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The feasibility of remotely sensed data to estimate urban tree dimensions and biomass☆

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ABSTRACT

Accurately measuring the biophysical dimensions of urban trees, such as crown diameter, stem diameter, height, and biomass, is essential for quantifying their collective benefits as an urban forest. However, the cost of directly measuring thousands or millions of individual trees through field surveys can be prohibitive. Supplementing field surveys with remotely sensed data can reduce costs if measurements derived from remotely sensed data are accurate. This study identifies and measures the errors incurred in estimating key tree dimensions from two types of remotely sensed data: high-resolution aerial imagery and LiDAR (Light Detection and Ranging). Using Sacramento, CA, as the study site, we obtained field-measured dimensions of 20 predominant species of street trees, including 30–60 randomly selected trees of each species. For each of the 802 trees crown diameter was estimated from the aerial photo and compared with the field-measured crown diameter. Three curve-fitting equations were tested using field measurements to derive diameter at breast height (DBH) (r^2 = 0.883, RMSE = 10.32 cm) from the crown diameter. The accuracy of tree height extracted from the LiDAR-based surface model was compared with the field-measured height (RMSE = 1.64 m). We found that the DBH and tree height extracted from the remotely sensed data were lower than their respective field-measured values without adjustment. The magnitude of differences in these measures tended to be larger for smaller-stature trees than for larger stature species. Using DBH and tree height calculated from remotely sensed data, aboveground biomass (r^2 = 0.881, RMSE = 799.2 kg) was calculated for individual tree and compared with results from field-measured DBH and height. We present guidelines for identifying potential errors in each step of data processing. These findings inform the development of procedures for monitoring tree growth with remote sensing and for calculating single tree level carbon storage using DBH from crown diameter and tree height in the urban forest.

1. Introduction

Accurate data on the biophysical dimensions of individual trees such as diameter at breast height (DBH), height, crown diameter, and biomass are essential for quantifying the economic value, social benefits, and ecological services of the urban forest. Over the past few decades, numerous studies have quantified the benefits of urban forests. These ecosystem services include the reduction of atmospheric carbon dioxide (Nowak et al., 2013; Nowak and Crane, 2002; Rowntree and Nowak, 1991), absorption of air pollutants (Morani et al., 2011; Nowak et al., 2006; Scott et al., 1998), savings of space-conditioning energy in buildings (Donovan and Butry, 2009; Ko and Radke, 2014; McPherson and Rowntree, 1993; Simpson and McPherson, 1998), mitigation of the urban heat island (Deng and Wu, 2013; Huang et al., 1987; McPherson, 1994; McPherson and Muchnick, 2005; Roberts et al., 2012; Weng, 2009), outdoor thermal comfort (Shashua-Bar et al., 2011) and reduction of stormwater runoff (Xiao et al., 1998). Other studies have assessed social and economic benefits, such as mental and physical health improvement (Donovan et al., 2013; Gidlöf-Gunnarsson and Öhrström, 2007; Kaplan and Kaplan, 1989; van den Berg et al., 2010), crime reduction (Kuo and Sullivan, 2001; Schroeder and Anderson, 1984), and increased property values (Anderson and Cordell, 1988; Sander et al., 2010). As more people recognize the value of these services it

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becomes increasingly important to develop accurate and economical methods for measuring trees' dimensions and quantifying their performance.

In the past decade, remotely sensed data with high spatial resolution has been used to supplement field measurements of forest stand structure and tree dimensions. Aerial photographs and photogrammetric techniques have been used to measure forest parameters such as species, size, canopy density, and number of trees (Gong et al., 1999; Spurr, 1960). In particular, photogrammetric measurements have become popular for extracting precise forest information, even at the level of individual trees, due to their high spatial resolution and accuracy (Dralle and Rudemo, 1997; Korpela, 2004; Larsen and Rudemo, 1998). Several studies have developed automated approaches to extract individual tree canopy from high spatial resolution digital images, but these automated approaches are most applicable on forest areas with uniform patterns and distinctive tree canopies (Culvenor, 2002; Gougeon, 1995; Gougeon and Leckie, 2006; Ke and Quackenbush, 2011; Wang et al., 2004; Wulder et al., 2000). In the case of heterogeneous urban areas, however, with many species of trees in a non-uniform distribution, human interpreters more effectively recognize tree objects than automated programs (Nowak, 1993; Nowak and Greenfield, 2012; Parlin, 2009). Recently, Light Detection and Ranging (LiDAR) technology is garnering attention because of the capability of extracting both horizontal and vertical information at high spatial resolutions using airborne (Alonzo et al., 2015; Hyyppä et al., 2008, 2004; Koch and Dees, 2008; Lim et al., 2003) and ground-based system (Lefsky and McHale, 2008; McHale et al., 2009). Combined with hyperspectral imagery, LiDAR data can provide detailed species information in complex urban areas (Alonzo et al., 2014). Remote sensing techniques have been used with plot-based estimates of carbon storage to quantify and map urban forest carbon stocks citywide (McPherson et al., 2013).

While recent remote-sensing techniques provide useful information on the structure, function and value of urban tree canopy, it remains unclear how errors propagate during the process of estimating individual tree dimensions and biomass using remotely sensed data (e.g., airborne digital images, aerial photos, and LiDAR). If remote sensing can serve as an effective supplement to field surveyed data, it could make monitoring more economical by reducing the frequency of field measurements. The accuracy of tree dimensions measured with remote sensing are influenced by errors that occur during each step of the calculation. For example, correctly locating the target tree for measurement can be a possible source of error when its location is not accurately noted because falsely matched tree information could affect the model calibration and validation. Classification or digitizing the tree crown (e.g., aerial image interpretation) is a major source of error due to difficulties separating the overlapping boundaries of tree crowns (Richardson and Moskal, 2014). Additional uncertainty is added with use of regression models to estimate tree dimensions such as DBH, which cannot be directly measured from airborne remotely sensed data (Mäkinen et al., 2006). Each step in the process can amplify the error of the estimated tree dimension. Given this challenge, it is imperative to assess the accuracy of estimated dimensions before they are used to calculate tree biomass, carbon storage or other urban forest functions.

This study aims to assess the accuracy of remotely sensed data for measuring urban tree dimensions and biomass. We identify and measure errors obtained at each step of the estimation process to (1) determine crown diameter, DBH and tree height from aerial photographs and LiDAR imagery and (2) calculate aboveground biomass using estimated DBH, tree heights, and allometric equations from each species (Fig. 1). Estimated tree dimensions are compared with actual dimensions obtained from field measurements of 818 trees comprising the 20 predominant street tree

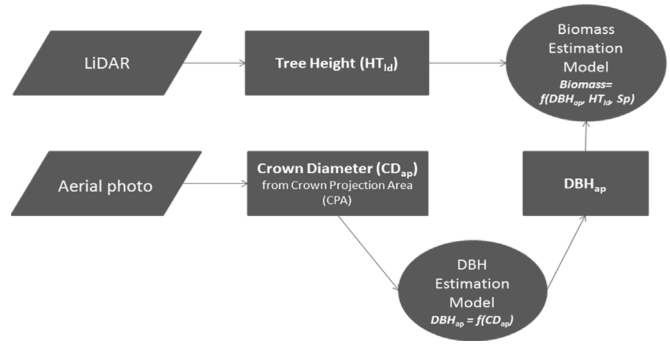

Fig. 1. Research design.

species (Table 1) in Sacramento, CA. For each tree we digitize the crown projection area (CPA), calculate the crown diameter (CD_{ap}), and compare it with field measured crown diameter. Using field measured data, we test three curve-fitting equations to establish relations between field measured crown diameter and DBH for each of the 20 sampled species, and identify the equation yielding the lowest error for each species. We apply the relevant equation to the remotely sensed CPA for each tree and calculate its diameter at breast height (DBH_{ap}). Similarly, the accuracy of each tree's estimated height is determined by comparing the field measured value with height extracted from a LiDAR-based surface model (HT_{ld}). These DBH_{ap} and HT_{ap} values are used with species-specific allometric equations to calculate each tree's aboveground biomass, which is compared to results from the field-measured DBH and height. It is important to note that we used publically available remotely sensed data that were not ideal. The LiDAR data were acquired during leaf-off condition and a time gap of several years exists between the time LiDAR was acquired and field measurements were recorded. However, these limitations are not unique to this study, and could be encountered by other cities and researchers interested in estimating the biophysical parameters and biomass of local trees. The effectiveness and limitations of the remote sensing-based measurements, biometric models and the resulting errors are discussed. We conclude that remotely sensed data can be a viable alternative to field measurements if the accuracies of derived tree dimensions are quantitatively assessed. These results will assist cities, consultants and others develop procedures to routinely monitor and measure tree dimensions with accepted levels of accuracy. When combined with periodic field surveys, this approach may reduce the cost of monitoring compared to solely relying on traditional field surveys.

2. Methods

2.1. Study area

The City of Sacramento covers 253.61 km^2 (38°33′20″N 121°28′8″W, Fig. 2) and has a population of 466,488, making it the 35th most populous city in the United States (US Census Bureau, 2014). Sacramento's Mediterranean climate is characterized by wet, mild winters and hot, dry summers. The average low temperature in January is 3.3 °C while the average high temperature in July is 33.9 °C. On average, 74 days a year are above 32.2 °C (90 °F) (City of Sacramento, 2012).

Sacramento's urban forest is nationally renowned because of its rich history (McPherson and Luttinger, 1998) and successful partnerships among local agencies, utilities and non-profits. American Forests, for example, selected the City of Sacramento as having one of the 10 best urban forests in the United States (American Forests, 2014). Urban tree canopy is 18.2% and there are approximately 6.9