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Three-dimensional characterization of pine forest type and red-cockaded woodpecker habitat by small-footprint, discrete-return lidar

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ABSTRACT

Accurate measurement of forest canopy structure is critical for understanding forest-wildlife habitat relationships. Although most theory and application have been based on in situ measurements, imaging technologies such as Light Detection and Ranging (lidar) provide measurements that are both vertically accurate and horizontally extensive. We use small-footprint, multiple-return lidar from a state-wide dataset (1-m footprint, 0.11 point/m^2) to characterize the vertical and horizontal structure of successional loblolly pine (*Pinus taeda*) and mature, fire-maintained longleaf pine (*Pinus palustris*) forests on the coastal plain of North Carolina, USA. The relationship between these characteristics and the federally-endangered red-cockaded woodpecker's (*Picoides borealis*, Vieillot) habitat preferences were assessed; as this species has a strong affinity for mature longleaf pine forests. Vertical structure was characterized by lidar-derived metrics (e.g., average and standard deviation of canopy height) and horizontal patterns of vertical structure were quantified by semivariograms and lacunarity analysis. Lidar metrics were compared with field measurements of stand structure and with woodpecker habitat use. We predicted woodpecker distribution using the Maxent species distribution modeling algorithm with elevation, landcover, and hydrography geospatial variables, with and without lidar-derived structural variables. Lidar successfully quantified canopy variation and differentiated between the structural characteristics of these two similar coniferous evergreen forest types (e.g. significant differences in maximum height, canopy cover, and size classes). Loblolly stands were found to have the tallest trees on average with a higher canopy cover. Both semivariograms and lacunarity analyses clearly differentiated between evergreen forest structural types (e.g. semivariogram range was 18.7 m for longleaf, 32.3 m for loblolly). By examining the immediate area around cavity nesting sites we found taller trees than those found across broader foraging sites. The species distribution model accurately predicted woodpecker distribution (tested with woodpecker presence, AUC > .85). The addition of lidar-derived variables improved the model's predictive power by 8% compared to the model based only on elevation, landcover, and hydrography environmental variables. We show that relatively low density lidar data are valuable for wildlife studies by characterizing and separating similar canopy types, describing different use zones (foraging vs. nesting), and for use in species distribution models.

1. Introduction

Vegetation canopies are complex, three-dimensional volumes. The vertical and horizontal structure of vegetation characterizes physiognomic types and biomes (e.g., savanna, shrubland, forest) and varies with plant community composition (e.g., Welden et al., 1991; Kruger et al., 1997). Vertical and horizontal canopy structure also impact the distribution of wildlife (Matlack, 1994; Didham and Lawton, 1999). Because of their great mobility in both horizontal and vertical dimensions, birds are especially affected by structural attributes in their selection and use of habitat (MacArthur and MacArthur, 1961; Erdelen, 1984; Desrochers and Hannon, 1997; others).

Vertical canopy structure also directly influences the scattering of radiation and therefore provides a potential means of relating vegetation structure to wildlife habitat (Vierling et al., 2008). Passive, optical remotely sensed imagery (e.g., Landsat Thematic Mapper) has been essential in the development of vegetation maps, habitat models, and site prioritization efforts, but these data provide limited information on vertical structure and typically have horizontal resolutions considerably coarser than the dimensions of individual trees or stands of trees (Woodcock and Strahler, 1987; Waring et al., 1995; Treuhaft et al., 1996; Lefsky et al.,

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2002; Vierling et al., 2008). Alternatively, fine-scale measurements of forest structure from active sensors such as radar and lidar can benefit forest inventories and characterizations of habitat for wildlife species influenced by forest structure (Chiao, 1996; Imhoff et al., 1997; Hyyppa et al., 2000; Lim et al., 2003).

Lidar (Light Detection and Ranging) provides fine-grain information about three-dimensional forest canopy structure and is horizontally extensive (Maclean and Krabill, 1986; Treuhaft et al., 1996; Lefsky et al., 2002; Maltamo et al., 2005; Ørka et al., 2009). It has been used for quantifying many aspects of forest structure because of its accuracy and scalability. In some cases, lidar measurements can be even more accurate than interferometric synthetic aperture radar measurements with respect to in situ tree measurements and also more accurate than field measurements of heights themselves (Sexton et al., 2009). Using discrete-return, small-footprint lidar data and field measurements, Hall et al. (2005) estimated stand height, total above ground biomass, foliage biomass, basal area, and other variables for a fire-prone ponderosa pine (*Pinus ponderosa*, Dougl.) forests. Discrete-return lidar measurements have been successfully compared to field measures of evergreen conifer forest height with RMSE (root mean square error) of <1 m (Sherrill et al., 2008). In conifer forests, field-measured stand attributes such as mean stand height, tree density, and basal area were significantly correlated with lidar estimates (Hudak et al., 2006).

Lidar studies have been used to characterize habitat for canopy-dwelling avian species (e.g. Hinsley et al. 2002; Hyde et al. 2005, 2006; Broughton et al., 2006; Clawges et al., 2008; see review by Vierling et al., 2008; Marinuzzi et al., 2009; Müller et al., 2010). However, most of these studies were based upon more specialized lidar datasets with either full waveform ability or very high point/posting density. Airborne lidar data was used to examine differences in the structural components between habitat and non-habitat for the marsh tit (*Poecile palustris*), finding a statistically significant difference of 1.6 m in canopy height between occupied and unoccupied areas (Broughton et al., 2006). Optical and lidar measurements were compared to quantify structural heterogeneity for predicting bird species richness in the Patuxent National Wildlife Refuge, Maryland. Canopy vertical distribution measured by lidar was consistently found to be the strongest predictor of species richness (Goetz et al., 2007). An ensemble decision tree modeling approach (random forests) was used to assess lidar-derived metrics as predictors of habitat use for the Neotropical migrant songbird, the Blackthroated Blue Warbler (*Dendroica caenulescens*). Results showed that canopy structure variables consistently provided unique and complimentary information that systematically improved model predictions (Goetz et al., 2010).

Counties, states and national governments are increasingly using lidar to produce precise bare-earth digital elevation models (DEMs) over large regions (Stoker et al., 2008), and there is considerable interest in a complete US national lidar data set (Ibid.). Currently, these data are collected at a lower spatial density, and have been relatively less explored for forest structure characterizations. Future systems for acquisitions may have the capacity to collect at higher densities, providing increased accuracies but more challenges in terms of analyzing such large datasets. Until this occurs, it's important to explore the utility of the current low density datasets for forest characterization. With lidar measurements at a density of less than 1 point/m^2, biomass and forest structure were successfully analyzed in Wisconsin, USA (Hawbaker et al., 2009). Lidar-derived measurements were used at a density of 0.11 point/m^2 from the statewide NC Floodplain Mapping Program (NCFMP, 2008) lidar dataset for an analysis of tree height accuracies in the Piedmont region of North Carolina (Sexton et al., 2009). As the first published analysis with this dataset, Sexton et al. (2009), found this low density lidar dataset to be a good representation of loblolly pine (*Pinus taeda*) canopy height.

The accuracy, precision, and scalability of lidar are particularly applicable to management of the endangered red-cockaded woodpecker (*Picoides borealis*, Epting et al., 1995; Rudolph et al., 2002), which occurs across the southeastern USA and is dependent on the structure of rare old-growth longleaf pine forests (Ligon et al., 1986; Walters, 1991; US Fish and Wildlife Service, 2003). The longleaf pine communities upon which red-cockaded woodpeckers depend have a savanna canopy structure that is unique among southeastern forests. Frequent fires in mature longleaf stands maintain open, low-density stands of relatively large trees compared to surrounding stands of loblolly pine. The open, mature longleaf pine woodlands provide old flat-topped pines that are required for roosting and nesting. The open park-like characteristic of this habitat aids in prevention of nest predation on the red-cockaded woodpecker, promotes uninhibited flight paths, and provides them with high quality foraging areas (Christensen, 1981; US Fish and Wildlife Service, 2003).

Populations of red-cockaded woodpeckers have declined drastically due to widespread conversion of old growth longleaf forests to naturally-regenerated loblolly pine or short-rotation loblolly pine plantations (Jackson, 1971; Lennartz et al., 1983; Ligon et al., 1986). Decreased fire frequency has also resulted in midstory encroachment by shade-tolerant trees in many places (Beckett, 1971; Hooper, 1988; Connor and Rudolph, 1989). Studies have suggested that hardwood midstory encroachment leads to site abandonment by red-cockaded woodpeckers due to increases in nest predation, negative effects on flight paths to active cavities, and decreases in foraging habitat quality (Beckett, 1971; Jackson, 1971; Costa and Escano, 1989; Wood, 1983; Kelly et al., 1994; Connor and Rudolph, 1991). Woodpecker conservation efforts involve maintaining and restoring the longleaf ecosystem as well as identifying new candidate sites for woodpecker release (US Fish and Wildlife Service, 2003).

Using the North Carolina Floodplain Mapping Program lidar dataset, our goals in this study were to evaluate the ability of low density multiple-return, small-footprint lidar at 0.11 point/m^2 to characterize structural attributes in both vertical and horizontal dimensions for red-cockaded woodpecker habitat quality. Specifically, we: (1) assess the utility of lidar for detecting differences between pine forest types by differences in their canopy structures and (2) examine the ability of lidar-based canopy structure metrics to map the distribution of red-cockaded woodpecker nesting and foraging habitat.

2. Methods

2.1. Study area

The primary area of focus for this study was the 38,445-ha US Marine Corps Base at Camp Lejeune (MCBCL) located in Jacksonville, North Carolina (Fig. 1). Camp Lejeune lies within the White Oak River Basin in Onslow County and encompasses habitat for several federally listed endangered, threatened, and rare species, including the red-cockaded woodpecker (US Marine Corps Base Camp Lejeune, 2006). Forest management is an important component of the Marine Corps' land stewardship responsibilities at Camp Lejeune, and restoration of historic native communities of longleaf pine and breeding colonies of red-cockaded woodpecker is especially important (US Marine Corps Base Camp Lejeune, 2006). Restoration and maintenance of longleaf communities typically involves thinning midstory trees and frequent prescribed fires (Brockway et al., 2005). Camp Lejeune also seeks to promote conservation and compatible land use in the larger region outside