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Mapping urban forest leaf area index with airborne lidar using penetration metrics and allometry

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ABSTRACT

In urban areas, leaf area index (LAI) is a key ecosystem structural attribute with implications for energy and water balance, gas exchange, and anthropogenic energy use. In this study, we estimated LAI spatially using airborne lidar in downtown Santa Barbara, California, USA. We implemented two different modeling approaches. First, we directly estimated effective LAI (LAI_e) using scan angle- and clump-corrected lidar laser penetration metrics (LPM). Second, we adapted existing allometric equations to estimate crown structural metrics including tree height and crown base height using lidar. The latter approach allowed for LAI estimates at the individual tree-crown scale. The LPM method, at both high and decimated point densities, resulted in good linear agreement with estimates from ground-based hemispherical photography ($r^2 = 0.82$, $y = 0.99x$) using a model that assumed a spherical leaf angle distribution. Within individual tree crown segments, the lidar estimates of crown structure closely paralleled field measurements (e.g., $r^2 = 0.87$ for crown length). LAI estimates based on the lidar crown measurements corresponded well with estimates from field measurements ($r^2 = 0.84$, $y = 0.97x + 0.10$). Consistency of the LPM and allometric lidar methods was also strong at 71 validation plots ($r^2 = 0.88$) and at 450 additional sample locations across the entire study area ($r^2 = 0.72$). This level of correspondence exceeded that of the canopy hemispherical photography and allometric, ground-based estimates ($r^2 = 0.53$). The first-order alignment of these two disparate methods may indicate that the error bounds for mapping LAI in cities are small enough to pursue large scale, spatially explicit estimation.

1. Introduction

Urban trees provide a broad array of ecosystem services that are governed by tree species, canopy structure, and locational context (Escobedo & Nowak, 2009; Manning, 2008; McCarthy & Pataki, 2010; McPherson, Simpson, Xiao, & Wu, 2011; Simpson, 2002; Urban, 1992). Leaf Area Index (LAI), commonly defined as one half of the total green leaf area per unit ground area (Chen & Black, 1992), is a critical structural attribute that has implications for urban energy balance, gas exchange, hydrological throughput, and anthropogenic energy use. It is an ecophysiological measure of leaf surface available for photosynthesis and transpiration (Chen, Rich, Gower, Norman, & Plummer, 1997). In addition, dry depositional uptake and intercellular suspension of air pollutants such as O_3, NO_2, SO_2, CO, and PM_x is partly mediated by effective leaf surface area (Baldocchi, Hicks, & Camara, 1987; Hirabayashi, Kroll, & Nowak, 2011). In urban areas, this process has been related to spatial variation in air pollution reduction (e.g.,Escobedo & Nowak, 2009). Increased canopy leaf area, especially over paved surfaces, delays stormwater peak flow through interception of precipitation (Xiao & McPherson, 2002). Higher urban vegetation fractional cover (Lu & Weng, 2006; Myint, Brazel, Okin, & Buyantuyev, 2010) and higher LAI (Georgi & Zafiriadis, 2006; Hardin & Jensen, 2007; Oke, 1989; Peters & McFadden, 2010) have been correlated with lowered urban temperatures and reduced summertime building cooling costs. At the same time, tree cover has also been linked to ecosystem disservices ranging from pollen allergies to sidewalk damage and the production of litterfall (Roy, Byrne, & Pickering, 2012).

Many cities have estimated urban LAI using the USDA Forest Service's Urban Forest Effects (UFORE) model (Nowak, Crane, et al., 2008). The UFORE model produces estimates of urban forest structure, including LAI, and ecosystem function using field measurements of tree species and crown dimensions acquired on ≥200 stratified random inventory plots across a city (Nowak, Crane, et al., 2008). The resulting estimates of ecosystem function are used by cities for urban forest management and planning (e.g., Million Trees LA: McPherson et al., 2011). However, the data collection process is labor intensive, and the results are only available at very coarse spatial resolution. Further, the LAI estimates become increasingly uncertain in regions where the model's allometric equations have not been parameterized by locally-evaluated, species-specific coefficients (Gower, Kucharik, & Norman, 1999; Peper & McPherson, 2003). By contrast, the estimation of *effective*

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LAI (LAI_e) in an urban area from hemispherical photography (hereafter "hemiphotos") may be more robust to the varying mixtures of tree species than allometric methods. LAI_e differs from true LAI in that it does not account for the non-random distribution of foliage throughout the canopy and does not differentiate between foliar and woody plant components (Chen & Black, 1991). However, measurement challenges such as discontinuous canopy cover, variability in canopy height, occlusion of foliage by buildings and other structures, and difficulty of accessing private property at times when sky conditions are appropriate for the method have limited the use of this technique in cities (Jensen, Hardin, & Hardin, 2012; Jensen et al., 2009; Osmond, 2009; Peper & McPherson, 2003; Richardson, Moskal, & Kim, 2009). Importantly, both allometry and hemispherical photography are field-sampling techniques that generate only point estimates of LAI that cannot easily be extended to a citywide map. Remote sensing data can be used to estimate and map urban LAI and LAI_e over large areas at fine spatial scales, possibly at significant cost savings compared to field campaigns (Nowak, Walton, Stevens, Crane, & Hoehn, 2008).

Maps of LAI_e in natural forest settings are frequently produced using laser penetration metrics (LPM) calculated from airborne lidar (e.g.,Hopkinson et al., 2013; Korhonen, Korpela, Heiskanen, & Maltamo, 2011; Solberg et al., 2009; Zhao & Popescu, 2009). LPMs, which report the penetration ratios of laser pulses through canopy, are favored in part due to the theoretical reliance on Beer-Lambert's law of light attenuation that they share with gap fraction calculated from hemiphotos. However, issues related to multi-scale clumping of foliage, the variable relationship between sensor scan angle and canopy path length, and the wide range of possible leaf angle distributions due to species diversity have largely precluded lidar mapping of LAI_e in heterogeneous areas (Holmgren, Nilsson, & Olsson, 2003; Morsdorf, Frey, Meier, & Itten, 2008; Van Gardingen, Jackson, Hernandez-Daumas, Russell, & Sharp, 1999). Despite these limitations, Richardson et al. (2009) showed that mapping LAI_e was possible in a biodiverse urban park and that the assumption of a spherical leaf angle distribution may be acceptable.

In this study we sought to improve LAI mapping capabilities in heterogeneous urban environments. We used two theoretically distinct modeling approaches and multiple types of validation evidence. It is important to acknowledge that indirect, ground-based measurements of LAI or LAI_e are problematic, exhibiting variability and bias with respect to true LAI and each other (Bréda, 2003; Peper & McPherson, 2003). We first examined the relationship between lidar estimates of LAI_e using a Beer-Lambert style approach and estimates from hemiphotos acquired at 71 field plots. Second, we adapted the allometric equations used in the UFORE model for use with crown dimension measurements (e.g., height, diameter) taken at the individual tree crown scale (hereafter "crown scale") using lidar. The specific objectives of this study were:

1. Map LAI_e in a heterogeneous, urban landscape at the field-plot scale through correlation of LPM derived LAI_e and hemiphoto gap fraction inversion.
2. Introduce methods for mitigating the effects of off-nadir lidar pulse angles and non-random foliage distribution on estimates of LAI_e in discontinuous canopy.
3. Map LAI of individual trees using automatically delineated crown objects, lidar-measured crown dimensions, and an allometric approach.
4. Compare plot-aggregated allometric LAI outputs with the plot-level outputs from the LPM method to characterize the covariation.

We anticipated that the plot-level metrics based on Beer-Lambert's law would offer a site-transferable means to estimate LAI_e with minimal model calibration from field data. This output could be useful for broad assessment and modeling of urban surface energy balance in terms of heat, moisture, and momentum fluxes (Grimmond et al., 2010) However, the resultant map resolution will not allow for estimates of urban tree ecosystem service provision in the manner desired by many cities (i.e., services that depend on crown location relative to buildings and impervious surfaces). Crown scale estimates of LAI validated against UFORE allometry offer a more direct path towards a spatially explicit urban forest inventory albeit one that internalizes the uncertainties of the UFORE model.

2. Materials and methods

2.1. Study area and field plots

This study was conducted in downtown Santa Barbara, California (34.42° N, 119.69° W) (Fig. 1). Santa Barbara is a city of about 90,000 residents, encompassing 51 km^2, located on a coastal plain between the Pacific Ocean to the south and the Santa Ynez mountains to the north. It has a Mediterranean climate and supports a diverse mix of native, introduced, and invasive urban forest species. Fractional canopy cover (*fCov*) was estimated in 2012 at 25.4% for the entire municipality of Santa Barbara using high-resolution digital imagery (City of Santa Barbara Urban Forest Management Plan, 2014, www.santabarbaraca.gov). Our study area was situated in the most densely built portion of the city and, according to UFORE estimates in 2012, *fCov* was approximately 20%.

In the fall of 2012, we inventoried vegetation within 105 plots, recording 108 unique species. The most commonly sampled species were the broadleaf persistent native *Quercus agrifolia* (Coast live oak) and the introduced *Syagrus romanzoffiana* (Queen palm). Each plot (Fig. 1) had a radius of 11.4 m in accordance with UFORE data collection protocols (i-Tree Eco User's Manual v. 4.1.0, www.itreetools.org). Species composition and structure in the plots was extremely heterogeneous: Thirty-eight plots had LAI values of <1 and 10 plots had values >3 (mean $= 1.39$). Average canopy height was also highly variable, ranging between 2 and 23 meters with significant internal variation as well. The number of trees per plot ranged between 1 and 57 with a median stem count of 4 trees. Plot centers were geolocated using differentially corrected GPS and were positionally accurate to 30 cm with respect to the lidar data. The distance and direction of each stem was measured from plot center with an Opti-Logic laser range finder and a compass. Of the 105 sampled plots, 71, with colocated field measurements, hemiphotos, and lidar data were retained for analysis.

2.2. LAI_e estimates from hemispherical photography

To characterize the extreme heterogeneity in urban forest gap fraction, one hemiphoto was acquired at plot center along with four additional photos 5.5 m from the center in each cardinal direction. Plots where only one photo site was accessible represented 16% of the total. While best practice dictates that hemiphotos are acquired under diffuse light conditions, this was not always possible. Southern California autumn days are frequently cloudless and the high likelihood of a field plot falling on private property limited our flexibility in acquisition time. The photos were taken at 1 m above ground using a Nikon Coolpix 5400 digital camera retrofitted by removing the manufacturer's infrared-blocking filter and replacing it with a filter that blocked wavelengths <590 nm such that it could record red and infrared light. The modified camera was used because hemiphotos acquired with near infrared (NIR) wavelengths can lead to more efficient and accurate image binarization of foliage (Chapman, 2007). This advantage is important in urban settings where hemiphotos frequently contain structures interspersed with foliage (Osmond, 2009).

At each hemiphoto location, we acquired images at three exposure settings: 1-stop underexposed, automatic exposure, and 1-stop overexposed. We combined these multiple exposures into a single high-dynamic range (HDR) image to enhance contrast between foliage and sky (Jonckheere, Nackaerts, Muys, & Coppin, 2005; Zhang, Chen, & Miller, 2005) and mitigate pixel saturation caused by direct beam radiation (Korhonen et al., 2011). HDR processing was completed with minimal changes to default settings in Dynamic-Photo HDR 5 (v 5.2.0). Foliage, plant stems, and branches were distinguished from all other