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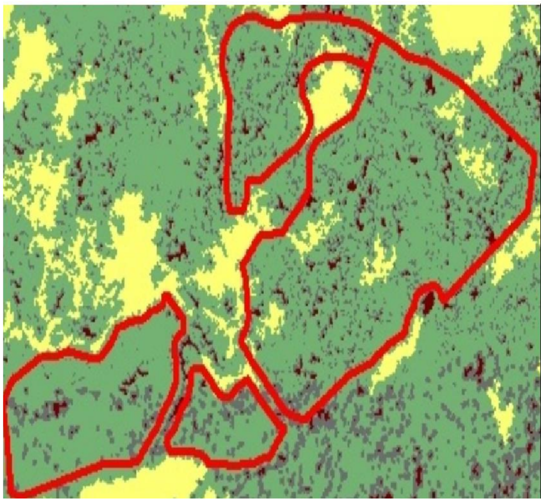
Natural diversification of black pine forests in the pre-Pyrenean mountains (NE Spain): the role of stand structure and canopy attributes.



MSc thesis under Erasmus Mundus Mediterranean Forestry and Natural Resources Management (MEDfOR).

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Abstract

The diversification of sub-Mediterranean pine forests is considered essential for the future resilience of these systems face to uncertain environmental conditions. To better understand the spontaneous diversification processes of these stands and in particular the role of environmental and structural factors acting at small-scales, we conducted a study in which we assessed broadleaves regeneration in a set of black pine (*Pinus nigra* Arn.) dominated forests of NE Spain. In the study, both canopy attributes determined by the analysis of LiDAR data and multispectral aerial imagery and stand structural variables obtained from field inventories were related with the abundance of seedling and saplings of broadleaves species (mainly sclerophylous holm and marcescent oaks).

The results of our analysis showed that critical role of some of both canopy and structural variables on recruitment success. At seedling stage holm and marcescent oaks were facilitated by the canopy and the shrub layer, with the latter showing more shade tolerance than the former. Interestingly a significant interaction between gap shape and gap size was found, with plants being able to survive in large gap sizes only under high irregularity values (gap forms far from the circular one). Once, established, plants seemed to require high light conditions to reach sapling stages as shown by the positive relationship with gap fraction percentage and the marked negative influence of northness on their abundance.

The knowledge generated in this study could be used as a basis for the establishment of silivicultural treatments oriented to the progressive diversification of such stands and to the enhancement of its resilience face to natural disturbances.

Key words: LiDAR data, Broadleaf Seedling, Sapling, Gap shape and size.

1. Introduction

1.1. General contextualization about the Iberian Mediterranean forests

The Mediterranean basin represents a peculiar but attractive prominence of both ecological and socio-cultural aspects (Scarascia-Mugnozza *et al.*, 2000). It depicts a fickle geology and topography (Di Castri & Mooney, 1973; Blondel, 2006) with craggy coastline and relatively immature mountains. It also constitutes a biodiversity hotspot and one of the world's richest centers in endemism (Medail & Quezel, 1999). In this geographical context, Mediterranean forests evolved over millennia with the effects of human practices (e.g. agricultural and pastoral activities) (Debussche *et al.*, 1999; Vallejo, 2005; FAO, 2013; Nocentini & Coll, 2013) up to the point that they are recognized as one of the clearest examples in the world of a long-term human-modified ecosystems (Nilsson, 1997; Carrión *et al.*, 2001; Blondel, 2006).

Periods of intense human disturbances (in which desirable species were favored against others) reached its peak in the end of the 19th century (García-Ruiz, 1993; Pausas *et al.*, 2004; Linares *et al.*, 2011). These periods were followed in the second part of the 20th century by extensive reforestation programs (most of which with pine species) with the aim of restoring most highly degraded areas (Pausas *et al.*, 2004; Nocentini & Coll, 2013). The consequence of all this long history of human-use was a significant reduction of the inherent structural and compositional heterogeneity of Mediterranean ecosystems (Ciancio & Nocentini, 2000).

From the second half of the 20th century, noticeable socioeconomic changes led to important land-use changes, characterized by Chauchard *et al.* (2007) in two ways: (i) land-use intensification in coastal regions and (ii) land abandonment in the marginal areas (generally mountain areas). This generalized process of land abandonment in mountainous areas was translated into three main processes: encroachment, densification and diversification of the forest stands (Navarro & Pereira,

2012) that affected a wide range of forest attributes at different scales (e.g., Roura-Pascual *et al.*, 2005; Navarro & Pereira, 2012; Stellmes *et al.*, 2013).

In parallel to land-use changes, Mediterranean forests are undergoing the effects of climate change, which are expected to increase in the following decades (Lucier *et al.*, 2009; Milad *et al.*, 2011; FAO, 2013). Climate change models predict increased aridity and higher temperatures across large areas of Europe in coming decades. The consequences of these effects are expected to be particularly important in the Mediterranean mountain areas, as they are transitional climatic regions (Palahi *et al.*, 2008). Forest disturbances, and particularly wildfires, are also expected to increase as a consequence of climate change, since prolonged droughts and hot spells will further aggravate forest fire risks (Lindner *et al.*, 2010).

1.2. The effects of spontaneous diversification of Mediterranean pine forests on their resilient attributes

The term resilience has been defined in many ways (see for example http://www.resalliance.org). In a context of managed forests, resilience could be defined as the capacity of the system to continue providing desired ecosystem goods and services following a perturbation (Folke *et al.*, 2002). For example, a pine-dominated forest providing soil and water protection would be considered resilient even if after the disturbance a new community emerges as far as this new system will continue providing all the main general functions of the previous one. It is clearly evident from different studies (e. g., Campbell *et al.*, 2009; Thompson, 2009) that the more structural and compositional heterogeneity an ecosystem holds, the more resilient it is. This is mainly due to the higher diversity of post-disturbance responses that an heterogeneous systems present (McGrady-Steed *et al.*, 1997; Naeem & Li, 1997). According to the wide array of communities and species present in Mediterranean ecosystems, the potential for managing them for enhancing resilience through increasing diversity are very high (Scarascia-Mugnozza *et al.*, 2000).

1.3. Gap dynamics and its role in the spontaneous diversification process

In the Mediterranean region (as well as in other regions of the world), the effects of large-scale disturbances on maintaining and enhancing forest diversity have been widely studied (e.g., Capitanio & Carcaillet, 2008). However, the role of other factors taking part at the micro-site level, such as the occurrence of small natural disturbances causing fine-scale variation of the attributes of the canopy cover, have not been sufficiently addressed although they are known to importantly modulate tree recruitment and understory diversity (Arévalo & Fernández-Palacios, 2006; Dobrowolska & Veblen, 2008). At present, the generalized abandonment of forest management occurred during the last decades is expected to increase spontaneous diversification processes driven by natural biotic and abiotic agents (e.g., fire, drought, pests and diseases, etc.) (Resco de Dios *et al.*, 2006; Pausas *et al.*, 2008; Nocentini & Coll, 2013).

In general, small-scale disturbances cause openings in the canopy cover that are often filled with tree recruitment (i.e. gap dynamics processes) (Watt, 1947; Kimmins, 2004). Gaps occur in several ways and can present different sizes and shapes depending on the biotic or abiotic causing agent. This creates different understory conditions (e.g., light, moisture, temperature) which in their turn modulate the abundance, composition and size of the regeneration (Runkle, 1981; Yamamoto, 2000). At the microsite level, light availability and soil resources greatly vary from the gap center to the neighboring forest thus allowing the coexistence of species with different light exigencies (i.e. shade-intolerant and intermediate-tolerant species) and resources needs into the gap. Understory species composition may also vary depending of the gap size (Schnitzer & Carson, 2001). Furthermore, the remnant trees surrounding the gap not only provide shade and a variety of regeneration niches, but also act as seed sources and vegetative material, further contributing to the spontaneous diversification of the forest stand.

1.4. The case of the Pre-Pyrenean black pine forests

European black pine (*Pinus nigra* Arnold) is a circum-Mediterranean pine species grouping a number of 15 subspecies along its distribution area (Ruiz de la Torre, 2006) and being considered as one of the most ancient European pine species. The subspecies *salzmannii* (*Pinus nigra* Arn ssp. *salzmannii*) is the only one being native in the Iberian Peninsula, where distributes in almost 500.000 ha (Ruiz de la Torre, 2006). The red list of the International Union for Conservation of Nature considers this species *'stable'* and classifies it as *'least concern'* (Farjon, 2013). Two varieties of black pine are discerned in the Iberian Peninsula, the var. *hispanica*, growing in the center and southern parts of the Peninsula, and the var. *pyrenaica*, growing from the center-east to the north-east (Ruiz de la Torre, 2006).

In Catalonia, black pine is the dominant species in near 150,000 ha, almost a half of which are pure black pine stands, and the rest are mixed stands (DGCN, 2005; Beltrán *et al.*, 2012). This species distributes in the low-montane belt (i.e. from 500 to 1400 m.a.s.l.) located in the foothills of the Pyrenees and the Pre-coastal mountain range under dry to sub-humid sites (i.e. minimum annual rainfall of 500 mm, minimum summer rainfall of 100 mm). In a good ecological conditions, this species can reach a height of 40 meters and an age of 800 years.

The main species sharing the dominant canopy with black pine are Scots pine (*Pinus sylvestris* L.), in sites in the highest elevation range, Aleppo pine (*Pinus halepensis* Mill), in the lowest elevation range and driest sites, and oak species such as the evergreen sclerophyllous holm oak (*Quercus ilex* L)., and the marcescent sub-Mediterranean oaks (*Quercus faginea* Lam., *Quercus humilis* Mill. and their hybridization, *Quercus cerrioides* Willk. & Costa). Apart from these species, other species frequently present in black pine forests are *Amelanchier ovalis*, *Prunus mahaleb*, *Acer* sp., *Buxus sempervirens*, *Sorbus* sp., *Juniperus* sp., etc.

Phytosociologists usually consider black pine forests as a regressive state of marcescent oak forests, in which pines are acting as pioneer species. However, although black pine is a species able to colonize open spaces it is noteworthy to mention that it has also some particularities which confer it a higher capacity to persist and establish under mature forests (i. e. high longevity, high resistance to low-intensity surface fires, mid shade-tolerance etc.) (Tíscar & Linares, 2011; Beltrán *et al.*, 2012).

Human activities have affected black pine forests over millennia, by modifying for example its distribution area (due to periods of forest depletion for pastures and cropland) and its structural and compositional attributes (consequence of activities such as grazing or wood and firewood harvesting). Wood from black pine was widely used during centuries for building and boat construction, due to the straightness of the trunk and its high resistance and durability. Because of this, black pine has historically been favored by man to the detriment of oak and other broadleaved species. Land-use during last decades affected to these forests similarly to other mountain forests in the Mediterranean basin. As a consequence, black pine has started re-colonizing abandoned arable lands and pastures, and has experienced general densification and maturation processes. These processes, together with the abandonment or huge decreasing of forest grazing and firewood harvesting are expected to contribute to the spontaneous diversification of the stands.

Assessing diversification processes associated to small-scale disturbances from systematic field inventories is a rather difficult and time consuming task (Schliemann & Bockheim, 2011; St-Onge *et al.*, 2014). Recently, remote sensing data have emerged as very interesting sources of data for characterizing forest structure and other attributes (Wulder *et al.*, 2007; Falkowski *et al.*, 2009). Their main advantages are the spatial continuity, cost effectiveness and accuracy (Garbarino *et al.*, 2012). Particularly, the combination of multispectral aerial photographs and LiDAR data has recently appeared as an excellent and affordable tool for the analysis of canopy cover dynamics and the identification of gap's attributes (e.g., Garbarino *et al.*, 2012).

1.5. Justification and Objective

The aim of this study is to deepen understanding the spontaneous diversification processes of long-term humanized black pine sub-Mediterranean forest. Particularly, this work will focus on the analysis of the role of canopy gaps and their main attributes (i. e., shape and size attributes) on the recruitment of the main broadleaf species. To this purpose, canopy opening in monospecific black pine stands will be assessed and characterized using a combination of multispectral aerial photographs and LiDAR data. Once this done, woody species' recruitment in black pine dominated forest stands will be measured in the field in a large set of forest plots covering a gradient of canopy conditions (i.e. gap abundance, and their shape and size attributes).

The general hypothesis of this study is that the canopy structure at the micro-site level is one of the main factors driving the spontaneous diversification of the forest system. At the micro-site level, it is hypothesized that broadleaves may establish under cover with very low to low canopy openness and optimal canopy conditions for establishment will vary between species. However, it is expected that all broadleaves will prosper up to sapling stadium when they develop below canopy gaps (thus benefiting from some light reaching the soil) but not when they do it below continuous canopy cover.

2. Materials and Methods

The methodological approach followed to assess the role of canopy attributes on the process of natural diversification of black pine forests used both remote sensing and field inventory data, and comprised the following steps (see Figure 1): (*i*) selection of black pine stands fulfilling a series of criteria, (*ii*) analysis of the canopy cover from LiDAR, and multi-spectral aerial imagery data), (*iii*) sampling design and measuring of field inventory plots, (*iv*) field data processing and (*v*) statistical data analysis.

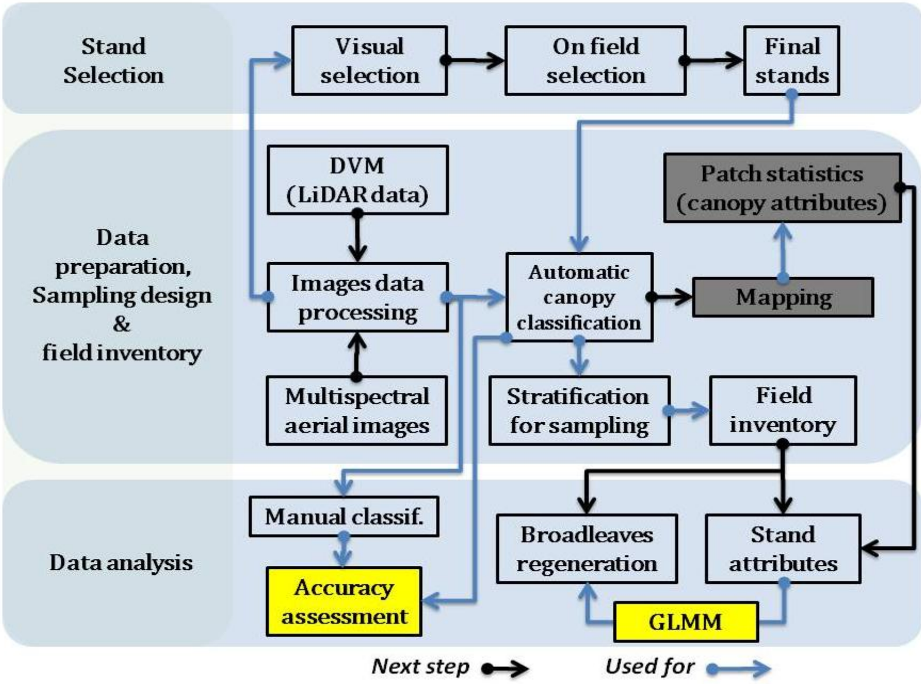

Figure 1: Stepwise flowchart of the whole study

2.6. Study area

The study area is located in the Catalan pre-Pyrenees, Northeastern Iberian Peninsula, in a mountainous range influenced by the rivers Segre and Cardener (1° 11' 6" E (East limit); 1° 36' 57" E (West limit); 41° 56' 57" N (South limit); 42° 3' 43" N (North limit)). These mountains are formed by folded structures of sedimentary rocks characterized by vertical elevation ranging from 400-1000 m.a.s.l. and narrow valleys of rough relief. Mean annual precipitation in this area is 710 mm, and mean annual temperature is 12ºC (Ninyerola *et al.*, 2005). Within this general geographic context, the study area focuses on the forest areas dominated by black pine (*Pinus nigra* Arn. ssp. *salzmannii).*

A set of eight stands were selected in the study area (Figure 2, Table 1). All stands need to reach the following criteria: (i) to be clearly dominated by black pine at the canopy level (i.e. with black pine occupancy > 90% of total basal area) without any representation of adult broadleaves (ii) to have not experienced important changes in density from 1956 up to now, and (iii) to not show signs of any recent silvicultural treatments or grazing activity.

Table 1: Summary of the main physiographic and climatic attributes data for the selected stands.

Stand No	Mean Elevation (m)	Mean Slope (%)	Central coordinates		Mean annual Temperature (ºC)	Mean annual precipitation (mm)
			X	Y		
St-2	596	29	350254	4654754	12.2	689
St-3	703	34	384917	4652978	11.6	724
St-4	701	42	366627	4657134	11.8	724
St-6	800	36	373019	4645769	11.3	689
St-7	700	42	371741	4657418	11.6	725
St-8	745	37	352207	4656921	11.5	728
St-9	702	30	366982	4651842	11.7	704
St-12	598	39	360767	4656140	12.2	707

Stands were selected and delineated with the help of the third Spanish National Forest Inventory plots (which provided information about the current structure and composition), the Spanish National Forest Map 1:50.000, the most recent aerial photographs of the area (taken in 2012) and the most ancient ones (taken in 1956).

2.2. Remote sensing data processing

Remote sensing data used for the characterization of the forest canopy was provided by the Cartographic and Geologic Institute of Catalonia (ICGC) and consisted in data from two different sources: aerial Light Detection and Ranging (LiDAR), and multi-spectral aerial imagery data, including RGB and near-IR bands. More specifically, the LiDAR data consisted in a 2-meter resolution DVM (Digital Vegetation Model) generated by the LiDARCAT project (Cartographic Institute of Catalonia & Spanish National Geographic Institute). Flight dates ranged from April 2009 to August 2009 and provided a minimum first-return density of 0.5 pulses/m^2 and an overall quantity of 4 height bins per first return. On the other hand, RGB and near-IR data came from multi-spectral aerial images (25 cm resolution) obtained from aerial photographs taken in the same period of time than LiDAR data (April to August) but years after (in 2012).

Both the multispectral bands from aerial images and the DVM from LiDAR were clipped with the aim of working only on those parts intersecting the 8 selected stands.

Then, an object oriented semi-automatic image analysis (Heurich *et al.*, 2009) was done through eCognition v.Developer 8 software in order to automatically classify the area within the stands into these three classes: "CANOPY", i.e. area covered by the main pine canopy showing a continuity larger than 10,000 m^2; "GAP", i.e. area not covered by the main pine canopy but surrounded by it and presenting an extent lower than 500 m^2 (Messier *et al.*, 2005; Schliemann & Bockheim, 2011) and "OF" (open forest) for the rest of the area (small canopy patches, isolated trees and open areas larger than 500 m^2).

2.3. Sampling design and field inventory

A stratified random sampling was used for selecting the inventory plots as the objective was to cover a wide gradient of canopy openness and heterogeneity. For this, a 20 x 20 meter mesh was created within the selected stands. Then the image classification obtained from the automatic image analysis (made with eCognition) was used to assess the percentage of GAP in the area surrounding each point in the mesh. Based on this value, four classes of gap abundance were created ("0" when gap percentage ranged from 0 to 2%; "1" when gap percentage ranged from 2 to 15%; "2" when the gap percentage range from 15 to 30% and "3" when gap percentage is above 30%). Those plots located at less than 10 m from any open area (e.g., roads, agricultural field, harvested areas, etc.) were rejected.

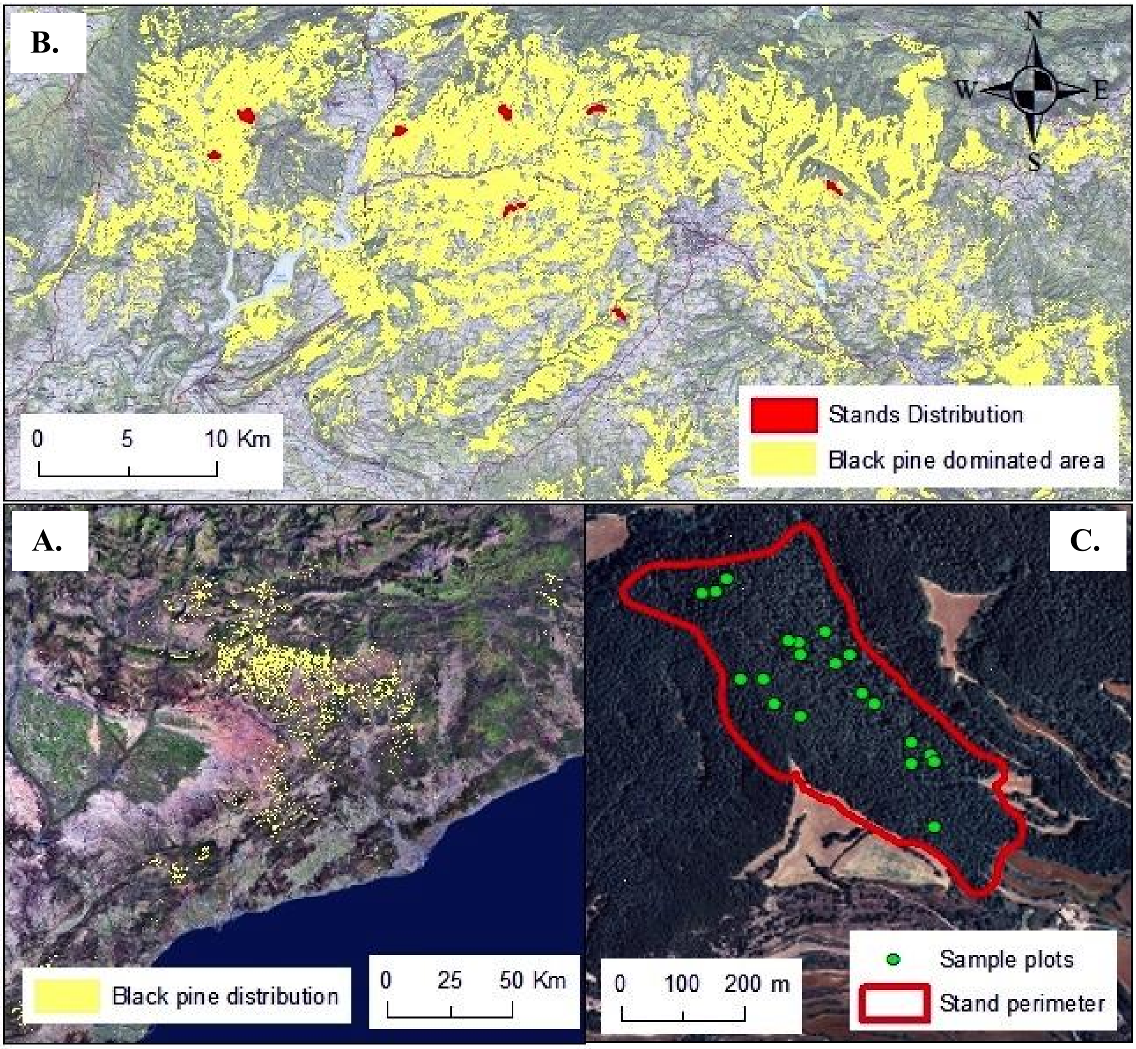

Figure 2: Location of the study area and final stands, A) Distribution of black pine over in Catalonia, B) Selected stands for final inventory and C) Sample plots distribution in a one of the selected stands

Finally, a stratified random sampling was executed selecting 5 points in each class of GAP abundance, from each stand. A total number of 160 plots (20 per stand, in 8 stands) were established.

Inventory plots were circular with 6-meter radius centered at the randomly selected points. In each plot, a set of variables were gathered in regard to five main aspects: (1) plot location and general characterization, (2) attributes of the main tree layer, (3) attributes of the tree recruitment (saplings and seedlings), (4) attributes of the shrub layer, and (5) attributes related to deadwood (data not presented here). Regarding the plot location and general characterization, GPS coordinates, slope, aspect, micro-relief (convex, concave or flat) and presence of stones on the forest floor were collected. The main tree canopy was characterized by identifying the species and measuring the diameter at breast height (*dbh*) of all the trees with *dbh* higher than 7.5 cm. The tree recruitment was assessed by counting the number of saplings (regeneration taller than 1.3 meters) classified by species and height class (class I: from 1.3 to 2 m; II: 2 to 3 m; III: more than 3 m), and the number of seedlings of each species (regeneration shorter than 1.3 meters). The species composing the shrub layer were identified and classified by abundance class (L: very few individuals, M: quite abundant, and H: very abundant). The total cover of high-shrubs (in %) and the abundance of herbs, low shrubs and moss (low, medium or high) were also collected.

2.4. Field data processing

Data gathered in the field were processed, and the following groups of variables were generated for the subsequent analysis: a first group of response variables related to broadleaves recruitment and three groups of explanatory variables related to canopy attributes, stand structure (tree and shrub layers), and environmental/physiographic factors (Table 2).

Table 2: Descriptive statistics of the variables included in the models structured by groups indicating type and descriptive statistics.

Variables	No. of Observation	Min.	Max.	Mean	Std. Dev.
Response variables					
No. of marcescent oak seedlings	160	0	170	37.66	33.67
No. of sclerophyllous oak seedlings	160	0	141	18.51	20.520
No. of total broadleaf seedlings	160	0	319	60.19	45.493
No. of total broadleaf saplings	160	0	56	6.32	7.949
Explanatory variables (Stand structure)					
Basal area (m^2/ha)	160	5.8	75.8	37.407	14.036
Number of stumps	160	0	796	102.23	156.654
Gap fraction (%)	160	0.01	0.72	0.213	0.131
High shrub cover (%)	160	1	95	48.29	24.836
Mean gap size (m^2)	160	0.03	1.46	0.214	0.198
Mean gap shape index	160	1.62	2.88	2.246	0.229
Regularity	160	0.302	0.980	0.497	0.128
Maturity	160	0	0.99	0.229	0.263
Explanatory variables (Physiographic)					
Northness	160	-.27	0.36	0.1237	0.101

The variable "NUMBER Of STUMPS" was converted in a dummy variable called “SELECTON CUTTINGS” for its use in the models, taking the value “0” when no stumps were counted, and “1” when some stumps were counted. It was used as an indicator of recent management, always in the form of SELECTION CUTTINGS (i.e. but not very recent since stands with clear signs of recent interventions were rejected in the stand selection process). The variable NORTHNESS was calculated by the product of the slope and the cosine of aspect, where aspect in degrees and slope in percentage were taken into consideration (Holden *et al.*, 2009). The REGULARITY of the stand was calculated by using “simpson index” over the distribution of basal area into three diameter classes; fine wood (*dbh* from 7,5 to 17,5 cm), medium wood (*dbh* from 17,5 to 27,5 cm) and thick wood (*dbh* higher than 27,5 cm). The MATURITY of the stand was calculated from the ratio of total basal area corresponding to thick wood.

2.5. Data analysis

2.5.1. Remote sensing based canopy cover analysis.

The development of object based image analysis (rule set) involved two main stages: segmentation and classification. Both stages used the DVM layer from LiDAR and the 4 multispectral bands as Image layers. The same rule set was developed for all the stands (see appendix 1 for detailed description). Image objects were extracted from the image in the segmentation procedure prior to classification. This is considered as the first basic step in the eCognition workflow, since it creates image objects from “similar” pixels. The idea behind this fractal net evolution algorithm is the minimization of the weighted heterogeneity of image objects. In each step, adjacent objects that define the smallest growth in heterogeneity are merged, but only if the heterogeneity growth is simultaneously applied across the whole image to obtain objects comparable size and quality (Baatz *et al.*, 2002). The parameter setting for the segmentation was determined in a bottom-up approach. The scale parameter defining the size of the image objects was increased iteratively, keeping the parameters color; shape, smoothness and compactness at the desired values. After segmentation, classification class's keys are laid under the assignment of all objects to "Canopy", "Gap" or "OF" (Open forest) depending on the image object's values for the different image layers and other variables calculated from them (see appendix 1). One of the variables created was the greenness index, which was calculated by following the equation provided by Liang-Chien Chen (2005):

$$Greenness = (G-R) / (G+R) \qquad (1)$$

Where, G is the value of the green layer and R is the value of red layer from RGB. It was used in order to intend to classify canopy. Classification strategy was based on working with image layers and calculated variables in successive steps in order to differentiate among the three classes of interest (see appendix 1). The total area of each stand was finally classified into "Canopy", "Gap" or "Open forest" (Figure 3).

Once the classification was finished, the result was exported to ArcGIS v10 (ESRI, 2011) and the Patch Analysis extension (Rempel, 2012) was used to calculate some canopy attributes around the inventory plots. These variables were calculated by using an area of influence around the plot that consisted in a buffer of 18 meter (i.e. equal to the mean dominant height for black pine in the selected stands). In this 18-meter radius circle centered in the inventory plot, the following variables were calculated: GAP FRACTION (%), the percentage of the area covered by gaps; MEAN GAP SIZE (in areas), the mean size of the gaps within the circle; and MEAN GAP SHAPE INDEX, describing the irregularity of the gaps within the area of influence around the plot, ranging from 1 when all gaps are circular to higher values when they are more irregular). Finally, the validity of the object-based image classification was evaluated by comparing the canopy class assigned in the automatic classification (i.e. "gap" or "canopy", without considering "open forest" due to be of minor importance for the study) against manual classification obtained by visually interpreting the canopy class in a set of 90 randomly distributed sampling points (60 which had been automatically classified as "gap", and 30 as "canopy"). A confusion matrix was generated to estimate the accuracy of the remote sensing-based assignations with respect to the visual ones.

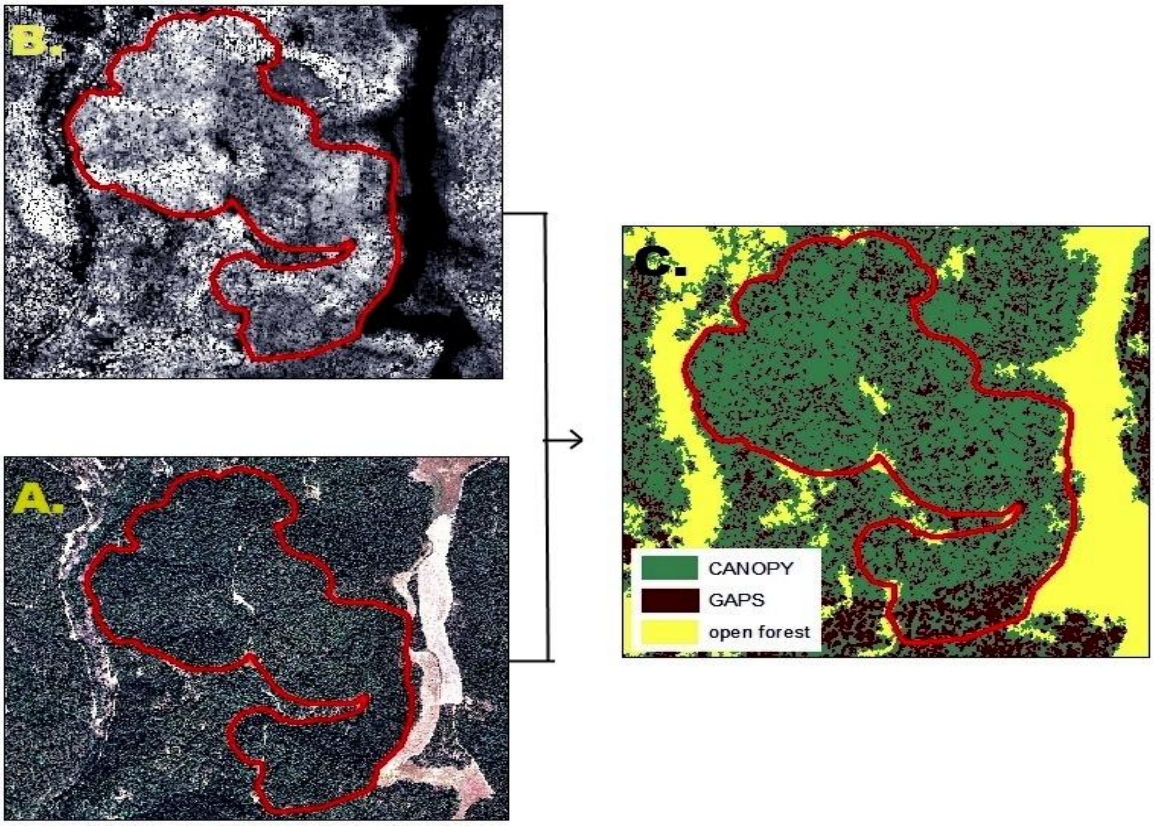

Figure 3: Example of remote sensing based canopy cover analysis in one of the stands: A) Ortho-photo (4 bands), B) Digital vegetation model from LiDAR and C) output of object oriented semi automatic image classification indicating gaps, canopy cover and open forest area.

2.5.2 Regeneration pattern analysis

The analysis of the effect of stand characteristics on plant regeneration was done at plot level (n=160). In the first stage, the complete set of candidate explanatory variables about stand canopy attributes, stand structure (tree and shrub layers), and environmental/physiographic factors were related to regeneration variables using the Pearson correlation coefficient and other exploratory analysis such as scatter plots, in order to detect and select those apparently more correlated with regeneration variables. Later, the explanatory variables selected in the first step were examined with the aim of detecting and avoiding much correlated variables which could cause co-linearity problems in the subsequent models.

Given that regeneration frequency data had frequent ‘zero’ counts and also a few very high counts, we assume a negative binomial distribution, and to be related with explanatory variables by using a log link function (Berrill, 2014). Generalized linear mixed effects models (GLMM) were then developed to explain the relationships between frequency of regeneration, the dependent variable, and explanatory variables (Table 2). The sample plot was nested within selected stands to specify the stand’s random effect in the mixed effect model. Two models were fitted to frequency data depending on the size of broadleaf species: seedlings (h<1.3 m) and saplings (h>1.3 m and dbh<7.5 cm). In the case of seedlings, individual models were fitted for the two main groups of species: the evergreen sclerophyllous holm oak (*Quercus ilex*) on the one hand, and the group of marcescent sub-Mediterranean oaks (*Quercus humilis, Querculs fagina and Quercus cerrioides)* on the other hand. Selection of variables for inclusion in the final model was based on Akaike’s Information Criterion (AIC) (Akaike, 1998). Models producing the lowest AIC values for each response variable were selected. The full model included quadratic terms for BASAL AREA and MEAN GAP SIZE and interaction among the explanatory variables. We used best GLMM to generate average (predicted) values of regeneration modulators for a range of stands.

3. Results

3.1 Canopy cover analysis

No differences were found between stands in GAP FRACTION, MEAN GAP SIZE and MEAN GAP SHAPE INDEX (Kruskal-Wallis test, p-value > 0.05). The GAP FRACTION ranged from 13% to 19% in the set of stands. Regarding to the analysis of gap shape, the mean values obtained reflected that gaps in these pine forests are quite irregular in average (mean values above 1). Finally, the number of gaps per hectare ranged from 53 to 108 in the studied stands, with an average of 79.

Table 3: Summary of the main attributes of the canopy cover in the selected stands.

Stand	Area (*ha*)	Gap fraction (%)	Mean gap size (m^2)	SD gap size	Mean gap shape index	Number of gaps/ha
ST-2	10.193	0.143	18.019	26.298	2.324	80
ST-3	9.7320	0.144	19.110	28.409	2.407	75
ST-4	20.551	0.163	19.676	35.348	2.389	83
ST-6	10.434	0.162	14.979	30.076	2.217	108
ST-7	13.528	0.165	19.483	32.547	2.397	85
ST-8	38.018	0.130	23.804	44.762	2.372	53
ST-9	13.975	0.190	28.191	60.808	2.362	68
ST-12	13.919	0.152	18.621	33.019	2.306	82
Average		**0.156**	**20.235**		**2.347**	**79**

The object oriented semi automatic image classification accuracy assessment indicated an overall percentage of correctly classified plots of 93%. The accuracy of the classification was almost perfect for "gap" class, with a 97% of success. It was slightly worse for "canopy" class, which gave an accuracy of 87% (Table 4).

Table 4: Confusion matrix constructed for accuracy assessment of the object oriented semi automatic image classification of the canopy cover

		Manual visual classification			
		Gap	Canopy	Total	Classification accuracy
Automatic object-based image classification	Gap	**58**	2	60	**97%**
	Canopy	4	**26**	30	**87%**
	Total	62	28	90	(58+26)/90 = **93%**

3.2. Broadleaves regeneration pattern analysis

The final models developed for explaining broadleaf seedling recruitment highlighted SELECTION CUTTINGS, BASAL AREA, MEAN GAP SIZE, HIGH SHRUB PERCENTAGE and the interaction between the latter two variables as the main driving factors for seedling recruitment when considering all broadleaved species together (i.e. the sum of seedlings of holm oak, marcescent oaks and the rest of broadleaved tree species) (Table 6). In the case of BASAL AREA, a quadratic effect was found. The same variables were found as drivers of the recruitment of marcescent oaks (when considered separately from the other species), with the only exception of the variable reflecting the occurrence of selection cuttings, which didn't appeared as significant in this case.

Table 5: Coefficients for generalized linear mixed-effects negative binomial log-link models of total broadleaf seedlings, marcescent oak seedlings, holm oak seedlings and total broadleaf saplings. Log-link models give expected values for natural logarithm of mean count per plot assuming negative binomial distribution.

	Total broadleaf seedlings	**marcescent oaks seedlings**	**holm oak seedlings**	**Total broadleaf saplings**
Random effect (stand)	0.127	0.218	0.459	0.395
Fixed effect				
Intercept	0.768	-0.981	-2.493	1.942**
Presence of stumps	-0.161**	–	–	-0.37**
Basal area	-0.099**	-0.106**	-0.126**	–
$(\text{Basal area})^{0.5}$	1.277**	1.419**	1.66**	–
Mean gap size	-9.596**	-10.554**	1.537	–
$(\text{Mean gap size})^2$	–	–	-2.627**	–
Mean gap shape index	-0.033	0.1	–	–
Northness	–	–	-2.49*	-2.319**
High shrub	-0.009*	-0.006	–	–
Gap fraction	–	–	–	2.708*
$(\text{Gap fraction})^2$	–	–	–	-5.279*
Mean gap shape index x Mean gap size	0.032**	3.37**	–	–
High shrub x Mean gap size	0.037*	0.046**	–	–
Northness x $(\text{Mean gap size})^2$	–	–	7.076*	–
AIC	**333.657**	**377.116**	**454.897**	**433.764**

Note: **=Highly significant (p<0.001) and *=Significant (p<0.05).

On the other hand, holm oak seedling recruitment was mainly affected by BASAL AREA (with a quadratic effect), MEAN GAP SIZE (also showing a quadratic effect), NORTHNESS and the interaction between NORTHNESS and MEAN GAP SIZE. In contrast, BASAL AREA and MEAN GAP SIZE were not found to affect the presence of saplings of the different broadleaved species. At this stage, sapling occurrence appeared to be related with NORTHNESS, SELECTION CUTTINGS and GAP FRACTION, this last one showing a quadratic effect (Table 6).

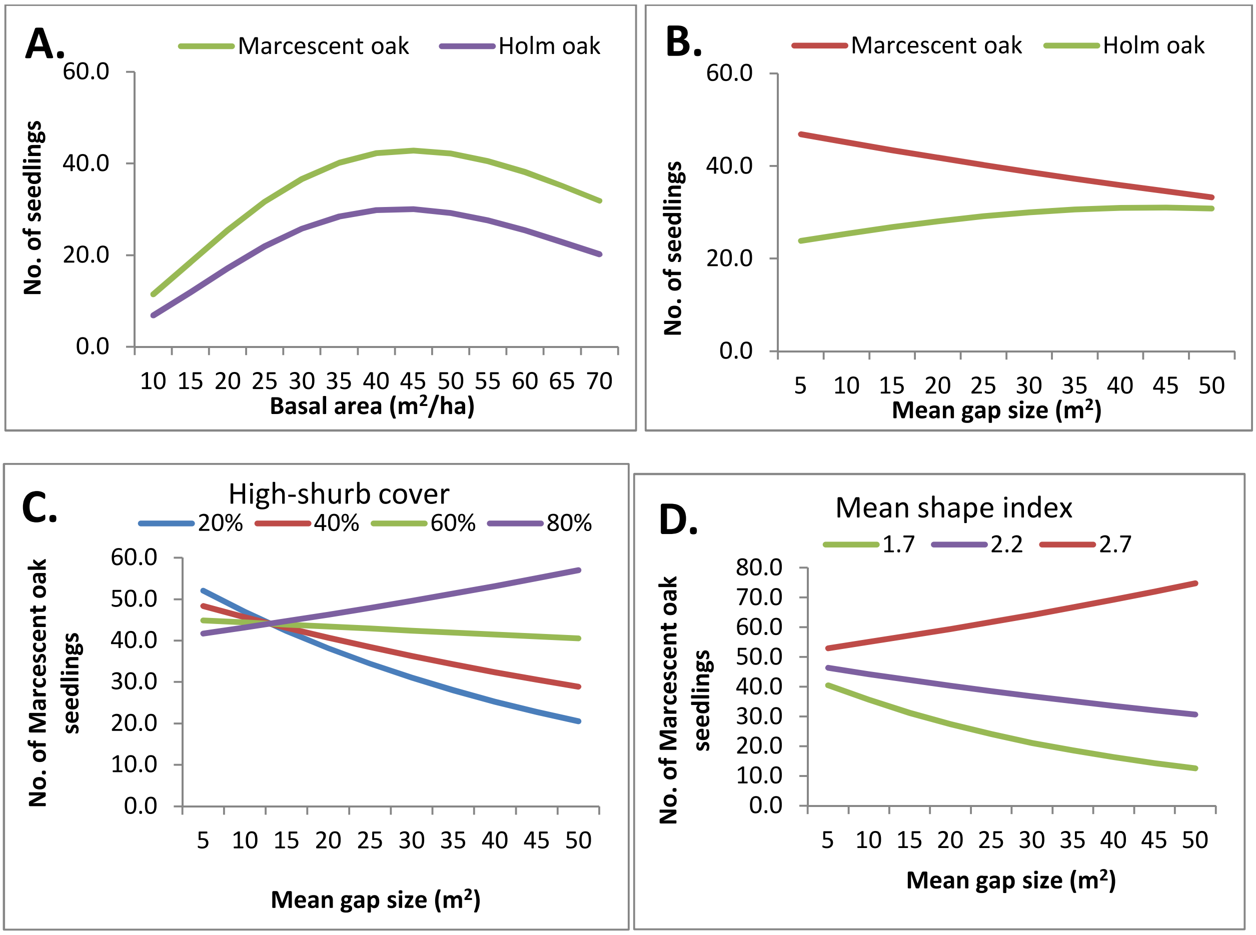

Figure 4: Expected seedling frequency of marcescent oaks and holm oak depending on different factors: A) depending on basal area (m2//ha), B) depending on mean gap size (m2), C) depending on mean gap size (m2) interacting with high shrub cover and D) depending on mean gap size interacting with mean gap shape index

Both marcescent and holm oak seedling recruitment are facilitated by higher values of BASAL AREA, up to a point in which the effect of BASAL AREA turns to negative when it becomes too high. This turning point appears in lower values of BASAL AREA for holm oak in relation to marcescent oaks (Figure 4).

Regarding the effect of MEAN GAP SIZE in seedling recruitment, our models showed important differences between holm oak and marcescent oaks. While holm oak seedlings are positively affected by the presence of larger gaps, the marcescent oaks are negatively affected by this factor (Figure 4). However, this negative effect turns weaker or even turns to positive when the HIGH-SHRUB COVER is high. Interestingly, gap shape plays a similar role than shrub cover in which regards to presence of marcescent oaks seedlings: the more irregular the shape of the gap, the weaker negative effect of MEAN GAP SIZE, which turns even to positive when very irregular gaps (Figure 4).

At later growth stages, our models showed broadleaf sapling abundances to be highly influenced by the GAP FRACTION (with a quadratic effect) jointly with SELECTION CUTTINGS. Moreover, NORTHNESS also showed a negative effect on the presence of saplings of broadleaves under the pine canopy (Figure 5).

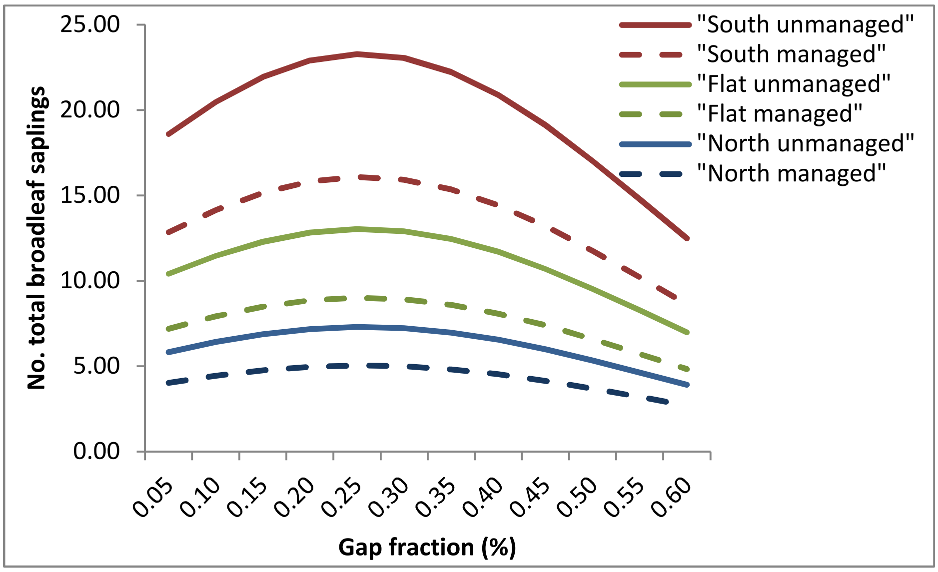

Figure 5: Expected sapling number based on gap fraction, northness and past management

4. Discussion

4.1. Canopy cover classification from remote sensing data

In this study we carried out an analysis of canopy cover attributes in the context of dense black pine-dominated forests in the Catalan pre-Pyrenees. We used for this object oriented semi-automatic image analysis with data coming from LiDAR and multispectral aerial imagery. The results obtained from the object-oriented analysis carried out with eCognition software revealed the utility of such dataset to provide an adequate classification of canopy cover in a spatially continuous way, based on the differentiation of continuous canopy, gaps and open-forest areas. The assessment realized in order to evaluate the success of the automatic classification for the classes of interest (i.e. 'gap' and 'canopy') showed very high accuracy levels. The evaluation was made comparing visual assignations with remote sensing-based ones. Although this method has been widely used in the literature (Hay *et al.*, 2005; Pascual *et al.*, 2008; Machala, 2014), it assumes that manual visual classification is more accurate than automatic classification made from layer values which could not always be the case.

The remote sensing-based classification process, used automated image segmentation for identifying homogeneous canopy objects followed by a set of classification rules (e.g.,Diedershagen, 2004). In this process, good results were achieved with the use of the variable 'Greenness' to discern tree canopy from the other layers (Liang-Chien Chen, 2005). The combination of multispectral bands with height information from LiDAR-derived DVM did also provided adequate identification of gaps and its delineation.

The study focused on the role of small-gaps (i.e. presenting an extent lower than 500 m^2) on the diversification of pine stands. Because of this, large openings caused by anthropogenic causes or rock outcrops were excluded for stand delineation and subsequent field inventory and analysis. This may explain the low values of GAP FRACTION and MEAN GAP SIZE we obtained in comparison to other studies carried out at larger scales and considering gaps of all sizes (e. g.,Worrall & Harrington, 1988; Vepakomma *et al.*, 2008). Some similarities regarding to these variables are nevertheless found between our study and other works analyzing gap dynamics in temperate forests when the effect of large gaps is minimized (see for example de Romer *et al.* (2007) or Garbarino *et al.* (2012)). On the other hand, we obtained gap abundance values (number of gaps per hectare) notably higher than the ones found in other studies conducted in similar systems (e.g., Battles *et al.*, 1995). This could be explained in part by the finer detection of small gaps achieved with our semi-automatic image classification compared with other field-based methods. In addition, the obtained high gap abundances are probably reflecting the consequences of the long history of traditional human interventions in the area, which used to maintain these black pine stands in a fairly open state.

4.2. Factors driving broadleaved seedling recruitment under pine canopy

Three main groups of factors were found to affect broadleaved seedling recruitment in the context of the black pine dominated forests: environmental/physiographic attributes, stand structural attributes and canopy attributes. Other variables not considered in this study such as the abundance of seed sources and to the distance from them are also of critical importance for defining oak seedling recruitment (Zamora *et al.*, 2010; González-Moreno *et al.*, 2011). However, the mechanisms behind these relationships are very complex and could not be assessed by simple species abundance assessments (Sheffer *et al.*, 2013). Given that no significant differences were found in the main canopy attributes among the eight selected stands, we assumed that our plots presented comparable abundance and distribution of seed sources.

We found canopy and stand structural attributes to be the most important factors determining broadleaf recruitment in pine stands. As stated above, our sampling was conducted in relatively homogenous environmental conditions as showed by the non-significance of the STAND factor in our models. In consequence the role of some potentially important recruitment drivers such as climate could not be properly tested. However, we found NORTHNESS (calculated as a combination of aspect and slope) to negatively affect holm oak recruitment in the smaller gaps. Although holm oak is considered an intermediate shade tolerant species (Valladares & Niinemets, 2008), the results of our study showed that in such marked northern slopes, openings of a certain size are needed to allow its recruits to survive. (see Figure 4). In contrast, this effect was not encountered for marcescent oaks and for the rest of broadleaved recruitment, suggesting the higher shade tolerance character of these species compared to holm oak (Ruiz de la Torre, 2006; Sevilla, 2008).

Regarding structural attributes, our results highlighted BASAL AREA and HIGH-SHRUB COVER as important factors driving broadleaved seedling recruitment. No significant effects of other attributes describing structural irregularity, stand maturity, or herbaceous cover were observed, in contrast to what has been reported in other studies (e.g., Prévosto *et al.*, 2011). Again, this could be due to the relative narrow range of variability of these structural variables presented in our study plots, since the selected stands presented rather similar histories of human use and natural disturbance dynamics.

In open canopy conditions, shrub cover has been found to be positively related with oak species recruitment. This has been attributed to facilitation mechanisms (shading, protection, etc.) (Rousset & Lepart, 1999; Smit *et al.*, 2008). Our models support this hypothesis for total broadleaved seedlings recruitment and for marcescent oaks. In both cases, a weak negative effect of shrub cover was found when plants grew under closed canopy. However, this effect turns to very positive with increasing mean gap size (Figure 4). Our results about the effect of basal area on broadleaved seedling recruitment matched with the positive effect of stand density showed in the context of *Pinus halepensis* and *Pinus sylvestris* forests (Lookingbill & Zavala, 2000; Galiano *et al.*, 2013). However, few studies have reported the quadratic effect of this attribute (Lookingbill & Zavala, 2000), suggesting that excessive stand density hampers broadleaved recruitment under pine canopy. The detailed canopy cover analysis that was carried out in our study allowed the detection of interesting fine-scale effects of canopy attributes and, in particular, gap characteristics on tree recruitment. Thus, a negative effect of gap size was found in the models of marcescent oaks and total broadleaved seedlings suggesting the high sensitivity of the recruits of these species to light exposure (and associated high evaporative demand). In contrast, holm oak seedlings resulted positively affected by the size of gaps, at least for the range of sizes monitored in our study. However, when developing under larger gaps, lower survival values might be expected (e.g., Marañón *et al.*, 2004; Prévosto *et al.*, 2011; Garcia-Barreda & Reyna, 2013). The results of this study suggest that holm oak recruitment might be favored in our study area by the application of selection cuttings, which would maintain medium to high stand density with presence of small gaps in the canopy. However, this type of intervention would not be so favorable for marcescent and deciduous broadleaves recruitment, which would prefer continuous cover conditions. In addition, the study revealed the importance of taking into account the shape of canopy openings when analyzing its effects on recruitment dynamics (Figure 4.D). Within this regard, the presence of irregular gaps, creating mid-shading conditions, would turn the general negative effect of canopy gaps on marcescent and deciduous broadleaves recruitment into a positive one.

4.3. Factors explaining broadleaf sapling occurrence under pine canopy

In contrast to what has been observed for seedling recruitment, no variables associated to stand structural factors (neither stand basal area, irregularity or maturity, nor shrub or herbaceous covers) showed significant effects on sapling abundance, what means that they didn't play a major role on driving survival and growth of well established seeding. However, beyond those structural factors the gap fraction percentage (inverse if tree canopy cover) emerged as a determinant factor, showing an interesting quadratic effect (Figure 5). This finding agrees with other recent studies that have already highlighted the higher abundance and better development of broadleaved saplings in low-density pine stands (Gomez-Aparicio *et al.*, 2009; Prévosto *et al.*, 2011). Our results did also reveal that canopy openness is more determinant for sapling growth and survival basal area. This was in the line of the findings of Retana *et al.* (1999) and Garcia-Barreda and Reyna (2013), who reported rapid shoot growth of oak seedlings when the overstorey is disturbed. According to this results, broadleaved seedling growth into sapling stage under black pine canopy could be promoted by the application of low-intensity selection cuttings or thinning treatments aimed at reducing tree canopy cover more than density (i.e. thinning from above would be more effective than thinning from below). Although we found the presence of stumps (i.e. the variable reflecting historic management) to be negative related with saplings abundance (which *a priori* seems to contradict to recommendations stated above), we could determine during the selection process of the stands (conducted before the field inventories) that in all cases these interventions have occurred more than twenty years ago. At that time, interventions used to be fairly intense, and thus they could have hampered broadleaves recruitment (Garcia-Barreda & Reyna, 2013) and therefore their growth into sapling over the ensuing decades. Finally, the strong negative effect of NORTHNESS on sapling abundance could be explained again by light deficit in north-facing slopes, As stated by Retana *et al.* (1999), Dillaway *et al.* (2007) or (Johnson, 2009), light deficit is one of the main factors limiting oak seedling growth into saplings. Under such conditions, recruits use to dieback and resprout several times before their death unless light conditions become more favorable.

5. Conclusion

The use of object oriented semiautomatic image analysis combining LiDAR with multispectral aerial photographs was found to be appropriate for characterizing forest canopy attributes at stand scale. In the particular case of dense black pine forest, such canopy attributes combined with structural attributes were shown to play a key role in the recruitment of broadleaves species and in the associated diversification of the stands. The relationship between the mentioned attributes on broadleaves recruitment was species-specific and may depend basically of the balance between species shade- and drought-tolerance. In general, both sclerophyllous and marcescent oaks were facilitated by the canopy layer, although the latter expressed more shade tolerance than the former. Facilitation effects of the shrub cover on seedling survival were also found when plants develop under high light exposures (at the larger gaps). Once established, plants seem to require high light conditions to reach sapling stages as shown by the positive relationship with gap fraction percentage and the marked negative influence of northness on their abundance. Overall the results of this study allow shedding some light on the role of different environmental and structural factors on the success of broadleaves recruitment under black pine dominated stands. This knowledge could be used as a basis for the establishment of silvicultural treatments oriented to the progressive diversification of such stands and to the enhancement of its resilience face to natural disturbances. Further research could be directed towards applying these kind of silvicultural treatments and examining their effects on broadleaves recruitment and development.

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Apendix 1: Explanation of the rule set developed with eCognition for the automatic classification of the forest canopy

Workflow	Description of action; in/output	Parameter setting/variables
ECOGNITION IMAGE PROCESSING		
Step 1	**Smoothing LiDAR (DVM) data**	
Method	Convolution filter	Type: Gauss Blur; Kernel size-3 with single slices
Outcome	Making the resolution of DVM layer closer to the resolution of the other layers	
Step 2	**Image segmentation**	
Method	Multiresolution segmentation	Image layer weights (Smoothed DVM: 2, Green:2 and Infra-red: 3), Color/shape 0.1; Compactness 0.5
Outcome	Image objects with minimized heterogeneity for a given resolution.	
Step 3	**Canopy identification**	
Method	1. Assign class based on its own height and the height of taller neighbors	Assign CANOPY when: Mean difference to nearest brightest neighbor ≤ 1.6 meter & mean smooth DVM ≥4.
	2. Assign class based on the calculated greenness of image objects	Assign CANOPY when: Greennees ≥ 0.1 & min. value of smooth DMV ≥ 5 meter.
	3. Assign class based on height values in the image object	Assign CANOPY when: Minimum pixel value of smooth DVM > 7
	4. Classification based on mean height in the image object.	Assign CANOPY when: Mean DVM smooth ≥ 10
	5. Classification based on object greenness and its height difference with CANOPY neighbors.	Assign CANOPY when: Greenness ≥ 0 & difference in mean value of smooth DVM with CANOPY neighbors > -1.
	6. Merge all image objects classified as canopy in the previous steps.	Merge region when: image objects classified as CANOPY
	7. Unclassify small canopy patches	Assign UNCLASSIFIED when: CANOPY with area < 10000 m^2.
Outcome	Identify and classify canopy cover of dense and continuous pine forest.	
Step 4	**Gap identification.**	
Method	1. Merge region of interest (Area not covered by dense pine forest)	Merge region when: image objects not classified as CANOPY
	2. Identification of canopy gaps	Assign GAP when: unclassified image object with area ≤ 500 m^2.
Outcome	Identify and classify canopy gaps	
Step 5	**Identification of open forest areas**	
Method	Classify all the unclassified area as open forest	Assign OPEN FOREST when: image objects not classified as CANOPY or GAP
	Identify and classify open areas, unsuitable for	

	later analysis.	
Outcome		
Step 6	**Export classification to GIS**	
Method	Export vector layer with CANOPY/GAP/OPEN FOREST classification	Export vector layer to SHP with attributes: Area and assigned class
	Final map	
Outcome		
ARCGIS/PATCH ANALYSIS PROCESSING		
Step 1	**Extract canopy attributes at the inventory plot level**	
Method	1. Clip the classification SHP file by using a buffer of 18 meter radius (equal to mean dominant height) from the plots center 2. Analysis of the canopy attributes around each plot, by using Patch Analyst extension.	
Outcome	Creation of the following variables at the plot level: GAPper (percentage of the area covered by gaps), MGS (Mean size of the gaps around the plots), MGSI (Mean gap shape index, ranging from 1 (circular) to higher values (more irregular)).	