetation is not a static measure because it is continuously re-shaped through human management and environmental factors. For example, it is estimated that about 4 million urban trees are lost each year in the United States (US), corresponding to about 1% of urban forests of the entire country (Nowak and Greenfield, 2012). On the other hand, hundreds of exotic and native species of trees and shrubs are regularly planted in urban greenspace (Clarke et al., 2013; Threlfall et al., 2016). As such, the evaluation of spatial and temporal changes of vegetation and trees in urban landscapes can provide insights on the environmental and social factors driving these dynamics. This is particularly relevant in residential landscapes where the diversity of people's preferences and attitudes toward trees and vegetation can greatly affect management practices of vegetation (Cook et al., 2012; Kendal et al., 2012; van Heezik et al., 2013; Pearce et al., 2015; Conway, 2016; Visscher et al., 2016).

Similar to assessments of urban tree cover, those evaluating urban forest dynamics (e.g., growth and mortality) have relied on the comparison of multi-temporal medium- and high-resolution imagery to date (Zhao et al., 2013; Zhao et al., 2016). Studies based on field-collected data examining temporal changes in vegetation structure have been generally restricted to small geographical areas due to the costs associated with field surveys, limited access to sites of interest (Quigley, 2002; O'Brien et al., 2012; Briber et al., 2015; Enloe et al., 2015; Vogt et al., 2015), or the sporadic occurrence of atmospheric events such as storms and hurricanes (Burley et al., 2008; Staudhammer et al., 2011). Similarly, few manipulative experiments designed to evaluate the effects of urbanization on tree and vegetation growth or productivity have been focused on comparisons between urban and rural sites (Gregg et al., 2003; Ziska et al., 2004; Searle et al., 2012; Singh et al., 2017). At large spatial scales, most literature on urban tree loss dynamics has focused on changes in canopy cover (Nowak and Greenfield, 2012; Hostetler et al., 2013). These studies, however, provide little information on location and structural characteristics (e.g., stem height) of trees lost, and as such, on the potential environmental and socio-economic factors driving these changes.

The recent availability of multi-temporal LiDAR datasets for some rural forests and plantations has allowed the investigation of vegetation structural dynamics over spatial scales ranging from individual plots to entire landscapes. For example, numerous attempts have been made to measure short-term (2–11 years) tree growth (Næsset and Gobakken, 2005; Hopkinson et al., 2008) and changes in tree biomass (Meyer et al., 2013; Økseter et al., 2015; Cao et al., 2016). Similarly, canopy gap opening and closure in rural forests and tree harvesting in plantations have been monitored using LiDAR (Yu et al., 2004; Vepakomma et al., 2008; Vepakomma et al., 2010; Vepakomma et al., 2011). The only LiDAR-based study investigating dynamics of vegetation structure in urban systems was restricted to a single urban park in Osaka, Japan, over a six-year period (Song et al., 2016).

This study addresses the following objectives: i) to devise a method based on medium-resolution LiDAR collected at a 5-year interval to measure dynamics of urban tree loss across entire residential landscapes, and ii) to apply this method in two US cities to identify potential relationships between dynamics of tree loss (i.e., number of stems lost in a 5-year period and their height), and the morphological and socio-economic characteristics of residential landscapes.

2. Methods and data

2.1. Study areas

The metropolitan areas of Denver, CO and Milwaukee, WI were selected for this study due to their contrasting urbanization trajectories and availability of geospatial datasets (Fig. 1).

Denver's metropolitan area is situated in the Colorado Piedmont of the Great Plains, between the High Plains and the Rocky Mountains in the South Platte River Valley. Located at an altitude ranging from 1564 to 1768 m above sea level, the area has a semi-arid continental climate (Kottek et al., 2006) with mean annual temperature of 10.3 °C and mean annual precipitation of 440 mm (PRISM Climate Group, 2015). Denver was founded in 1858 and its population has recently grown to >750,000 people, making it one of the fastest growing US cities (US Census Bureau, 2010).

Milwaukee's metropolitan area is located on the western shore of Lake Michigan at an altitude between 179 and 259 m above sea level. Due to its proximity to the Great Lakes, Milwaukee has a humid continental climate (Kottek et al., 2006) with a mean annual temperature of 9.0 °C and mean annual precipitation of 861 mm (PRISM Climate Group, 2015). European immigrants settled in the area in the 1830s and the population peaked in the 1960s to then decrease to 850,000 inhabitants to date (US Census Bureau, 2010). As such, Milwaukee is currently considered a shrinking city. The Milwaukee study area (516 km^2) is larger than that in Denver (448 km^2), comprising some peri-urban forest and agricultural land intermixed with developed areas.

2.2. Data sources

Two airborne LiDAR point cloud datasets with similar point density were used for each city (Table 1).

LiDAR point clouds were collected in 2008 and 2013 for Denver, and in 2010 and 2015 for Milwaukee, resulting in LiDAR datasets collected at a 5-year interval. LiDAR datasets for Denver and Milwaukee were acquired by USGS and the Southeastern Wisconsin Regional Planning Commission, respectively, and are publicly available for download (Denver, http://nationalmap.gov/; Milwaukee, http://county.milwaukee.gov/mclio/geodata.html). Ground returns were already classified by the data provider. Aerial 4-band visible (RBG) and near-infrared (NIR) imagery at 1 m resolution were obtained from the National Agricultural Imagery Program (NAIP, United States Department of Agriculture; http://datagateway.nrcs.usda.gov/). NAIP imagery for Denver was acquired in 2009 and 2013, and for Milwaukee in 2010 and 2015. The collection of LiDAR and NAIP data was not simultaneous because LiDAR data are preferentially collected in winter when leaves are absent ("*leaf off*"), and NAIP imagery is acquired in summer at the peak of the growing season ("*leaf on*"). A time offset up to 3 years in the collection of LiDAR data and NAIP imagery was assumed to not significantly change urban vegetation structure in Chicago, IL (Davis et al., 2016). In this study, the maximum offset between LiDAR and NAIP data was limited to 1 year (i.e., Denver 2008–2009).

Land use/zoning and parcel maps were used to locate residential properties within the urban landscape (n = 187,478 and 213,227 for Denver and Milwaukee, respectively). Publicly available land use and parcel data for Denver were acquired from the City of Denver (https://www.

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