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Urban tree species mapping using hyperspectral and lidar data fusion

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ABSTRACT

In this study we fused high-spatial resolution (3.7 m) hyperspectral imagery with 22 pulse/m^2 lidar data at the individual crown object scale to map 29 common tree species in Santa Barbara, California, USA. We first adapted and parallelized a watershed segmentation algorithm to delineate individual crowns from a gridded canopy maxima model. From each segment, we extracted all spectra exceeding a Normalized Difference Vegetation Index (NDVI) threshold and a suite of crown structural metrics computed directly from the three-dimensional lidar point cloud. The variables were fused and crowns were classified using canonical discriminant analysis. The full complement of spectral bands along with 7 lidar-derived structural metrics were reduced to 28 canonical variates and classified. Species-level and leaf-type level maps were produced with respective overall accuracies of 83.4% (kappa = 82.6) and 93.5%. The addition of lidar data resulted in an increase in classification accuracy of 4.2 percentage points over spectral data alone. The value of the lidar structural metrics for urban species discrimination became particularly evident when mapping crowns that were either small or morphologically unique. For instance, the accuracy with which we mapped the tall palm species *Washingtonia robusta* increased from 29% using spectral bands to 71% with the fused dataset. Additionally, we evaluated the role that automated segmentation plays in classification error and the prospects for mapping urban forest species not included in a training sample. The ability to accurately map urban forest species is an important step towards spatially explicit urban forest ecosystem assessment.

1. Introduction

As of 2011, more than 50% of all humans live in cities (UN-Habitat, 2011). Cities play an outsized role in driving global climate change (Schneider, Friedl, & Potere, 2010) and are uniquely susceptible to climate change impacts. Urban areas suffer from higher temperatures, poorer air quality, and increased peak flow of stormwater runoff, when compared to their rural neighbors (Escobedo & Nowak, 2009; Lee & Bang, 2000; Voogt, 2002). Optimally arranged green infrastructure in cities can reduce impacts by facilitating reduced urban temperatures, improving air quality, and dampening peak flow (Bolund & Hunmammar, 1999; Myint, Brazel, Okin, & Buyantuyev, 2010). Urban trees in particular provide a range of ecosystem services, along with some disservices (e.g. Lyytimaki et al., 2008), but the magnitude of service depends on tree species, structure, and locational context (Escobedo & Nowak, 2009; Manning, 2008; McCarthy & Pataki, 2010, McPherson, Simpson, Xiao, & Wu, 2011; Simpson, 2002; Urban, 1992). Presently, the Urban Forest Effects model (UFORE, Nowak et al., 2008) is commonly implemented in urban areas worldwide to produce city-wide estimates of urban forest structure, species diversity, and ecosystem function. However, urban forest inventory, particularly on private properties, is labor intensive and the results are not spatially explicit.

Mapping the extents of urban tree canopy using aerial or satellite imagery is currently operational (MacFaden, O'Neil-Dunne, Royar, Lu, & Rundle, 2012; McGee, Day, Wynne, & White, 2012). However, these maps rarely provide information on tree species, age class, or leaf area index (LAI), which are common prerequisites to estimates of ecosystem function. Mapping tree species is challenging in urban environments due to the fine characteristic scale of spatial variation (Welch, 1982) and potentially very high species diversity. While some space-borne, broadband sensors (e.g., IKONOS, GeoEye) are capable of achieving <3 m multispectral spatial resolution, they lack the spectral range and resolution required to resolve the subtle chemical and structural signatures upon which species discrimination relies (Clark, Roberts, & Clark, 2005). Hyperspectral imagery has proven useful in mapping tree species at the pixel level based on variability in spectral reflectance at leaf to crown scales (Boschetti, Boschetti, Oliveri, Casati, & Canova, 2007; Clark et al., 2005; Dennison & Roberts, 2003; Franke, Roberts, Halligan, & Menz, 2009; Martin, Newman, Aber, & Congalton, 1998; van Aardt & Wynne, 2007; Yang, Everitt, Fletcher, Jensen, & Mausel, 2009; Youngentob et al., 2011). In an urban setting, Xiao, Ustin, and McPherson (2004) mapped 22 common species in Modesto, California with 70% accuracy at the species level and 94% accuracy at the leaf-type (i.e., broadleaf, conifer, palm) level.

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Classification accuracies for pixel-based algorithms in highly mixed urban landscapes are limited by extreme spectral variation over small spatial extents. In response there has been increased use of object-based image analysis (OBIA), which relies on image segmentation routines to group spectrally similar and spatially proximate pixels into objects to reduce undesirable noise common in pixel-level results (Benz, Hofmann, Willhauck, Lingenfelder, & Heynen, 2004; Blaschke, 2010; Myint, Gober, Brazel, Grossman-Clarke, & Weng, 2011). This technique has been applied with some success to tree species identification using hyperspectral imagery either through crown-level spectral averaging or pixel-majority classification (Alonzo, Roth, & Roberts, 2013; Clark et al., 2005; van Aardt & Wynne, 2007; Zhang & Qiu, 2012). In a suburban setting north of Dallas, Texas, Zhang and Qiu (2012) achieved a classification accuracy of 69% for 40 tree species using a "treetop-based" approach. They selected the single highest pixel per crown object in order to ensure sunlit spectra whenever possible. Alonzo et al. (2013) showed that for manually delineated urban tree crowns in Santa Barbara, the pixel majority approach using all crown pixels exceeding a Normalized Difference Vegetation Index (NDVI) threshold was effective, especially with limited training data. Their classification of 15 urban species with Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data resulted in an overall accuracy of 86%. Nevertheless, Castro-Esau, Sanchez-Azofeifa, Rivard, Wright, and Quesada (2006), while producing strong species classification results using leaf-level spectra, show a linear decline in classification accuracies with increasing numbers of species. This suggests that 1) it may not be currently possible to map all species simultaneously in biodiverse forests and 2) that expanding the classification feature space with non-spectral data may be required for significant advances.

Lidar data allow for the generation of a set of crown structural variables based on either the ranges and intensities of individual pulse returns or characterization of the full waveform. Lidar data have been employed frequently to measure forest parameters such as tree height (e.g., Andersen et al., 2006; Edson & Wing, 2011; Lim, Treitz, Wulder, St-Onge, & Flood, 2003), biomass (e.g., Asner et al., 2011; Mascaro, Detto, Asner, & Muller-Landau, 2011; Næsset & Gobakken, 2008; Popescu, Wynne, & Nelson, 2003; Shrestha & Wynne, 2012), and LAI (e.g., Morsdorf, Kotz, Meier, Itten, & Allgower, 2006; Solberg et al., 2009; Tang et al., 2012; Zhao & Popescu, 2009). Classification of trees using pulse range and intensity metrics has been undertaken at the leaf type (e.g., Kim, Mcgaughey, Andersen, & Schreuder, 2009; Ørka et al., 2009; Yao, Krzystek, & Heurich, 2012), genus (e.g., Kim, Hinckley, & Briggs, 2011), and species levels (e.g., Brandtberg, 2007; Holmgren & Persson, 2004). Other work has shown that retaining the full lidar waveform can provide a set of discriminatory variables derived from, for example, echo width and amplitude (Heinzel & Koch, 2011; Vaughn, Moskal, & Turnblom, 2012). Suites of canopy structural variables (e.g. tree height, crown base height, vertical intensity profiles) extracted from the lidar point cloud at the individual tree level offer complementary information to the biochemical and biophysical data garnered from optical data. However, it has thus far not been demonstrated that lidar-variables alone are sufficient for discriminating among large numbers of species in biodiverse environments.

"Fusion" is a ubiquitous term in the remote sensing literature that generally refers to the combination of multisensor spatial data, at either the pixel, feature, or decision level (Pohl and Van Genderen, 1998). Increasingly, lidar and either multispectral (e.g., Holmgren, Persson, & Söderman, 2008; Ørka et al., 2012) or hyperspectral (e.g., Asner et al., 2008; Dalponte, Bruzzone, & Gianelle, 2008; Dalponte, Bruzzone, & Gianelle, 2012; Dalponte, Ørka, Ene, Gobakken, & Næsset, 2014; Jones, Coops, & Sharma, 2010; Liu et al., 2011; Voss & Sugumaran, 2008) data are fused together at the pixel or feature level for tree species classification and quantification of forest inventory parameters (e.g., Anderson et al., 2008; Clark, Roberts, Ewel, & Clark, 2011; Latifi, Fassnacht, & Koch, 2012; Lucas, Lee, & Bunting, 2008; Swatantran, Dubayah, Roberts, Hofton, & Blair, 2011). In some cases the value of fusion has come from the addition of structural variables (e.g., height, standard deviation of all height points within a pixel) that are minimally correlated with spectral bands (Dalponte et al., 2008; Dalponte et al., 2012; Jones et al., 2010; Voss & Sugumaran, 2008). In others, fusion has added value indirectly through improved image segmentation and crown-object creation (Alonzo et al., 2013; Dalponte et al., 2014; Voss & Sugumaran, 2008; Zhang & Qiu, 2012). However, to the authors' knowledge, there has been minimal research focused on improving tree species classification using crown-object level fusion of hyperspectral imagery and structural metrics extracted directly from the 3-D lidar point cloud. Moreover, the prospects for mapping an *entire*, biodiverse urban forest to the leaf-type level with hyperspectral-lidar data fusion, have not been evaluated. Finally, there is limited knowledge of how automated image segmentation impacts the accuracy of classification results in a highly complex urban environment.

The goal of this study is to improve the accuracy of tree species mapping in the biodiverse city of Santa Barbara, California, through crown-object level fusion of AVIRIS (Green et al., 1998) imagery and high point-density lidar data. This paper builds significantly on the work by Alonzo et al. (2013) which focused on classifying manually-delineated tree crowns using hyperspectral imagery. In particular, we now include lidar-derived structural metrics in classification algorithms and delineate crowns using watershed segmentation. The specific aims of this paper are:

1) For our urban study area, within crown objects delineated using watershed segmentation, classify 29 common tree species using crown-level fusion of hyperspectral imagery and lidar data.
2) Test the extent to which *all* of the urban forest's canopy can be classified to the leaf type level using classification functions developed for the 29 common species. Leaf-type level classification is frequently sufficient for parameterizing estimates of urban ecosystem function that are largely mediated by crown structure measurements and total leaf area.
3) Evaluate the impact of segmentation error on classification accuracy through comparison of results from automatically delineated and manually delineated crowns.
4) Isolate particular spectral regions and lidar-derived structural variables that hold promise for improving discrimination among urban tree species and leaf types.

Our study helps cities move closer to a spatially explicit accounting of the common species in their urban forest. Further, it facilitates better understanding of the spectral and structural contributions to species discrimination as well as the benefits and errors associated with object-oriented approaches.

2. Data and methods

2.1. Study area and sample

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 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. A spatial database maintained by the City of Santa Barbara contains one or more specimens from >450 species. In a Fall 2012 inventory following UFORE protocols, 105 plots were sampled and 108 species recorded. Despite this diversity, far fewer species provide the bulk of the city's canopy cover: In Santa Barbara, based on UFORE and municipal data, we estimate that approximately 70% of the study area's trees represent over 80% of the city's canopy area yet comprise fewer than 30 species.

This study's first objective was to map approximately 80% of Santa Barbara's canopy to the species level by training a classifier on 29 common species. The 80% canopy cover threshold was chosen based on