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# Canopy fuel modelling in Mediterranean forest stands with airborne LiDAR data at regional scale: preliminary results

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**Abstract**

Canopy fuel characterization is highly relevant for wildfire prevention, especially in the context of extreme events involving crown fires. Airborne laser scanning has been proven very useful to retrieve 3D forest structure at large scales, becoming freely available in many countries in the recent years which provide an opportunity to map fuel parameters that are critical for fire behaviour simulation. Previous studies on canopy fuel modelling predict canopy base height (CBH), fuel load (CFL) and bulk density (CBD) mainly in tree species from temperate conifer forests, with specific models still lacking for the main Mediterranean forest stands and especially deciduous species. This work presents first results of models obtained from low density airborne LiDAR data (1.5 p/m2) for canopy fuel characterization of critical structural variables (CBH, CFL and CBD) in the main Mediterranean forest stands existing in Andalusia region, including Pinus sp, Quercus sp and Eucalyptus sp tree species. The study is part of an ongoing project that include field inventory in 750 plots to characterize canopy fuels in 15 different forest stands representative of Mediterranean tree species, with a samplig design that consider structural heterogeneity in a wide study area (29000 km2). Different modelling techniques (linear regression and random foresst) were tested to assess the best formulation and input LiDAR metrics to be included in the models for each fuel parameter estimation, that will be used to generate high resolution maps of canopy fuels at regional scale. Preliminary models obtained from a set of 170 field plots in pure stands of Quercus ilex, Quercus suber, Pinus halepensis, Pinus pinea and Eucaliptus sp show promising results for canopy fuel characterization from low density airborne LiDAR data in these widely distributed species. However, our results also highlight a significant effect of the different modelling tecniques on the input metrics and accuracy of the models.

## 1. Introduction

Canopy fuel characterization is highly relevant for wildfire prevention and management, especially regarding potential extreme fire behaviour involving crown fires. Canopy base height (CBH), fuel load (CFL) and bulk density (CBD) are the main canopy structure variables conditioning fire initiation and spread rate in the transition of flames from surface fuels to canopy fuels (Van Wagner, 1977; Cruz et al., 2003; Molina et al., 2014). Fire simulation software can be used to predict fire behaviour but requires high resolution fuel maps of both surface and canopy fuels. Fire managers are increasingly using this kind of simulation programs for operational use, fuel treatment planning and fire severity assessment, demanding updated fuel cartography at regional scales.

LiDAR (Laser Imaging Detection and Ranging) technology has been proven very useful to characterize 3D forest structure, including canopy fuels (Riaño et al. 2003; Andersen 2005; Hudak et al. 2008). Free LiDAR data from airborne platforms are becoming available in more countries in the recent year (e.g. Spain, Finland, Slovenia or France), being a revolution on data gathering for forest monitoring at large scales. For example, the Spanish National Plan for Aerial Orthophotography (PNOA) is providing the second nation-wide coverage of LiDAR data at low pulse density in Spain and already planning the third coverage to start next year. Hence, airborne LiDAR data give an opportunity to get spatially-explicit information to map fuel parameters that are critical for fire behaviour simulation.

Previous studies on canopy fuel modelling with airborne LiDAR include CBH, CFL and CBD models, showing different success depending on the fuel parameter and laser pulse density used. The main tree species assessed include North-American and European conifers, mostly typical of temperate forests (Andersen et al. 2005, Riaño et al. 2003; González-Olabarria et al, 2012; Gonzalez-Ferreiro et al. 2014, 2017; Alonso-Rego et al., 2021), and some studies for Mediterranean tree species but fitted with field data from small areas with limited transferability (Botequim et al, 2019; Ferrer Palomino y Rodriguez y Silva, 2021). Specific models are needed to get reliable estimation of canopy fuels at regional scale, but information is still lacking for many Mediterranean forest stands, especially deciduous species.

The aim of the present study is to explore different modelling techniques to obtain models for canopy fuel varaibles (CBH, CFL and CBD) from low density airborne LiDAR data for the main Mediterranean forest stands, including *Pinus sp*, *Quercus sp* and *Eucalyptus sp* tree species, and considering the structural heterogeneity from a wide study area. The work is part of a wider project on forest fuel characterization in Andalusia region that is currently ongoing. The best models obtained will be used to generate high resolution maps of canopy fuels at a regional scale.

## 2. Methods

### 2.1. Study area and field data

The study area includes the forest stands located in the Andalusia region, in the south of Spain (Figure 1). Most of them are located within the High Wildfire Risk areas ("Zonas de Alto Riesgo de incendio forestal", ZAR) which cover 58% of the whole Andalusian territory, e.i. more than 29000 km$^2$. The most representative forest stands in terms of area covered and potential fire risk were selected for canopy fuel characterization in the field, resulting in 15 different forest ecosystems (Table 1). Tree species composition was derived from a detailed vegetation map (1:10000 scale) available for Andalusia region. Selected forest ecosystems included pure stands (one dominant tree species) and mixed stands (minimum of 25% of relative canopy cover of the secondary tree species), covering 85% of the forest areas in the region.

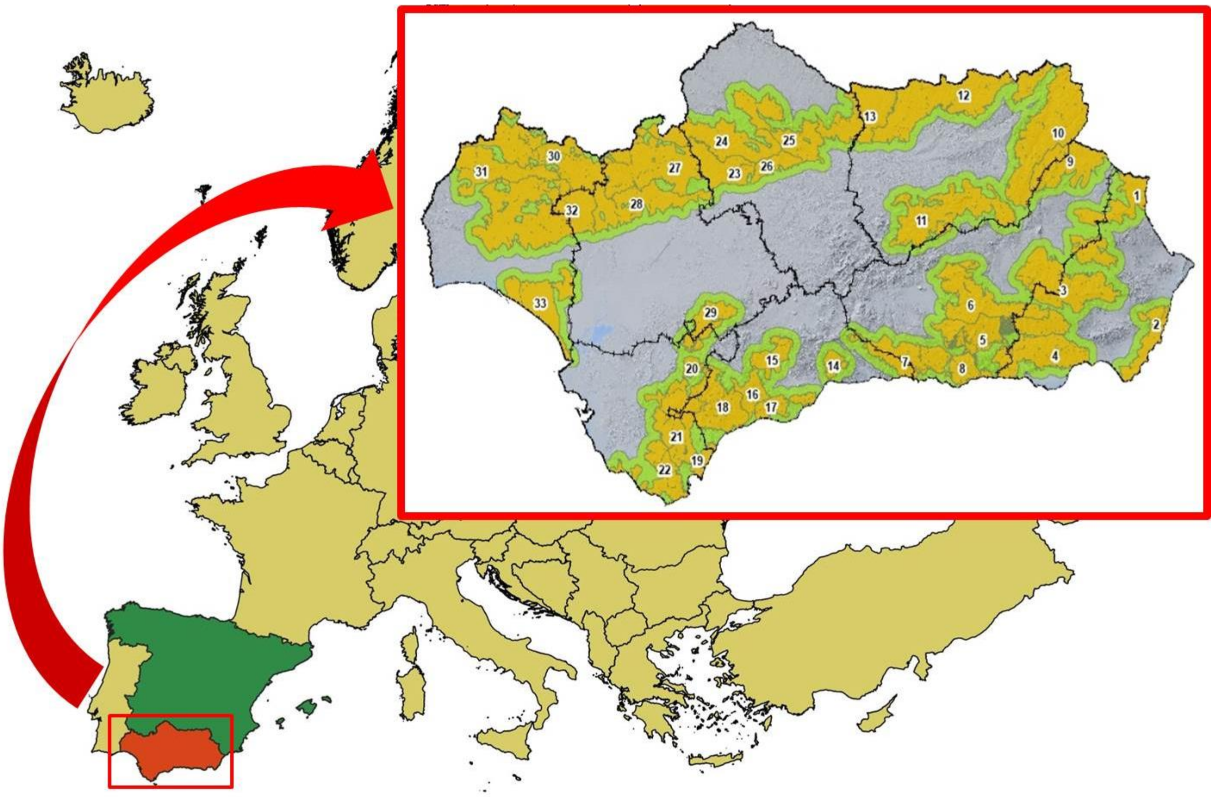

***Figure 1- Study area, with detail of the High Wildfire Risk areas (ZAR) in Andalusia (orange) and a 5-km buffer included (green)***

A total of 750 field plots will be placed in the selected forest stands including the main Mediterranean tree species. According to the area covered by each forest ecosystem in the study region, between 30 to 90 circular plots will be measured to retrieve canopy fuel data for each forest stand type. Plot locations are chosen in order to cover the range of structural variability according to the Spanish National Forest Inventory IFN3 (MARM, 2008) and LiDAR data, considering metrics related to fractional canopy cover (FCC), height (H) and canopy relief ratio (CRR) to identify structural heterogeneity in each forest ecosystem (Parker and Russ, 2004).

A GPS providing sub-metre accuracy is used to registered plot centre coordinates for proper LiDAR data comparison in the modelling process. Field measurements are performed in 11.3-m-radius circular plots, equivalent to the 20-m-pixel canopy fuel maps to be generated for the study area. In each plot, diameter at breast height (DBH) of trees thicker than 7.5 cm is measured and used to calculate crown foliar biomass from previous allometric equations developed for each species (Montero et al. 2005). Available canopy fuel load at plot level (CFL) is calculated as the foliar biomass in the stand (kg/$m^2$).Tree height and crown base height are registered in 4 representative trees per plot, selecting one tree within each quarter section of the circular plot to characterize the mean stand height and canopy base height (CBH). Canopy bulk density (CBD) is calculated from CFL and mean canopy length at plot level, the latter being obtained as H minus CBH.

***Table 1- Selected forest stands for canopy fuel modelling at regional scale. *P: pure stands; M: mixed stands; P & M: pure and mixed stands***

| **Forest stand** | **Area (ha)** | **Stand type*** |
|---|---|---|
| *Quercus ilex* | 1218082 | P |
| *Pinus halepensis* | 241798 | P |
| *Pinus pinea* | 206213 | P |
| *Quercus suber* | 190698 | P |
| *Eucalyptus sp* | 138373 | P |
| *Olea europaea var. sylvestris* | 138334 | P & M |
| *Pinus pinaster* | 116117 | P |
| *Pinus nigra* | 61436 | P |
| *Quercus ilex & Pinus halepensis* | 47254 | M |
| *Pinus sylvestris* | 28766 | P |
| *Pinus pinaster & Quercus ilex / Quercus suber* | 27535 | M |
| *Quercus faginea / Quercus pyrenaica & Quercus ilex / Quercus suber* | 18934 | P & M |
| *Pinus pinea & Quercus ilex / Quercus suber* | 19370 | M |
| *Quercus suber & other Quercus sp* | 17460 | P & M |
| *Eucalyptus sp & Pinus sp* | 10510 | M |
| **TOTAL** | **2480268** | |

## 2.2. LIDAR data

The LiDAR data used in this study correspond to the 2nd regional cover of Spanish PNOA in Andalusia, acquired between 2020 and 2021 at a pulse density of 1.5 p/$m^2$. Point cloud files were provided in LAZ format and processed using R software (R Development Core Team, 2014) with lidR package (Roussel *et al*. 2020) and QGIS software (QGIS Development Team, 2014). Points classified as soil returns were used to generate a digital terrain model (DTM) at 2m resolution. Points classified as vegetation returns were normalized with DTM to retrieve heights to soil level. LiDAR metrics were extracted from point clouds at plot level to compare with field measurements (Figure 2). Two different thresholds, 2 m and 4 m, were used to get LiDAR metrics from canopy returns in order to considered the heterogeneity of Mediterranean vegetation (Table 2).

Selected LiDAR metrics were also extracted in a 20m grid for the whole study area to characterized the structure of forest stands prior to field measurement (see details in section 2.1), in order to assess FCC (percentage of first returns above 2m), H (percentile 95% of vegetation returns) and CRR (canopy relief ratio). Once the LiDAR models for each canopy fuel variable (CBH, CFL and CBD) and forest type (Table 1) will be fitted and validated with field data, selected input metrics included in the final models will be also obtained as 20m raster files to generate high resolution wall-to-wall canopy fuel maps of the study area.

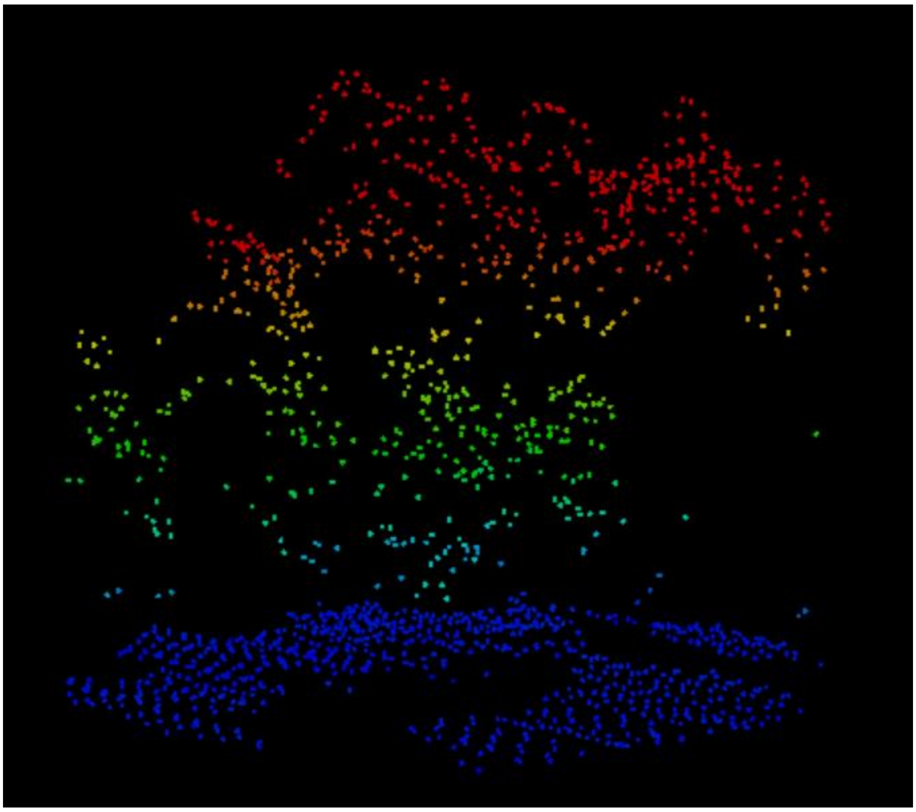

***Figure 1- Example of LiDAR point cloud (1.5 p/m2) extracted in a field plot***

***Table 2- LiDAR metrics used as potential explanatory variables. All metric were extracted and tested at both threshold levels: 2m and 4m***

| Metric | Description |
|---|---|
| zmax | Maximum return height |
| zmean | Mean return height |
| zvar | Variance of return heights |
| zsd | Standard deviation of return heights |
| zcv | Coefficient of variation of return heights |
| ziq | Interquartile range of return heights |
| zskew | Skewness of return heights |
| zkurt | Kurtosis of return heights |
| pzabove | Percentage of first returns above threshold |
| pzabovezmean | Percentage of first returns above mean height |
| crr | Canopy relief ratio |
| $p_i$ | Percentile *i* of return heights (5,10,20,25,30,40,50,60,70,75,80,90,95,99) |

### 2.3. Statistical analysis

Parametric and non-parametric regression methods were used to model canopy fuels with LiDAR data. Different modelling techniques including linear regression and random forests were tested in order to compare the performance of different models. Models were fitted in R software, using crossvalidation for final model selection based on minimum root mean squared error (RMSE) and maximum variability explained.

## 3. Preliminary results

The field inventory is ongoing, and most of the plots in the main ecosystems are expected to be finished during the summer 2022. At present, there were more than 300 plots available out of 750 planned in the 15 forest types included in the study. However, here we are presenting preliminary results retrieved from only 170 plots in five pure stands, including *Quercus ilex* (n=41), *Quercus suber* (n=16), *Pinus halepensis* (n=18), *Pinus pinea* (n=44) *and Eucaliptus sp* (n=51), where at the time of writing this communication there were enough field data to perform the statistical analysis. Main statistics describing canopy parameters in each forest stand are summarized in Table 3.

***Table 3- Summary of the canopy fuel characteristics of the selected pure forest stands. H = Stand height, CBH = canopy base height, CFL = canopy fuel load, CBD = canopy bulk density, s.d. = = standard deviation***

| **Forest species (field plots)** | **H (m)** | | **CBH (m)** | | **CFL (kg/m²)** | | **CBD (kg/m³)** | |
|---|---|---|---|---|---|---|---|---|
| | **mean (range)** | **s.d.** | **mean (range)** | **s.d.** | **mean (range)** | **s.d.** | **mean (range)** | **s.d.** |
| *Quercus ilex* (n=41) | 7.27 (3.53-11.48) | 1.69 | 2.08 (0.67-3.7) | 0.53 | 0.20 (0.04-0.76) | 0.15 | 0.04 (0.01-0.14) | 0.03 |
| *Quercus suber* (n=16) | 8.60 (5.30-14.65) | 2.26 | 2.58 (2.10-3.7) | 0.50 | 0.04 (0.01-0.08) | 0.02 | 0.01 (0.003-0.01) | 0.003 |
| *Pinus halepensis* (n=18) | 9.48 (5.15-17.63) | 3.22 | 3.43 (0.10-9.4) | 2.52 | 0.28 (0.07-0.59) | 0.14 | 0.05 (0.01-0.13) | 0.03 |
| *Pinus pinea* (n=44) | 10.71 (5.28-21.30) | 3.62 | 5.85 (1.45-13.0) | 3.12 | 0.61 (0.17-2.19) | 0.37 | 0.14 (0.04-0.59) | 0.11 |
| *Eucalyptus sp* (n=41) | 12.56 (5.75-19.98) | 3.04 | 6.17 (2.15-14.2) | 2.66 | 0.66 (0.02-3.02) | 0.49 | 0.12 (0.003-0.88) | 0.13 |

In general, first results showed better models for *Pinus sp* than *Quercus sp* and *Eucalytus sp* stands (Table 4). CBD was the canopy fuel parameter more difficult to estimate, with even unsuccessful model fitting in some cases. Comparing parametric and non-parametric modelling techniques, linear regression generally provided better goodness-of-fit than random forest. In terms of LiDAR metrics, we also observed and effect of the different modelling techniques on the input variables selected as predictors in the models.

When field inventory would be completed, further analysis will be performed to improve these models and to include the rest of selected forest stands. Additional LiDAR metrics (e.g. percentage of returns normalized by height strata) and statistical methods (e.g. non-linear formulations) will be also tested. The final models fitted will allow retrieving predictions of CBH (m), CFL (kg/m$^2$) and CBD (kg/m$^3$) based on low-density LiDAR data (1.5 p/m$^2$) to obtain high spatial resolution canopy fuel maps of the study area adapted to the particularities of the main forest ecosystem in Andalusia. These results could be also applied to get canopy fuel maps from LiDAR data available in other forest stands in the Mediterranean region, as the selected species are very representative not only of the Iberian Peninsula but also of other South-European forest ecosystems, e.g. autochthonous stand composed by the main *Pinus sp* and *Quercus sp* as well as *Eucalyptus sp* plantations (Table 1).

Results from this study are expected to provide relevant information to improve fuel mapping in forest stands for enhance wildfire prevention and management, especially with regard to most conifer and deciduous tree species that are commonly involved in large wildfires in the Mediterranean region but are currently lacking specific LiDAR models for canopy fuel characterization.

***Table 4- Statistics of the preliminary models fitted to estimate canopy fuel characteristics in the selected pure forest stands from LiDAR data. CBH = canopy base height, CFL = canopy fuel load, CBD = canopy bulk density,*** $R^2_{adj}$ ***= adjusted*** $R^2$, $R^2_{ps}$ ***= pseudo-***$R^2$***, RMSE = root mean square error, n.a. = not applicable (unsuccessful model fitting)***

| **Forest species** | **Lineal regression** | | **Random Forest** | |
|---|---|---|---|---|
| | $R^2_{adj}$ | **RMSE (%)** | $R^2_{ps}$ | **RMSE (%)** |
| *Quercus ilex* (n=41) | | | | |
| CBH (m) | 0.30 | 0.432 (20.6 %) | 0.19 | 0.478 (23.0 %) |
| CFL (kg/m²) | 0.38 | 0.076 (37.2 %) | 0.37 | 0.121 (59.6 %) |
| CBD (kg/m³) | 0.34 | 0.018 (43.1 %) | 0.43 | 0.021 (51.5 %) |
| *Quercus suber* (n=16) | | | | |
| CBH (m) | 0.52 | 0.326 (12.6 %) | 0.55 | 0.328 (12.7 %) |
| CFL (kg/m²) | n.a. | n.a. | 0.43 | 0.013 (31.2 %) |

| | | | | |
|---|---|---|---|---|
| CBD (kg/m$^3$) | 0.38 | 0.002 (28.6 %) | n.a. | n.a. |
| *Pinus halepensis* (n=18) | | | | |
| CBH (m) | 0.88 | 0.774 (22.6 %) | 0.75 | 1.188 (34.6 %) |
| CFL (kg/m$^2$) | 0.85 | 0.051 (18.2 %) | 0.49 | 0.098 (35.1 %) |
| CBD (kg/m$^3$) | 0.63 | 0.025 (50.0 %) | 0.31 | 0.026 (52.3 %) |
| *Pinus pinea* (n=44) | | | | |
| CBH (m) | 0.92 | 0.892 (15.2 %) | 0.88 | 1.063 (18.2 %) |
| CFL (kg/m$^2$) | 0.51 | 0.192 (31.5 %) | 0.23 | 0.322 (52.8 %) |
| CBD (kg/m$^3$) | n.a. | n.a. | 0.09 | 0.105 (75.1 %) |
| *Eucalyptus sp* (n=41) | | | | |
| CBH (m) | 0.44 | 1.952 (31.6 %) | 0.42 | 2.023 (32.8 %) |
| CFL (kg/m$^2$) | 0.75 | 0.179 (27.1 %) | 0.41 | 0.379 (57.4 %) |
| CBD (kg/m$^3$) | n.a. | n.a. | 0.23 | 0.115 (95.8 %) |

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