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3-D mapping of a multi-layered Mediterranean forest using ALS data

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ABSTRACT

This study presents a robust approach for characterization of multi-layered forests using airborne laser scanning (ALS) data. Fuel mapping or biomass estimation requires knowing the diversity and boundaries of the forest patches, as well as their spatial pattern. This includes the thickness of the main vegetation layers, but also the spatial arrangement and size of the individual plants that compose each stratum. In order to decompose the ALS point cloud into genuine 3-D segments corresponding to individual vegetation features, such as shrubs or tree crowns, we apply a statistical approach based on the mean shift algorithm. The segments are progressively assigned to a forest layer: ground vegetation, understory or overstory. Our method relies on a single biophysically meaningful parameter, the kernel bandwidth, which is related to the local forest structure. It is validated on 44 plots of a Portuguese forest, composed mainly of eucalyptus (*Eucalyptus globulus* Labill.) and maritime pine (*Pinus pinaster* Ait.) trees. The number of detected trees varies with the dominance position: from 98.6% for the dominant trees to 12.8% for the suppressed trees. Linear regression models explain up to 70% of the variability associated with ground vegetation and understory height.

1. Introduction

Forests, woodlands, and shrub formations are very important ecosystems because they provide foundations for life on Earth through their ecological functions: regulation of climate and water, habitat for animals, and supply of food and goods. They exhibit various canopy structures, from homogeneous to heterogeneous, and from single- to multi-layered (Landsberg & Gower, 1997). Today we know the horizontal structure that describes the patchiness in forest stands better than the vertical structure, which is difficult to quantify and yet is an important characteristic (Hall et al., 2011). The canopy layers (overstory, understory, and ground vegetation) are distinct from each other in their density, thickness, and water content. A better appraisal of this vertical arrangement, at high spatial resolution, would be valuable for many applications in forestry (Ares et al., 2010), carbon cycle studies (Moore et al., 2007), and ecology (Brokaw & Lent, 2000; Camprodon & Brotons, 2006). As an example, foresters use fuel models for predicting fire behavior (Pyne et al., 1996), and fire behavior models, such as FARSITE (Finney, 2004) or BehavePlus (Andrews et al., 2005), require information about vegetation strata thickness to detect areas where fire easily propagates and spreads (Anderson, 1982; Sandberg et al., 2001).

Airborne laser scanning (ALS) is an active remote sensing technique that provides georeferenced distance measurements between a remote sensing platform and the surface (Mallet & Bretar, 2009; Shan & Toth, 2009). In recent years, it has been applied over natural landscapes to extract terrain elevation (Bretar & Chehata, 2010; Kraus & Pfeifer, 1998), classify land cover (Antonarakis et al., 2008; Asner et al., 2008; Breidenbach et al., 2010; Hyyppä et al., 2008; Yoon et al., 2008), evaluate wildlife habitat (Clawges et al., 2008; Martinuzzi et al., 2009), estimate biomass (Asner et al., 2010; García et al., 2010; Zhao et al., 2009), and assess fuel characteristics (Andersen et al., 2005; Hollaus et al., 2006; Mutlu et al., 2008; Riaño et al., 2003). Depending on the nature of the target, a single pulse emission may induce one or

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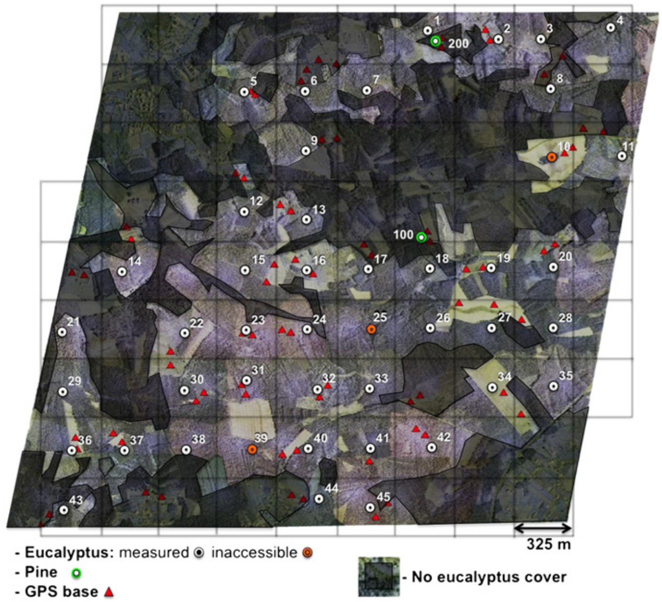

Fig. 1. Regular grid superimposed on the land cover map of the study area.

several backscattered echoes. As the laser beam penetrates down into the forest canopy layers, an unstructured 3-D point cloud that is a discrete model of the target is obtained. There are two main spatial scales for tackling the extraction of forest parameters from ALS data: at the plot scale, the biophysical variables are averaged over an area encompassing several trees (e.g. mean canopy height, biomass, stem density, leaf area index), while at the individual scale, they are estimated for a single tree (e.g. tree height, crown diameter, crown base height).

Vertical stratification has been assessed at the plot scale (Maltamo et al., 2005; Riaño et al., 2003, 2004; Zimble et al., 2003). Morsdorf et al. (2010) use the ALS intensity to discriminate different vegetation strata. They apply a supervised cluster analysis, assuming that some species have a better light reflection ratio than others. This method works fairly well in forest ecosystems made of mono-species strata. The intensity is somewhat difficult to analyze because it depends on the sensor as well as on the geometry, orientation, and optical properties of the target (leaves, branches, trunks). Some authors delineate vegetation strata by fitting continuous probability distributions, like the Weibull distribution or mixture models, to the ALS density profiles (Coops et al., 2007; Dean et al., 2009; Jaskierniak et al., 2010; Maltamo et al., 2004). However, plot-based methods are not the most appropriate means to describe the vertical stratification of complex ecosystems, such as Mediterranean forests that are characterized by an open dominant canopy and a lush undergrowth made of herbaceous and woody plants (Di Castri, 1981). These are often highly fragmented forests, the stratification of which varies locally due to small ownerships administered according to different management rules (EEA, 2008).

So far, single-tree based methods rely on a canopy height model (CHM), which is an oversimplified representation of reality in vertically heterogeneous canopies (Hyyppä et al., 2004; Morsdorf et al., 2004; Persson et al., 2004; Popescu & Wynne, 2004; Solberg et al., 2006). In order to investigate the spatial pattern of dominated trees, some authors developed multi-stage approaches. For instance, Richardson and Moskal (2011) first delineate groups of trees in the CHM and then calculate the number of trees by fitting a statistical relationship to the corresponding point cloud distribution. Reitberger et al. (2009) identify the taller trees within each group, determine the stem position, and apply a normalization-cut segmentation method to extract the smaller ones. Despite good performance, these approaches are site-dependent because they require several empirical parameters. Moreover, they do not properly address the issue of vertical stratification in multi-layered forests because, even if they delineate the topmost tree crowns, many ALS points corresponding to ground or understory vegetation remain unassigned.

Therefore, it seems that an approach that simultaneously segments vertical and horizontal structures of forest canopies is lacking. This paper validates a segmentation method based on the mean shift algorithm. This method has been tested on a 3-D point cloud acquired with a small-footprint ALS in a multi-layered Mediterranean forest. We first present the experimental data and the algorithm. The segmentation of the forest into different strata and the derivation of the geometry of individual vegetation features are then detailed.

Table 1
Biophysical characteristics of stand #30.

Height class (m)	Species	% Dominance	Mean height (m)	% Cover
0–2	Ferns	95	1.2	50
	Ulex	5		
2–8	*Acacia*	70	6.0	8
	Pinus	30		
>8	*Eucalyptus*	100	21.2	20

Table 2
Field inventory of ground vegetation and understory, all stands.

	Mean height (m)		% Cover	
	Ground vegetation	Understory	Ground vegetation	Understory
Minimum	0.15	0	2	0
Maximum	1.3	6	100	95
Mean	0.53	2.41	52.1	15.6
Standard deviation	0.3	1.64	33	20.2

2. Experiment

2.1. Study area

The study area is located near the city of Águeda in northwest Portugal (40°36′ N, 8°25′ W). It covers 9 km^2 and its altitude varies

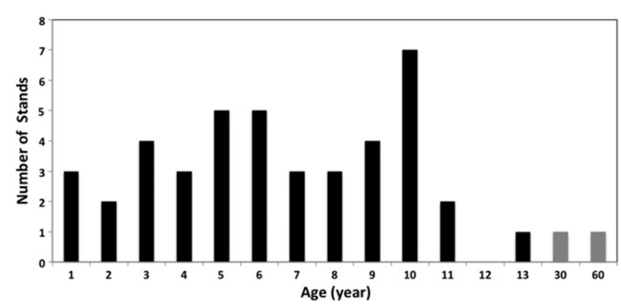

Fig. 2. Age class of the stands. The black bars correspond to the eucalyptus and the gray bars to the pines.

Table 3
Field inventory statistics for trees in mature eucalyptus and pine stands.

		DBH (cm)	CBH (m)	Total height (m)	Crown depth (m)	Atypical shape (%)
Eucalyptus	Minimum	1.5	2.5	3.7	0.4	17.2
	Maximum	70.0	22.5	35.4	14.2	
	Mean	9.7	9.4	13.3	3.9	
	Standard deviation	5.3	3.9	5.2	2.4	
Pine	Minimum	4.9	7.1	8	0.4	7.7
	Maximum	41.4	22.3	25	9.0	
	Mean	23.5	13.7	17.5	3.8	
	Standard deviation	8.3	4.8	5.0	1.5	