



An efficient, multi-layered crown delineation algorithm for mapping individual tree structure across multiple ecosystems



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ABSTRACT

Deriving individual tree information from discrete return, small footprint LiDAR data may improve forest above-ground biomass estimates, and provide tree-level information that is important in many ecological studies. Several crown delineation algorithms have been developed to extract individual tree information from LiDAR point clouds or rasterized canopy height models (CHM), but many of these algorithms have difficulty discriminating between overlapping crowns, and also may fail to detect understory trees. Our approach uses a watershed-based delineation of a CHM, which is subsequently refined using the LiDAR point cloud. Individual tree detection was validated with stem mapped field data from the Smithsonian Environmental Research Center (SERC), Maryland, and on a plot and stand level through comparisons of stem density and basal area to delineated metrics at both SERC and a study area in the Sierra Nevada, California. For individual tree detection, the algorithm correctly identified 70% of dominant trees, 58% of codominant trees, 35% of intermediate trees and 21% of suppressed trees at SERC. The algorithm had difficulty distinguishing between crowns of small, dense understory trees of approximately the same height. Delineated crown volume alone explained 53% and 84% of the variability in basal area at the SERC and Sierra Nevada sites, respectively. The algorithm produced crown area distributions comparable to diameter at breast height (DBH) size class distributions observed in the field in both study sites. The algorithm detected understory crowns better in the conifer-dominated Sierra Nevada site than in the closed-canopy deciduous site in Maryland. The ability for the algorithm to reproduce both accurate tree size distributions and individual crown geometries in two dissimilar and complex forests suggests great promise for applicability to a wide range of forest systems.

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1. Introduction

LiDAR has become the dominant technology for mapping 3D forest structure (Wulder et al., 2012; Zolkos, Goetz, & Dubayah, 2013). Discrete return and waveform LiDAR have been widely applied for forest height, crown volume and biomass estimation. While medium or large footprint (20–70 m) LiDAR data are useful for characterizing the vertical distribution of canopies at the resolution of the footprint, small footprint (10s of cm) LiDAR provides both vertical and horizontal information at the scale of individual trees (Wulder et al., 2012). Estimates of forest biomass have largely ignored the highly detailed spatial information from discrete return LiDAR and focused on metrics such as canopy height and cumulative vertical distributions at plot level, as in Chen, Gong, Baldocchi and Tian (2007); Popescu, Wynne and Nelson (2003); and Popescu (2007). Providing more spatially detailed information such as the number, location, spacing, and size distribution of indi-

vidual trees may improve biomass estimation at varying spatial resolutions, and should provide a more ecologically meaningful structural description of a forest.

Various methods for extracting individual tree information from high resolution LiDAR datasets have been developed. These techniques generally fall into three categories: local maxima detection and expansion (Kaartinen et al., 2012; Leckie et al., 2003; Maltamo, Mustonen, Hyypä, Pitkanen, & Yu, 2004; Persson, Holmgren, & Soderman, 2002; Popescu & Wynne, 2004; Vastaranta et al., 2011; Wulder, Niemann, & Goodenough, 2000), watershed-based delineation (Breidenbach, Næsset, Lien, Gobakken, & Solberg, 2010; Chen, Baldocchi, Gong, & Kelly, 2006; Koch, Heyder, & Weinacker, 2003; Kwak, Lee, Lee, Biging, & Gong, 2007), and point-cloud clustering (Ferraz et al., 2012; Rahman & Gorte, 2009). Local maxima algorithms typically involve the selection of a search radius and detection of local maxima from a CHM. Popescu and Wynne (2004) used both circular and square windows with site-specific window sizes to increase local accuracy of maxima detection. Leckie et al. (2003) applied a valley-following approach to isolate crowns based on CHM topography that yielded both tree

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locations and crown geometries with 80% accuracy. However, the trees in this study were well spaced and easily visible in the CHM. Vastaranta et al. (2011) used a minimum curvature approach with local maxima detection for a boreal forest and although they did not present an individual tree accuracy, they used delineated crowns to predict basal area ($R^2 = 0.48$) and volume ($R^2 = 0.71$). Maltamo et al. (2004) also worked in a boreal forest with a local maxima detection algorithm and reported that while as much as 80% of dominant crowns were correctly detected, the total accuracy was 40% due to issues identifying understory crowns. Although local maxima techniques are computationally the fastest and simplest algorithms, these algorithms often fail to detect understory and overlapping trees in structurally complex forests, and have difficulty detecting crown edges, typically oversimplifying crown geometry (Kaartinen et al., 2012).

Watershed-based delineations offer an improvement for crown geometries, and function on inverted CHMs by segmenting neighboring crowns along lines of local minima (Chen et al., 2006). Watershed approaches can be combined with local maxima detection to limit the number of local maxima within a segment to one. Koch et al. (2003) used a modified watershed approach, allowing for merging and refinement of delineations with *a priori* knowledge of forest structure. They found that for conifer trees, approximately 87% of trees were correctly identified using this technique but for deciduous species only 50% were correctly delineated, with errors arising from understory and overlapping crowns. Breidenbach et al. (2010) also found that their watershed approach could not detect understory or overlapping crowns when local maxima were undetected.

Point cloud based techniques are the newest and most computationally demanding of the three delineation approaches. Point cloud-based techniques use the full information content from discrete return LiDAR datasets and therefore offer great promise for future advancement in this field. However, current point cloud-based techniques have focused on small areas within a single study site and may not be applicable across a range of forest types. Rahman and Gorte (2009) use the density of LiDAR returns for crown detection, while Ferraz et al. (2012) use an iterative clustering approach based on a mean shift algorithm to detect trees in 3D space. Ferraz et al. (2012) reported that although 99% of overstory trees were detected by their algorithm, only 12.8% of suppressed trees were detected, suggesting that even detailed site-specific point cloud methods have difficulty detecting understory trees.

Most algorithms for crown delineation have remained focused on conifer dominated, boreal forests, with plot level validation. Kaartinen et al. (2012) conducted an analysis of several delineation algorithms in boreal systems and reported accuracies that range from 40 to 95% for open conifer trees, 5–45% for trees neighboring a larger tree, and less than 20% for intermediate or suppressed canopies. Boreal forests are less structurally complex than temperate or tropical broadleaf forests, and therefore algorithms developed in boreal areas may be less effective in more complex forests. Current crown delineation algorithms inadequately identify understory and overlapping trees, and have rarely been tested across different biomes. There is consequently a need for an understory-sensitive algorithm that can be efficiently applied to LiDAR datasets with a range of point densities in a variety of ecosystems. The goal of this paper is to present the development and testing of a novel crown delineation algorithm that offers both applicability over varying forest types and improvement for understory and overlapping tree detection.

2. Methods

2.1. Study areas

Our delineation algorithm is tested in the eastern and western USA. The first study site is a broadleaf dominated experimental forest in Maryland managed by the Smithsonian Environmental Research Center

(SERC). SERC is located near Edgewater, Maryland, adjacent to a sub-estuary of the Chesapeake Bay. The area is generally comprised of two forest types: mature secondary upland forest and floodplain forests. Dominant species in the upland forest include tulip poplar, several species of oak, beech, and several species of hickory, with mid canopy red maple and sour gum and understory American hornbeam, spicebush and paw-paw. Dominant species in the flood plain area are ash, sycamore, and American elm. Both the upland and the floodplain forests have been relatively undisturbed for approximately 120 years.

The second study site is the Teakettle Experimental Forest in the western Sierra Nevada mountain range, California. Dominant species include California black oak, white fir, ponderosa pine and red fir (Hunsaker, Boroski, & Steger, 2002). The elevation ranges from approximately 1000 m to 2500 m, with aboveground biomass values averaging ~200 Mg/ha with individual trees up to 20.0 Mg. The forest is mature, featuring clusters of trees in flatter areas of the land with thicker soils, and rocky outcrops in steeper areas (Swatantran, Dubayah, Roberts, Hofton, & Blair, 2011).

2.2. Field data

In the SERC study area, field data were taken from the SIGEO field acquisition, in which a 16.0 ha plot was laid out and every tree greater than 1 cm DBH was sampled and stem mapped between 2008 and 2011 (<http://www.sigeo.si.edu/>). Tree location, species, DBH, crown class (dominant, codominant, intermediate or suppressed) and crown condition were recorded. Dead and damaged trees were eliminated from the dataset prior to comparison with delineation results due to a lack of description of the type of damage. For validation, the 16 ha stem map was subset into 16, 90 meter square subplots. The stem map at SERC is based on georegistered based on a series of monumented posts that were located every 200 m on a true N–S geographic grid. The location of these posts had an accuracy of less than 1–2 m. Additional posts were located at 10 by 10 meter spacing within the SIGEO area, and trees were stem mapped using measuring tapes. The additional posts were laid out using a combination of laser rangefinders and compasses, as well as a total station (Parker, G., Pers. Comm.).

In the Teakettle forest area, 90 m square sample plots were collected in the summer of 2008 ($n = 12$). The DBH, species and condition of all trees were recorded. Dead trees were removed from the analysis. Within each central sub-plot the location and height of trees were also recorded. However, given issues with georegistering tree locations to LiDAR data, stem mapped data were not used to pursue an individual-based tree validation for the Sierra Nevada site.

2.3. LiDAR data

LiDAR data for SERC were collected with NASA Goddard's LiDAR, Hyperspectral and Thermal Imager (Cook et al., 2013) instrument. G-LiHT uses a 300 kHz multi-stop scanning LiDAR with a 60° field of view and 10 cm diameter footprint, and the site was flown with 50% overlap in north–south and east–west directions to achieve a mean return density of up to 50 laser pulses/m². Leaf-off and leaf-on data were acquired during March, 2012 and June, 2012, respectively.

LiDAR data for the Sierra Nevada site were flown in the summer of 2008 with the University of Florida's OPTECH GEMINI ALSM unit, operating at 100–125 kHz with a maximum 25° scanning angle. Data were flown ~600–750 m above ground, with 50%–75% swath overlap yielding an average return density of approximately 18 pts/m².

2.4. Algorithm development

Fig. 1 shows the processing framework applied by our algorithm. The only inputs to the algorithm are raw LiDAR point cloud files. These LiDAR point clouds are preprocessed adding a 20 m buffer to LiDAR tiles to ensure that tile edges do not affect the outputs. The

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