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TESIS DOCTORAL

Processing and analysis of airborne full-waveform laser scanning data for the characterization of forest structure and fuel properties

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Forest structure is defined as the horizontal and vertical distribution of the vegetation elements (Kükenbrink et al., 2017). Its significance is visible on different factors such as biodiversity and spreading of wildfires. For the latter, fire behavior may be modeled through fire models. To do this, input parameters representing the forest structure and fuel properties are required (García et al., 2011). The use of more recent and detailed 3D fire behavior models based on computational fluid dynamics methods, require more information about the heterogeneity of vegetation fuels in the different vertical strata (Mell et al., 2011). In this sense, discrete airborne laser scanning (ALS_D) has been successfully used to characterize forest structure and fuel properties (Hevia et al., 2016). More specifically, full-waveform airborne laser scanning (ALS_{FW}) goes one step further and registers the complete signal response from the different vertical strata (Mallet and Bretar, 2009). Nevertheless, its use has been limited due to three main points: (*i*) unknowledge of data, (*ii*) large amount of data, and (*iii*) lack of processing tools. The main objective of this thesis was the development of processing and analysis methods based on full-waveform airborne laser scanner data to characterize the vertical forest structure, in particular, the understory vegetation. Moreover, six more specific objectives are also described and addressed in the next paragraphs.

Airborne laser scanning (ALS) data are not homogeneous due to several factors such as the presence of side-lap areas between different flight stripes. This leads to a heterogeneous pulse density that affects the extraction of ALS_{FW} metrics extracted, and forest attributes estimated from the latter. In the first specific objective we assessed the influence of the pulse density, methodological parameters of the voxelization procedure (voxel size and assignation value) and regression method on the extraction of ALS_{FW} metrics and on the estimate of forest attributes. Results show that variations of ALS_{FW} metric values by either using a minimum pulse density or modifying voxel parameters may be reduced. Additionally, estimate of forest attributes is also influenced by pulse density variations, and its influence may be reduced by increasing voxel size and modifying the regression method (Crespo-Peremarch et al., 2018a).

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One of the drawbacks of using ALS_{FW} data is that there is a lack of processing tools, and most of the existing ones do not include some functionalities such as the radiometric correction or metrics related to understory vegetation. In the second specific objective we developed a software tool named *WoLFeX* (Waveform Lidar for Forestry Extraction), freely available for download at [http://cgat.webs.upv.es/software/]. This software tool allows for clipping, radiometrically correcting, voxelizing the original ALS_{FW} waveforms, creating pseudo-vertical waveforms and extracting an exhaustive set of object-oriented metrics (Crespo-Peremarch and Ruiz, 2020). Among these metrics, some new ones related to understory vegetation are the most remarkable, since they allow for the characterization of these strata, which is a key factor for the prediction of wildfires.

The use of radiometric correction for ALS data is not very widespread compared to remote sensing imagery. However, it is an essential step for ALS_{FW} due to the reliance between ALS_{FW} metrics and amplitude values (Wagner, 2010). The use of ALS_{FW} data without a radiometric correction may involve modified ALS_{FW} metric values, and consequently modified estimates of forest attributes. In the third specific objective we assessed the influence of relative radiometric correction and scan angle acquisition on ALS_{FW} metric values and estimate of forest fuel attributes. Results showed that ALS_{FW} metric values and estimates of forest fuel attributes are influenced by scan angle.

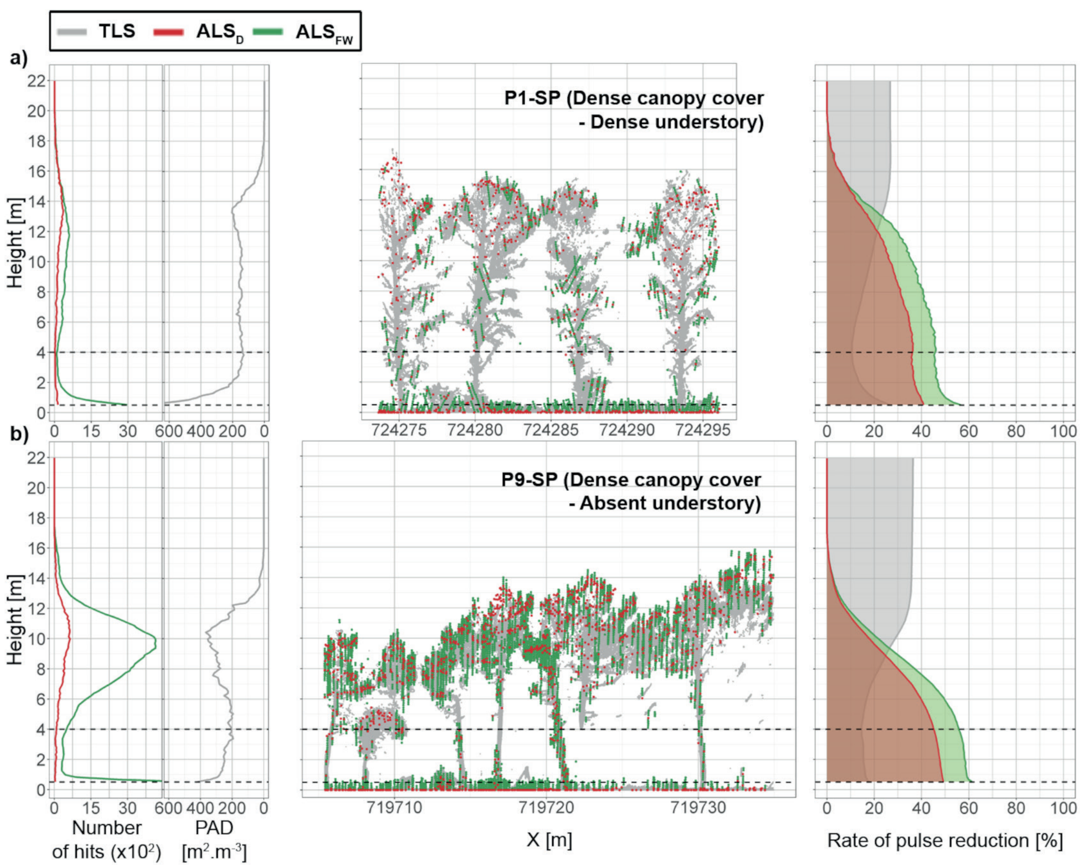

Figure 1. Vertical profiles representing two contrasted plots (P1-SP and P9-SP) in a Mediterranean forest. The figures from left to right represent: (i) the number of hits from ALS and cumulative Plant Area Density from TLS, (ii) a one-meter wide point cloud transect, and (iii) the rate of pulse reduction from the three configurations (i.e., TLS, ALS_D and ALS_{FW}). Dashed lines represent the limits of the lower strata (i.e., 0.5 and 4 m).

Nevertheless, this influence may be considerably reduced by using the radiometric correction, but not completely removed.

Detection of forest horizontal and vertical structure by laser scanning can be limited by signal occlusion caused by vegetation. The amount of signal occlusion may be reduced using several strategies such as increasing the number of flight stripes for ALS, combining data from multiple sensors, registering the plot with multiple scans for terrestrial laser scanning (TLS), or compute the Plant Area Density (PAD) also for TLS (Pimont et al., 2018). Despite using these strategies, signal occlusion is hardly ever completely removed. Hence, it is essential to analyze signal occlusion to better understand the limitations of the different laser scanning sensors in the detection of vertical forest structure. In the fourth specific objective we characterized the signal occlusion along the vertical forest structure using different laser scanning sensors: ALS_D, ALS_{FW} and TLS. Results showed that the vertical profile extracted was dependent on signal occlusion (Figure 1). This signal occlusion may be quantified in the

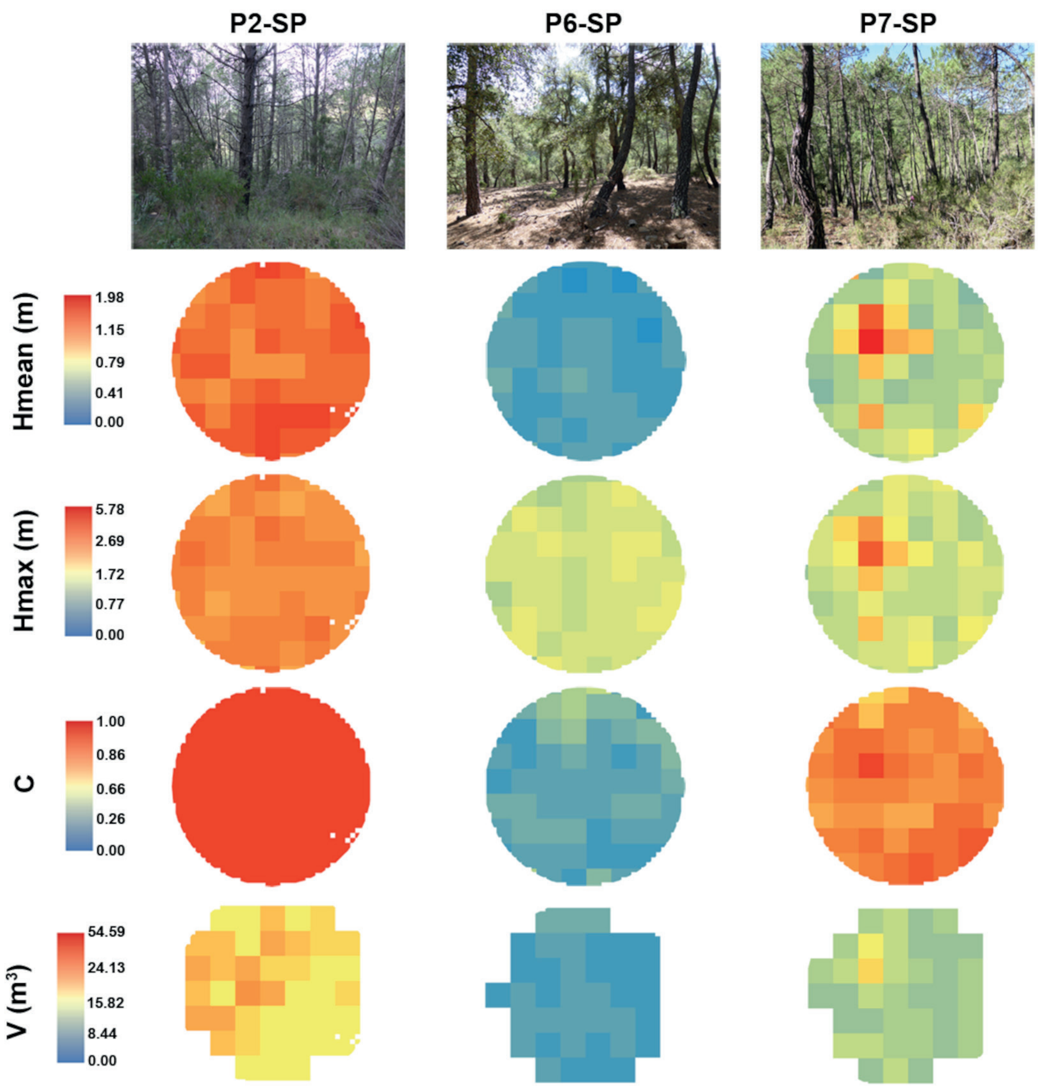

Figure 2. Understory vegetation attributes (i.e., H_{mean} and H_{max}: mean and maximum height, respectively; C: cover; and V: volume) derived from ALS_{FW} at subplot-level, and field photographs from three plots representing from left to right, dense, low and moderate understory cover.

Table 1. Estimate results at plot-level for understory vegetation attributes mean and maximum height (H_{mean} and H_{max}, respectively), cover (C), and volume (V).

Attributes	R^2	RMSE	nRMSE (%)	CV (%)
H_{mean}	0.949	0.08 m	7	11
H_{max}	0.758	0.52 m	12	15
C	0.871	0.09	11	12
V	0.951	56.49 m^3	7	9

different vertical strata by using the rate of pulse reduction, which is a good indicator of the reliability in the detection of vertical forest structure (Crespo-Peremarch et al., 2020).

Among the different vertical strata, understory vegetation is critical for wildlife habitat, as well as a key driver of fire behavior through ladder fuels, which drive crown fires (Molina et al., 2011). Its detection can be challenging from ALS sensors due to signal occlusion caused by overstory (Anderson et al., 2016). In the fifth specific objective we determined how understory vegetation density classes can be detected and further determined by ALS sensors (i.e., ALS_D and ALS_{FW}) in a boreal and Mediterranean forest. Results showed the capabilities of both ALS sensors to detect understory vegetation. Nevertheless, ALS_{FW} showed a higher accuracy than ALS_D, demonstrating its potential to detect and determine understory vegetation density classes in a boreal and Mediterranean forest by using the Gini index (see Table 1) (Crespo-Peremarch et al., 2020).

The characterization of understory vegetation by means of ALS sensors is uncertain due to signal occlusion. In the sixth and last specific objective the characterization of understory vegetation in a Mediterranean forest by using the new ALS_{FW} metrics proposed and implemented in the software tool *WoLFeX* was evaluated. Results showed that maximum and mean height, cover and volume of understory vegetation can be estimated very accurately at subplot- and plot-level using ALS_{FW} data (Table 1 and Figure 2) (Crespo-Peremarch et al., 2018b). In addition, and contrary to ALS_D, the use of the proposed metrics makes that ALS data do not require a height filter to only keep data corresponding to understory vegetation.

The use of ALS_D data is adequate for most of the current ALS applications. However, it presents some limitations in the characterization of intermediate and lower strata, where ALS_{FW} can be used instead. Therefore, ALS_{FW} has demonstrated to be a powerful tool to characterize the entire vertical forest structure, but especially understory vegetation, where ALS sensors have been traditionally limited. Nevertheless, the use of ALS_{FW} data requires the identification of the appropriate parameters, such as the optimal minimum pulse density and voxel parameters, as well as the application of the radiometric correction prior to undertake any data processing. Additionally, there are some general limitations common for ALS sensors, such as the signal occlusion caused by overstory, especially in dense tropical forests. The results lead the way for the estimation of understory vegetation variables from ALS_{FW} data at voxel level, to be used as input in the new 3D physical fire behavior models.

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