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Mapping the height and spatial cover of features beneath the forest canopy at small-scales using airborne scanning discrete return Lidar

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ABSTRACT

The objective of the current study was to develop methods for estimating the height and horizontal coverage of the forest understorey using airborne Lidar data in three managed pine plantation forest typical of the south eastern USA. The current project demonstrates a two-step approach applied automatically across a given study site extent. The first operation divided the study site extent into a regularly spaced grid (25 × 25 m) and identified the potential height range of the main Loblolly pine canopy layer for each grid-cell through aggregating Lidar return height measurements into a 'stack' of vertical height bins describing the frequency of returns by height. Once height bins were created, the resulting vertical distributions were smoothed with a regression curve line function and the main canopy vertical layer was identified through the detection of local maxima and minima. The second operation sub-divided the 25 × 25 m grid-cell into 1 × 1 m horizontal grid, for which height-bin stacks were created for each cell. Vertical features below the main canopy were then identified at this scale in the same manner as in the previous step, and classified as understorey features if they were lower in height than the 25 × 25 m estimate of the main canopy layer. The heights of the tallest understorey and sub-canopy layers were kept, and used to produce a rasterized map of the understorey layer height at the 1 × 1 m scale. Lidar derived estimates of the 25 × 25 m lowest vertical extent of the coniferous canopy correlated highly with field data (R^2 0.87; RMSE 2.1 m). Estimates of understorey horizontal cover ranged from R^2 0.80 to 0.90 (RMSE 6.6–11.7%), and maximum understorey layer height ranged from R^2 0.69 to 0.80 (RMSE 1.6–3.4 m) for the three study sites. The automated method deployed within the current study proved sufficient in determining the presence and absence of vegetation and artificial structures within the understorey portion of the current forest context, in addition to height and horizontal cover to a reasonable accuracy. Issues were encountered within older stands (e.g. more than 30 years old) where understorey deciduous vegetation layers intersected with the coniferous canopy layer, resulting in an underestimation of sub-dominant heights.

1. Introduction

The three-dimensional structure of forest environments plays an important role in ecosystem function. Such roles include influencing the micro-climate, habitat and forage for wildlife, nutrient cycling, fire behavior and light availability (Falkowski et al., 2009; Leagare et al., 2002). These structures can vary from relatively simple single-story canopies to more complex multi-story canopies which may be divided into different horizontal and vertical components and extents.

In recent years, the retrieval of forest structural attributes across a landscape have been advanced considerably following the development of airborne remote sensing technologies, in particular discrete return Light Detection and Ranging (Lidar) (Lim et al., 2003a). Airborne Lidar can characterize both horizontal and vertical structures within forested environments, in the case of small-footprint systems providing high point densities. The use

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of Lidar has rapidly come into prominence in estimating forest biophysical characteristics, such as canopy height, basal area, timber volume, and biomass (Evans et al., 2009), frequently through the use of statistical methods using metrics related to the return vertical distribution and intensity of Lidar returns (Anderson et al., 2008; Lefsky et al., 2002; Lim et al., 2003a,b; Maltamo et al., 2005; Næsset, 2002).

The forest understorey layer comprises plant life growing beneath the forest canopy. The understorey typically consists of trees stunted through lack of light, other small trees with low light requirements, saplings, shrubs, vines and undergrowth. Recent studies employing Lidar data have defined understorey vegetation as all the woody vegetation in this strata, or suppressed trees (e.g. Hill and Broughton, 2009; Maltamo et al, 2005; Riaño et al., 2003).

The understorey layer in particular can influence overstorey species, growth increment and structural characteristics over time. Understorey vegetation cover has been used for wildlife habitat, fire fuel load and behavior characterization, and understanding forest competition dynamics (Chen et al., 2008). The sampling of forest understorey layers through field based inventory can be both costly and laborious, especially over large area and complex terrain. As a result field inventory may be limited in terms of sampling a sufficient variety of land cover types. The estimation and prediction of understorey vegetation cover using models derived from field-derived explanatory variables has proven to be difficult (e.g. Eskelson et al., 2011; Kerns and Ohmann, 2004).

For many commercial forestry applications the understorey is routinely cleared. This is typically determined through field assessment or the application of chemical or mechanical removal treatments, which represents a significant investment in time when employed in large commercial forests. Understorey vegetation influences availability of nutrients within a region, and represents a flow of resources away from the commercially valuable trees, which results in lower productivity (Albaugh et al., 2012). The ability to estimate the presence of competing vegetation beneath the dominant canopy continuously over large spatial extents would therefore be of benefit. One such application could be the identification of understorey locations and tasking field teams to remove vegetation in specific locations.

Given airborne Lidar's ability to penetrate through the forest canopy and return from the lower vegetated elements and ground (e.g. Pesonen et al., 2008), there is the potential to estimate or infer the presence and characteristics of discrete vertical vegetation layers. This process is dependent on suitable relationships being determined between the Lidar returns and the physical characteristics of interest. For example, Hill and Broughton (2009) demonstrated it was possible to estimate understorey vegetation presence in closed deciduous woodland by using two separate Lidar acquisitions collected under leaf-on and leaf-off conditions. Martinuzzi et al. (2009) estimated the presence and absence of deciduous understorey vegetation cover in temperate conifer forest. Wing et al. (2012) predicted understorey vegetation cover (including shrubs and seedlings) for coniferous forest by filtering Lidar returns in a specified vertical range by intensity value and combining this with the number of relative ground returns. The method used in Morsdorf et al. (2010) used Lidar derived height and intensity data to predict vertical layer information in a number of Mediterranean forest environments. Singh et al. (2015) estimated the presence of an invasive understorey species in mixed forest through statistical modelling.

Whilst Lidar derived statistical analysis, such as linear regression, have found relationships between dependent and independent variables for many examples of forest inventory metrics, each model is calibrated and validated against local field data. Typically, these Lidar metrics are derived from the distribution of return heights, or intensity, such as the mean height of all returns, for a discrete or plot-level vertical or horizontal extent. The high dimensionality of potential Lidar derived metrics and often large volumes of the Lidar datasets presents a number of problems to be overcome when considering their use in statistical models. Issues such as the idiosyncrasies of individual lidar acquisitions, site-specific relationships and multicollinearity make the process of variable selection and choice of an appropriate analysis spatial scale critical (e.g. Andersen et al., 2005; Mascaro et al. 2011). These metrics have been used alone or combined in linear or nonlinear models (e.g. Lim et al., 2003a). The Lidar metrics selected for these statistical models reported in many of these studies often lack commonalities, and due to the effects of different Lidar acquisition parameters (Næsset, 2009), temporal separation between the collection of remote sensing and field data collection used for model calibration (e.g. Villikka et al., 2012), and/or calibration for a specific forest type or spatial context (e.g. Sumnall et al., 2016a) can lead to doubt over the transferability of such models to different contexts. In addition, for a specific application there often exists an optimal spatial scale that may not be valid to other applications (Marceau et al., 1994). Studies have also shown, however, that assessments of understorey vegetation with Lidar is less accurate under dense tree canopies due to the lower proportion of Lidar returns reaching the lower forest strata (Maltamo et al., 2005; Bork and Su, 2007).

A number of authors have attempted to derive relationships with field measurements based upon the vertical arraignment of the Lidar returns. Lidar returns can be classified vertically in specific height ranges, also knowns as "bins" or volumetric pixels (voxels). Each voxel element will contain a single value for the Lidar returns located within the set three-dimensional extent, such as the number of returns, or the average intensity value of returns (e.g. Chasmer et al., 2004; Lee et al., 2004; Popescu and Zhao 2008; Wang et al., 2008). A statistical curve function can be fit to the values of each of the voxels in a vertical column (i.e. those which are vertically sequential) to allow vertical features to be inferred as features along this line (e.g. a bell-shaped curve). The height-bin based approaches have commonly been applied to estimate the characteristics of the dominant canopy layers at plot-level scales, however a number have focused on the characterization of features beneath the canopy. The research presented in Wang et al (2008) implemented an initial curve-fitting approach to determine the vertical extents of the dominant and sub-dominant vegetation layers, and a three-dimensional segmentation approach to delineate individual tree objects. The method developed in Lee and Lucas (2007), calculated the likelihood of laser pulses penetrating through the canopy to the ground based upon the relative number of populated voxels vertically. Both canopy and suppressed trees could then be delineated. The work published in Jaskierniak et al. (2011) utilized plot-level voxels and mixture modelling to separate the over- and under-story components of multi-layered Eucalyptus forest.

While the afore mentioned studies suggest a great potential for the use of discrete return Lidar in forest analysis, however, the prediction of understorey components presents a number of challenges, where successful predictions and spatial analysis scale are dependent on the underlying dataset. Voxel-analysis approaches to identifying vertical features does not implicitly rely on a regression relationship and could be transferable to other contexts in a manner regression models may be inappropriate for. Thus, the current approach will evaluate the capacity for the potential features detected within the Lidar point cloud to be related to those features located in the field using general assumptions of forest vertical architecture and its interaction with the distribution of Lidar returns. With a particular focus on providing support information to forest managers on the locations of competing vegetation, the overall goal of the current study was to develop new