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Quantifying understory vegetation density using small-footprint airborne lidar

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ABSTRACT

The ability to quantify understory vegetation structure in forested environments on a broad scale has the potential to greatly improve our understanding of wildlife habitats, nutrient cycling, wildland fire behavior, and wildland firefighter safety. Lidar data can be used to model understory vegetation density, but the accuracy of these models is impacted by factors such as the specific lidar metrics used as independent variables, overstory conditions such as density and height, and lidar pulse density. Few previous studies have examined how these factors affect estimation of understory density. In this study we compare two widely-used lidar-derived metrics, overall relative point density (ORD) and normalized relative point density (NRD) in an understory vertical stratum, for their respective abilities to accurately model understory vegetation density. We also use a bootstrapping analysis to examine how lidar pulse density, overstory vegetation density, and canopy height can affect the ability to characterize understory conditions. In doing so, we present a novel application of an automated field photo-based understory cover estimation technique as reference data for comparison to lidar. Our results highlight that NRD is a far superior metric for characterizing understory density than ORD ($R^2_{NRD} = 0.44$ vs. $R^2_{ORD} = 0.14$). In addition, we found that pulse density had the strongest positive effect on predictive power, suggesting that as pulse density increases, the ability to accurately characterize understory density using lidar increases. Overstory density and canopy height had nearly identical negative effects on predictive power, suggesting that shorter, sparser canopies improve lidar's ability to analyze the understory. Our study highlights important considerations and limitations for future studies attempting to use lidar to quantify understory vegetation structure.

1. Introduction

Understory vegetation plays a large number of critical roles in forest ecosystems. It is often the most species rich and diverse portion of a forest (Eskelson et al., 2011). Low-lying vegetation cover provides prey species with visual cover to aid in avoiding predation (Lone et al., 2014). For forest-dwelling mammals, much of the nutritious and palatable forage is found in the understory (Nijland et al., 2014). The quantity and size of tree regeneration has important implications not only for forest health, but also economic importance for timber production (Korpela et al., 2012). Understory biomass contributes to carbon sequestration and soil nutrient cycling (Estornell et al., 2011; Suchar and Crookston, 2010). Understory plants also play an important role in maintaining soil structure and reducing erosion (Suchar and Crookston, 2010). Surface fuel loading and bulk density are some of the most important predictors of wildland fire intensity and rate of spread (Keane, 2014). The presence of ladder fuels in the understory of a forested environment can facilitate the transition from a surface fire to a crown fire, which can have dramatic impacts on post-fire ecosystems (Kramer et al., 2016; Stephens, 1998). Understory vegetation density has also been linked to firefighter safety, given that more dense understories can reduce the ability to efficiently traverse wildland environments (Campbell et al., 2017a) and impacts safety zone suitability (Campbell et al., 2017b). For these reasons and many others, it is essential to be able to quantify the abundance and spatial distribution of understory vegetation in forested environments.

As with many biophysical variables, there are two primary approaches for characterizing forest understory vegetation structure: (1) in the field; and (2) through the use of remote sensing technology. Performed in isolation, each approach has its strengths and weaknesses.

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Field-based forest biometry benefits from the accuracy and precision of ground-based, physical mensuration of a targeted set of variables, and being able to control for extraneous, confounding factors. However, field work is both labor-intensive and time-consuming, particularly when considering the limited spatial extent of the data that result from a plot- or transect-based field campaign. The strengths and weaknesses of remote sensing are very much the inverse of those inherent to field work: remote sensing-based analyses of forest structure benefit from broad, "wall-to-wall" spatial coverage, rather than a plot-based sampling of the landscape. However, data collected from a remote perspective does not measure forest biometrics directly; instead, remote sensing data typically characterize objective measures of the interaction of electromagnetic energy with objects on the earth's surface. Indeed, the very nature of a forest understory – existing underneath a forest canopy – complicates the analysis thereof from a remote perspective, where the ability to "see through" the canopy can be severely limited. Accordingly, in order to accurately map understory conditions in complex forested environments, it is necessary to link the objective measures of light interaction provided by remote sensing to field-based measures of specific biometrics, such as vegetation density.

There are many ways to characterize understory vegetation in the field (Higgins et al., 2005). One of the most common methods for doing so is through the use of cover boards, which rely on visually estimating of the relative proportion of a board of known dimensions that is being obscured by vegetation from a given vantage point (Jones, 1968; Nudds, 1977). Cover boards have received widespread use for estimating vegetation density for decades, particularly in the field of wildlife biology, benefitting from their conceptual simplicity and efficiency of field implementation (Duebbert and Lokemoen, 1976; Griffith and Youtie, 1988; Jones, 1968; Musil et al., 1994; Sage et al., 2004; Winnard et al., 2013). Although cover boards have been rarely used as such, they have much potential for use in conjunction with remote sensing technologies such as airborne light detection and ranging (lidar) (Kramer et al., 2016). A widely-acknowledged limitation of cover board analysis, however, is that the subjectivity inherent to the visual estimation of cover board cover is prone to error (Collins and Becker, 2001; Limb et al., 2007; Morrison, 2016). This has motivated the more recent implementation of digital image processing into the semi-automated analysis of cover board photos (Jorgensen et al., 2013).

In recent decades, lidar has emerged as a leading technology in the mapping of three-dimensional vegetation structure. Lidar is particularly useful in characterizing understory structure, as narrow beams of laser light emitted in rapid succession from an airborne sensor can exploit small gaps in a forested canopy. The pulses interact with features in the understory (tree leaves, branches, and boles, shrubs, grasses and forbs) and reflect back to the sensor; the timed pulse returns can provide detailed information on understory structure. Particularly in the past 15 years, as lidar technology and associated data processing capacities have improved, the number of studies involving the use of lidar to characterize understory conditions has grown rapidly (Alexander et al., 2013; Campbell et al., 2017a; Chasmer et al., 2006; Clark et al., 2004; Estornell et al., 2011; Hamraz et al., 2017; Korpela et al., 2012; Kramer et al., 2016; Kükenbrink et al., 2017; Maltamo et al., 2005; Martinuzzi et al., 2009; Morsdorf et al., 2010; Mutlu et al., 2008; Nijland et al., 2014; Riaño et al., 2003; Singh et al., 2015; Su and Bork, 2007). However, like any remote sensing dataset, lidar does not make direct measurements of forest understory structure. Particularly under dense forest canopies, where pulse energy can occlude prior to reaching the understory, it is essential to select appropriate ground reference information capable of linking ground conditions to remotely sensed data. Given their widespread use as an efficient and reliable method for characterizing vegetation density, cover boards could conceivably form an ideal link between ground-based and remotely-sensed measurements. Thus, developing a robust workflow for combining digital cover board analysis to airborne lidar analysis could greatly benefit the many disciplines in which understanding and mapping conditions in the forest understory are critical.

In addition, the selection of relevant lidar-derived metrics for statistical comparison is of critical importance. Many such metrics have been used throughout the literature, but two height stratum-based metrics have dominated in characterizing the understory: overall relative point density (ORD) and normalized relative point density (NRD). A roughly equal number of studies have employed the use of ORD (Hudak et al., 2008; Jakubowksi et al., 2013; Maltamo et al., 2005; Martinuzzi et al., 2009; Mutlu et al., 2008; Riaño et al., 2003; Singh et al., 2015) and NRD (Campbell et al., 2017a; Goodwin et al., 2007; Kramer et al., 2016; Lone et al., 2014; Seielstad and Queen, 2003; Skowronski et al., 2007; Su and Bork, 2007), but none has compared the two for their respective predictive capabilities. Lastly, there are many factors that can affect the accuracy of the resulting understory structural models that must be carefully considered when attempting to characterize the understory, including lidar pulse density, overstory vegetation density, and canopy height. Although these factors are often assumed to affect lidar's ability to model understory conditions, their specific, quantitative effects have only been studied sparingly.

The objectives of this study are to: (1) develop a method for automated cover board photo analysis for use as reference data in lidar understory density estimation; (2) compare two widely-used lidar vertical stratum metrics (ORD and NRD) for their respective abilities to accurately characterize understory vegetation density; and (3) determine the relative effects of lidar pulse density, overstory vegetation density, and canopy height on the ability to accurately characterize understory vegetation density.

2. Background

2.1. Characterizing understory structure using cover boards

There are a number of ways to characterize forest understory structure in the field. Higgins et al. (2005) present a comprehensive review of these methods. Some of the most oft-employed field methods for estimating understory cover are visual obstruction methods. Though the specific methods vary slightly, the assessment is generally based on the determination of the degree to which a distant reference object of known dimensions is being covered by vegetation from a given vantage point. The underlying assumption is that denser vegetation will result in a greater proportion of the object being covered. The two most common reference objects are cover poles (Robel et al., 1970) and cover boards (Jones, 1968; Nudds, 1977), the former enabling obstruction estimation in one dimension, the latter in two. Cover poles are simpler to analyze, given the ease with which one can quantify the proportion of vegetation cover in a single dimension, but cover boards, with their larger sample area, provide more detailed information to the analysis. Cover boards have been used extensively, particularly in wildlife habitat studies (Duebbert and Lokemoen, 1976; Griffith and Youtie, 1988; Jones, 1968; Musil et al., 1994; Sage et al., 2004; Winnard et al., 2013).

The main problem with cover board analyses is the subjectivity of field- or photo-based cover interpretation. Studies have repeatedly demonstrated significant variability in individual analysts' cover estimates Collins and Becker, 2001; Limb et al., 2007; Morrison, 2016. A number of authors have attempted to overcome the issue of interpreter subjectivity by capturing a digital photo of the cover board and subsequently classifying between board and non-board pixels in some semi-automated fashion (Boyd and Svejcar, 2005; Carlyle et al., 2010; Jorgensen et al., 2013; Limb et al., 2007; Marsden et al., 2002; Winnard et al., 2013). Limb et al. (2007) compared this procedure to visual interpretation of a cover board and cover pole, finding that the classification approach greatly reduced the variability in cover estimates and attained the highest degree of correlation with field-sampled biomass. However, many of these studies rely on manually thresholding the pixel value brightness to distinguish between board and vegetation, which can be even more error-prone than visual interpretation (Booth et al.,