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Vertical forest structure analysis for wildfire prevention: Comparing airborne laser scanning data and stereoscopic hemispherical images

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ABSTRACT

Vertical fuel structure is critical for fire hazard assessment in forest ecosystems. Forest stands with ladder fuels are more prone to crown fires because of canopy fuel continuity. However, characterization of ladder fuels is difficult in the field and few studies have developed explicit measurement procedures to account for these hazardous fuel situations. This study compares vertical profiles derived from airborne laser scanning (ALS) data and stereoscopic hemispherical images obtained in *Pinus sylvestris* stands in central Spain to test their ability to detect the presence or absence of vertical fuel continuity (VFC). Vertical fuel profiles based on canopy cover fraction estimations at different height strata were assessed at plot level and compared with field observations. The quadratic form distance (QFD) was the metric used to quantify the similarity between histogram distributions defined by the vertical profiles from different datasets. Logistic regression analysis was tested to discriminate areas with and without VFC from ALS data at two threshold levels (15% and 30%). The vertical fuel profiles of canopy cover showed a different level of correspondence depending on the relative amount of ladder fuels. Significant logistic models were found ($p < 0.0001$, c-index > 090) for different combination of ALS metrics, with low percentiles (up to P30), canopy relief ratio (CRR) and the percentage of returns normalized by height strata (PRN) up to 8 m as the best predictors to identify the presence of VFC. Results indicated that both datasets were useful in retrieving variability of forest fuel distribution, but further methodological improvements (e.g. understory segmentation in stereoscopic images, new algorithms to better account for occlusions, or ground calibration for laser attenuation in ALS) are needed to increase accuracy in highly continuous areas.

1. Introduction

Wildfire is a complex phenomenon with a global impact on ecosystems (Bowman et al., 2009). Fire behavior is highly conditioned by vegetation characteristics, and particularly by the amount and spatial distribution of fuels. The presence of ladder fuels, i.e. regeneration trees and understory vegetation between ground fuels and the upper tree canopy, creates forest stand structures with vertical fuel continuity that facilitates fire propagation into the crowns (Agee and Skinner, 2005; Scott and Reinhardt, 2001). Strategic fuel treatment planning at landscape level is commonly based on simulations of potential fire behavior that need spatial information on fuel load and arrangement in both understory and overstory vegetation (Finney, 2001; Finney et al., 2007; Stephens et al., 2009). More detailed 3D information of fuel complex structure is required in advanced wildfire modelling in order to better account for the effect of spatial heterogeneity on fire behavior predictions (Parsons et al., 2011).

Identifying the presence of vertical fuel continuity in forest areas is key for fuel treatment planning to prevent crown fires, but it is also very difficult to measure in the field (Kramer et al., 2014). Canopy or crown base height (CBH) is generally used as a surrogate to account for ladder fuels (Scott and Reinhardt, 2001). However, CBH estimation does not provide information on the complete distribution of the vertical fuel profile as model predictions generally refer to a specific tree species (Fernández-Alonso et al., 2013) and, hence, do not include understory fuels. Cruz et al. (2004) proposed the concept of fuel strata gap (FSG), the distance between tree canopy and the lower fuel strata, to better account for the potential transition from a surface to a crown fire due to the quantification of fuel discontinuity in the vertical profile. Forest dynamics impact fuel distributions in the middle to long term, but forest structure does not develop in a linear fashion. Moreover, unplanned perturbation events (e.g. wildfires, strong winds, droughts,

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pests or diseases) can dramatically affect fuel arrangement and fire risk across forested landscapes (Seidl et al., 2011; Simard et al., 2011). Thus, measuring forest structural conditions rather than relying on development models is important to estimate stand structure complexity (Kane et al., 2010).

A variety of technologies can be used to spatially describe forest biomass distribution. Active sensors such as airborne laser scanning (ALS), based on distance measurement from laser returns, as well as passive sensors acquiring the radiation level, have been increasingly employed in forest monitoring in the last decades. ALS data has been proved very useful to characterize 3D forest structure (Andersen et al., 2005; Kane et al., 2010; Lefsky et al., 2005; Morsdorf et al., 2006; Wang et al., 2016; García et al., 2018). However, the interception by the upper canopy strata may prevent accurate understory strata assessment with ALS (Hamraz et al., 2017; Kukenbrink et al., 2017; Wang et al., 2016). Optical methods, such as hemispherical photography, have been widely used for Leaf Area Index (LAI) estimation from below-canopy photographs using the inverse gap fraction model (Weiss et al., 2004), but a single photograph does not allow spatial structure assessment. Field data on tree height added to the hemispherical images allow canopy spatial pattern characterization (Montes et al., 2008). Terrestrial laser scanner (TLS) is another promising tool for field assessment of forest structure and complexity (Liang et al., 2016; Martin-Ducup et al., 2016; Seidel et al., 2016; Skowronski et al., 2011). Some studies compare conventional optical methods, such as hemispherical photography, with TLS data (Seidel et al., 2012), showing the potential of TLS for vertical canopy profile assessment. Recently, stereoscopic hemispherical images have been used for tree diameter, basal area and density retrieval in forest stands (Sánchez González et al. 2016). In the present study, the use of stereoscopic hemispherical images is explored as a costly-efficient way to obtain 3D reconstruction of crown elements through stereo-matching.

Different metrics have been proposed to characterize forest structural heterogeneity. Vertical structure indices are widely used to measure stand complexity in forests (Barbeito et al., 2009; Parker and Russ, 2004). Ehbrecht et al. (2016) proposed the calculation of the effective number of layers *(*ENL) to quantify vertical structure at subplot level derived from TLS information. Several techniques have been also proposed for the segmentation of understory and overstory layers (Ferraz et al., 2012; Hamraz et al., 2017; Hill and Broughton, 2009; Morsdorf et al., 2010; Riaño et al., 2004) or the identification of forest structural complexity (Kane et al., 2010) from ALS data.

Regarding forest fuel characterization, previous authors have shown methods to predict crown fuel parameters from ALS (Andersen et al., 2005; Gonzalez-Ferreiro et al., 2014; Maguya et al., 2015; Riaño et al., 2003, 2004;) or TLS data (García et al., 2011; Pimont et al., 2015). However, few studies have addressed the use of these technologies to characterize the presence of vertical fuel continuity. García et al. (2011) estimated FSG from the vertical profile provided by TLS. Kramer et al. (2014) used ALS data to differentiate between high and low levels of ladder fuels after forest fuel treatments. The canopy release ratio (CRR) suggested by Parker and Russ (2004) has been also used to differentiate the presence or absence of vertical fuel continuity for ALS-derived fuel model mapping (Marino et al., 2016).

The objective of the present study was the development of methods for the identification of ladder fuels, i.e. the absence or presence of vertical fuel continuity, in forest stands from remote sensing technologies based on both active and passive sensors. For this purpose, we compared the performance of airborne laser scanning data and stereoscopic hemispherical images with field inventory focusing on canopy fuels (understory and overstory trees).

2. Material and methods

2.1. Study area

The study area is located at Valsaín in Segovia (central Spain) covering 7448 ha of Sierra de Guadarrama National Park (40° 51′ N, 04° 01′ W). The area is a mountain forest dominated by Scots pine (*Pinus sylvestris*). The forest has been managed for production of high quality wood during more than a century, resulting in a variety of forest structures from tall mature stands to dense young stands due to the excellent regeneration of the species. Topography is characterized by a wide range of altitude (1260–1995 m) and very rugged terrain, with 59% of the area having steep slopes over 30%. Understory vegetation includes other tree species, mainly *Quercus pyrenaica* Willd. in the lower elevations and *Ilex aquifolium* L. Ferns (*Pteridium aquilinum* (L.) Kuhn) are commonly found, whereas shrubs such as *Juniperus communis subsp. alpine* (Suter) Čelak*, Cytisus oromediterraneus* Rivas Mart. & al. and *Adenocarpus hispanicus* (Lam.) DC. are only abundant at high elevations. Mean annual precipitation increases with elevation, ranging from 720 mm to 1320 mm, with snow often present in winter. Average minimum and maximum temperature are -1 ^{0}C in January and 22 ^{0}C in July.

2.2. Datasets

Three types of data were used in this study: field inventory, stereoscopic hemispherical images (ForeStereo system), and ALS data.

2.2.1. Field inventory

A set of 30 circular plots (radius = 14.1 m) were established in 2016 from an existing net of systematic sampling plots for forest inventory previously performed within the study area in 2010 (Fig. 1). Plot locations were selected to cover structural variability according to prior forest inventory and ALS data. Location of each plot was recorded using a Trimble Geo 7x unit, a hand-held GNSS GPS receiver providing submeter accuracy after post-processing. Post-processing consisted of differential corrections of the raw receiver files using the Base Station Network at the Spanish National Geographic Institute (IGN). Areas with disturbance or management activities during the time lag between field inventory and ALS data acquisition were excluded when choosing plot locations.

Field measurement protocols in 2016 were similar to the methods used for the previous 2010 inventory, but including additional structure variables related to forest fuels distribution (e.g. crown dimensions). Tree measurements included the diameter at breast height (DBH) of all trees thicker than 7.5 cm. Tree height, crown base height, crown diameter, and position relative to plot center (azimuth and distance) were registered for 10 randomly selected trees per plot. Crown base height was computed as the distance of the first living branch relative to the ground. Crown diameter was the average of two perpendicular values for each tree to avoid errors due to asymmetric crowns. Understory vegetation, including regeneration and shrubs, were measured in line transects following the line intercept method, recording vegetation cover and height for each plot.

Following an approach based on Menning and Stephens (2007) and Kramer et al. (2014), the percentage of plot surface with ladder fuels presence (vertical fuel continuity, VFC) was estimated and used to classify plots in three levels: class 0, no ladder fuels (VFC = 0%); class 1, low ladder fuels (VFC < 30%); and class 2, high ladder fuels (VFC > 30%). The percentage referred to the proportion of plot surface with presence of VFC in the whole vertical profile of vegetation, i.e.

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