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Characterizing understory vegetation in Mediterranean forests using full-waveform airborne laser scanning data

Crespo-Peremarch Pablo[a,*], Tompalski Piotr[b], Coops Nicholas C.[b], Ruiz Luis Ángel[a]

[a] Geo-Environmental Cartography and Remote Sensing Group (CGAT), Department of Cartographic Engineering, Geodesy and Photogrammetry, Universitat Politècnica de València, Camí de Vera s/n, 46022 València, Spain
[b] Integrated Remote Sensing Studio (IRSS), Department of Forest Resources Management, Forest Science Centre, 2424 Main Mall, University of British Columbia, Vancouver, BC V6T 1Z4, Canada

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ABSTRACT

The use of laser scanning acquired from the air, or ground, holds great potential for the assessment of forest structural attributes, beyond conventional forest inventory. The use of full-waveform airborne laser scanning (ALS_{FW}) data allows for the extraction of detailed information in different vertical strata compared to discrete ALS (ALS_D). Terrestrial laser scanning (TLS) can register lower vertical strata, such as understory vegetation, without issues of canopy occlusion, however is limited in its acquisition over large areas. In this study we examine the ability of ALS_{FW} to characterize understory vegetation (i.e. maximum and mean height, cover, and volume), verified using TLS point clouds in a Mediterranean forest in Eastern Spain. We developed nine full-waveform metrics to characterize understory vegetation attributes at two different scales (3.75 m square subplots and circular plots with a radius of 15 m); with, and without, application of a height filter to the data. Four understory vegetation attributes were estimated at plot level with high R^2 values (mean height: $R^2 = 0.957$, maximum height: $R^2 = 0.771$, cover: $R^2 = 0.871$, and volume: $R^2 = 0.951$). The proportion of explained variance was slightly lower at 3.75 m side cells (mean height: $R^2 = 0.633$, maximum height: $R^2 = 0.470$, cover: $R^2 = 0.581$, and volume $R^2 = 0.651$). These results indicate that Mediterranean understory vegetation can be estimated and accurately mapped over large areas with ALS_{FW}. The future use of these types of predictions includes the estimation of ladder fuels, which drive key fire behavior in these ecosystems.

1. Introduction

Understory vegetation is an essential component of forest ecosystems (Suchar and Crookston, 2010). The understory is critical for wildlife habitat, nesting and foraging (Hill and Broughton, 2009; Martinuzzi et al., 2009; Wing et al., 2012), impacts overstory regeneration (Royo and Carson, 2006), provides protection against soil erosion (Suchar and Crookston, 2010), as well as mediates microclimatic conditions below the canopy. The height, cover, and condition of the understory are also key drivers of fire behavior through fuel ladders, which drive crown fires (Molina et al., 2011). These types of fires are the most dangerous in terms of economic impacts and tree death (Molina et al., 2009).

Despite its importance, understory vegetation has conventionally been difficult to describe spatially, particularly over large areas (Wing et al., 2012). Traditional techniques, such as the line interception method (Canfield, 1941), often used in field surveys (Vierling et al., 2013), are very costly and only provide information over small spatial extents (Riaño et al., 2007). Airborne or satellite-borne passive optical remote sensing approaches can acquire data over large areas, but have limitations for characterizing vertical forest structure (Kerr and Ostrovsky, 2003; McDermid et al., 2005; Wulder and Franklin, 2012).

Active remote sensing techniques, such as Light Detection and Ranging (lidar), provide horizontal and vertical information of different canopy layers (Ruiz et al., 2018). Several studies have estimated characteristics of understory vegetation cover using discrete return airborne lidar, also known as discrete airborne laser scanning (ALS_D, Table 1). Most of these studies utilise classification approaches, where understory vegetation is classified based on a set of characteristics derived from point cloud data (Hill and Broughton, 2009; Martinuzzi et al., 2009; Morsdorf et al., 2010). Less common approaches involve regression, where understory characteristics are mapped in a continuous fashion (Wing et al., 2012). Martinuzzi et al. (2009) defined and classified two categories of understory cover (above and below

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[*] Corresponding author.
E-mail address: pabcrepe@cgf.upv.es (P. Crespo-Peremarch).

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Table 1
Summary of existing studies about the characterization of understory using ALS with overstory presence.

Study	Study Area	Ecosystem	Definition of forest types	Target attributes	Data	Density (points·m^{-2})	No. of plots (plot size m^2)	Results
Martinuzzi et al. (2009)	Private industrial and experimental managed forest in Moscow Mountain in Northern Idaho, USA (30,000 ha)	Ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western red cedar (*Thuja plicata*) and western larch (*Larix occidentalis*)	Mixed temperate coniferous	Presence/absence of understory shrubs and snags (where cover > 25%)	ALS_D	–	83 (405)	Overall accuracy = 0.83 kappa = 0.66 (Classification)
Hill and Broughton (2009)	Monks Wood National Nature Reserve in Cambridgeshire, England (157 ha)	Ash (*Fraxinus excelsior*), English oak (*Quercus robur*), field maple (*Acer campestre*), silver birch (*Betula pendula*), aspen (*Populus tremula*) and small-leaved elm (*Ulmus carpinifolia*)	Temperate deciduous woodland	Presence/absence of understory combining data from leaf-on and leaf-off	ALS_D	Leaf-off: 1 pulse·m^{-2} Leaf-on: 0.5 pulse·m^{-2}	132 (400)	Overall accuracy = 0.77 kappa = 0.53 (Classification)
Morsdorf et al. (2010)	Experimental Mediterranean region of Lamanon, France (16.5 ha)	Aleppo pine (*Pinus halepensis*) and holm oak (*Quercus ilex*)	Mediterranean pine-evergreen oak woodland	Presence/absence of different vertical strata	ALS_D	3.7	63 (25)	Overall accuracy = 0.48 (Classification of shrub layer)
Wing et al. (2012)	Managed Blacks Mountain Experimental Forest in northeastern California, USA (4358 ha)	Ponderosa pine (*Pinus ponderosa Dougl. ex P.* and *C. Laws*), fir (*Abies concolor* (*Gord.* And *Glend.*) *Lindl*), incense-cedar (*Calocedrus decurrens* (*Torr.*) *Florin*) and Jeffrey pine (*Pinus jeffreyi*)	Interior ponderosa pine	Understory vegetation cover	ALS_D	6.9	154 (40.5)	$R^2 = 0.74$ bias = 0 RMSE = 0.064–0.0735 nRMSE = 22% (Regression)
Hancock et al. (2017)	Luton, England (100 ha)	Woodland, scrubland, and parkland	Urban area	Understory vegetation cover	ALS_{FW}	0.5–4 pulses·m^{-2}	8 (subplot = 1.5 m)	nRMSE = 24% (Verification at voxel-level)