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Shrub fuel characteristics estimated from overstory variables in NW Spain pine stands

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ABSTRACT

Understanding the relationships between forest overstory and the understory shrub layer is important for predicting biomass changes in response to forest management. The shrub fuel stratum is a critical fire hazard in the Mediterranean region, hence managing the canopy cover to control the understory could be an option for managing fire hazard. In this study we determined the relationship between overstory and understory shrub variables for *Pinus pinaster* Ait., *Pinus radiata* D. Don and *Pinus sylvestris* L. in a large geographical area (NW Spain) using data from the Spanish National Forest Inventory. CHAID and quantile regression procedures were used for obtaining mean and maximum response models, respectively, of shrub characteristics (cover, height and fine fuel load). Overstory variables, especially stand basal area, explained the variation in the mean response of shrub variables. According to maximum response models, maximum shrub development was also limited by overstory variables in *P. pinaster* and *P. radiata* stands. This does not apply to *P. sylvestris*, suggesting that altitude or other non-measured environmental factors are more active limiting constraints for shrub development in stands of this species. Simulation of surface fire behaviour and crown fire initiation was exemplified from *P. pinaster* data, using quantile regression models as inputs. Fire behaviour outputs revealed that the control of understory shrubs through high overstory basal area can decrease surface fire intensity. Nonetheless, the effect of overstory basal area on crown fire initiation is negligible, and is unlikely to increase fire suppression effectiveness, at least in young stands. Moreover, the potential for crown fire spread and intensity is expected to increase in high-density stands because of the higher canopy bulk density. Forest management can benefit from fire behaviour models, namely in the design of silvicultural treatments targeting crown fire hazard mitigation.

1. Introduction

The existence of interactions between overstory and understory vegetation mediated by relationships among light, water and nutrients is well established (e.g., Messier et al., 1998; Légaré et al., 2001). It has been recognized that understory cover and biomass increase with an increase in incident solar energy, although some other factors such as climate, topography and the previous occurrence of natural disturbances or management practices also influence this relationship (e.g., Gràcia et al., 2007; LaRade and Bork, 2011; Parresol et al., in press).

On the other hand, the understory stratum (which roughly defines the surface fuel complex) is a critical fire hazard in Southern European regions, namely in NW Iberia. In this area, characterized by high vegetation productivity, surface fuel loads are among the highest attained in pine stands in temperate climates (e.g., Fernandes et al., 2009).

One of the main targets of silvicultural practices aimed at protecting forest stands from wildfire is to modify the structure or quantity of surface fuels, in order to decrease fire-inflicted tree injury and to enhance effective fire suppression (Agee and Skinner, 2005; Fernandes and Rigolot, 2007; Graham et al., 2004; Keyes and O'Hara, 2002). Surface fuels in general and shrubs in particular are clearly involved in the initiation of crown fires by increasing fire intensity and serving as the ladder that establishes continuity between the understory and overstory fuel layers.

Surface fire behaviour characteristics, namely spread rate and intensity, depend on wind speed, slope and fuel properties such as moisture, bulk density, loading distribution by size classes, depth, and fuel strata continuity. Understory vegetation cover and height and fine fuel loading are frequently used as inputs for fire behaviour

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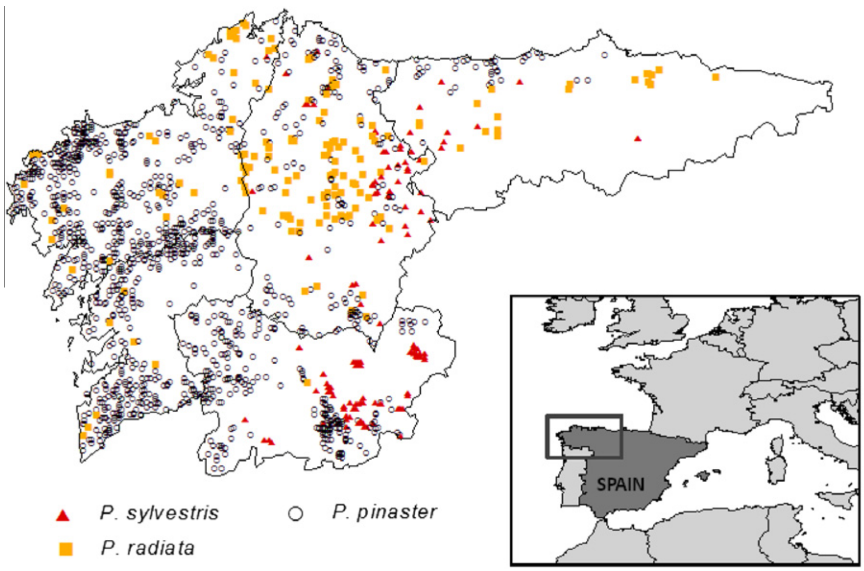

Fig. 1. Spatial distribution of the SNFI plots for *P. pinaster*, *P. radiata* and *P. sylvestris* in the study area.

models, either to calculate fuel-complex descriptors for physically-based models or directly in empirical models (e.g., Fernandes et al., 2009; Gould et al., 2007). These variables can reflect the overall effect of understory structure on fire spread, and have the advantage that their estimation is relatively straightforward.

Several techniques to manage surface fuels are available, singly or in combination, including distinct mechanical treatments with different physical impacts, herbicides, controlled grazing, and prescribed burning (Fernandes and Rigolot, 2007; Graham et al., 2004). Mechanical treatment is currently the most widely used method to control the understory, but it is a rather short-lived solution, especially in resprouting species (Marshall et al., 2008). The most efficient alternative method is prescribed fire, but its current use in NW Spain is restricted to localized areas. However, little effort has been put in analyzing the expected effect of the overstory in controlling understory development, and therefore surface fire behaviour and crown fire initiation. The understanding and modelling of this effect would help forest managers in the objective and effective planning of silvicultural treatments.

The primary objective of this study is to model the forest overstory influence on understory shrub vegetation for the major pine species in NW Spain. Specifically, we analyze and model the effect of forest overstory on: (i) shrub cover, (ii) shrub height, and (iii) available shrub fuel load. Additionally, for *Pinus pinaster* stands we exemplify and discuss the application of the developed models to estimate surface fire behaviour and crown fire initiation and for decision-making in stand-level silvicultural treatments.

2. Material and methods

2.1. Data

Data from the third Spanish National Forest Inventory (SNFI) carried out in Asturias and Galicia regions (NW Spain) (DGCN, 2002, 2003) were used in this study (Fig. 1). Only these regions were selected in order to lessen the variability of the climate conditions and floristic composition of the understory. Both Asturias and Galicia are included in the Eurosiberian phytogeographic region, roughly characterized by two months of dryness (precipitation, mm < 2 × temperature, °C) (Moreno et al., 1990).

The SNFI is a systematic sample of permanent, circular-combined plots distributed on a square grid of 1 km, in which trees are sampled within different radii according to their diameter at breast height. For each plot, species, diameter at breast height (to the nearest 0.1 cm) and total tree height (to the nearest 0.5 m) were recorded in all sampled trees. In addition, the composition of woody shrub layer, the percent cover, and the mean height were also recorded for each species or group of species. Percent cover was visually assessed as the percentage of area occupied by the vertical projection of the whole foliage in a circular plot of 10 m radius, whereas mean height was measured using a pole to nearest 0.1 m.

All plots where *Pinus pinaster*, *Pinus radiata* or *Pinus sylvestris* were dominant (more than 80% of total stand basal area) were selected. Additionally, SNFI plots with explicit signs, as judged by forest surveyors, of recent human activity (harvest residues from thinning, branches from pruning, shrub mastication or extraction, etc.) or fire occurrence were removed from the analysis. Altitude (m) for each selected plot was derived from available *X*, *Y* coordinates and a digital elevation model.

Stand variables available for each plot included: number of trees per hectare (*N*, trees ha^{-1}), stand basal area (*G*, m^2 ha^{-1}), quadratic mean diameter (d_g, cm), average stand diameter (D_m, cm), average stand height (H_m, m), dominant height (H_0, m) and dominant diameter (D_0, cm) (defined as the mean height and mean diameter of the 100 largest diameter trees per hectare, respectively), and relative spacing index (*RSI*, %; defined as [10,000/($H_0 \cdot N^{0.5}$)], i.e., the average spacing divided by dominant height).

Total shrub cover (*SCOV*, %) for each plot was obtained by summing the percent cover of the individual species (or group of species) in the plot, which can exceed 100%. Mean shrub height (*SH*, m) was calculated as the weighted (by cover) average of the species (or group of species) height measurements. Available shrub fuel load (*SWa*) (i.e., the dry weight of fine fuel elements less than 6 mm in diameter) could only be estimated for the plots where overstory and the understory were dominated by *P. pinaster* and by species of the genera *Erica*, *Calluna*, *Ulex* and *Genistella*, respectively (Fernandes et al., 2002), since no prediction models are currently available in NW Spain for other understory communities or other overstory species. These genera were considered dominant whenever the sum of their percent cover was higher than 75% of *SCOV*. In these cases, available shrub fuel load (t ha^{-1}) was

Table 1
Basic description of overstory and shrub variables in the plots of the three pine species.

Over/understory variables	*P. pinaster* (n = 1107)				*P. radiata* (n = 154)				*P. sylvestris* (n = 125)			
	Mean	Max.	Min.	S.D.	Mean	Max.	Min.	S.D.	Mean	Max.	Min.	S.D.
N	689	2864	133	463	850	3652	143	551	1273	3275	222	614
G	26.2	92.7	1.69	13.6	29.5	72.7	6.38	16.2	29.8	59.2	2.38	13.2
d_g	23.8	49.1	8.6	7.0	22.5	48.8	9.7	7.9	17.9	30.3	9.9	4.8
H_0	17.5	34.3	6.6	4.7	18.1	36.3	7.6	5.7	11.6	19.0	6.2	3.8
D_0	34.6	58.2	10.0	8.5	32.5	55.6	13.0	9.8	25.2	39.3	12.0	6.0
H_m	13.4	26.4	5.7	4.1	14.2	27.3	5.9	4.6	9.8	17.4	4.6	3.6
D_m	22.2	48.8	8.6	6.9	21.3	48.2	9.2	7.7	17.4	29.7	9.7	4.7
RSI	26.5	49.9	8.39	9.37	24.0	48.8	7.92	10.3	27.3	49.5	12.3	9.21
$SCOV$	76.6	230	1.00	46.7	70.3	200	3.00	45.2	55.6	140	1.00	39.2
SH	0.86	3.5	0.10	0.50	0.96	3.1	0.12	0.60	0.90	1.9	0.20	0.46
SWa	11.8	39.4	0.168	7.98	–	–	–	–	–	–	–	–

Note: S.D., standard deviation; N, number of trees per hectare; G, stand basal area ($m^2\ ha^{-1}$); d_g, quadratic mean diameter (cm); H_0, dominant height (m); D_0, dominant diameter (cm); H_m, average stand height (m); D_m, average stand diameter (cm); RSI, relative spacing index (%); $SCOV$, total shrub cover (%); SH, mean shrub height (m); SWa, available shrub fuel load ($t\ ha^{-1}$), this variable was estimated only for 732 plots where understory is dominated by species of genera *Erica*, *Calluna*, *Ulex* and *Genistella*.

estimated by the equation $SWa = 0.555 \cdot IV^{0.743}$ (R^2 = 0.94; n = 37), where IV is the product of shrub cover (%) and mean shrub height (m). According to Fernandes et al. (2002), this model is robust for prediction throughout the western Iberian Peninsula when species of the genera *Erica*, *Calluna*, *Ulex* and *Genistella* dominate the understory layer.

The number of plots used and the basic description of the stand and shrub variables are summarized in Table 1. The data set covers the entire duration of stand development for all the species and rotations usually applied in NW Spain.

2.2. Methodology

Mann–Whitney U statistical test was used for determining if the mean plot values of $SCOV$, SH and altitude for the three sample pairs of species are different from each other. This nonparametric test was used because the three dependent variables were not normally distributed. On the other hand, models for estimating both mean and maximum development of the shrub stratum were developed. Mean response models can be adequate for exploratory purposes and for assessing the general trends between overstory and understory variables, whereas maximum response models represent the potential effects of a limiting factor on understory shrub development.

2.2.1. Mean response models

The non-parametric method CHAID (Chi-squared Automatic Interaction Detector) was used to determine the interaction between shrub variables and the available overstory stand variables. CHAID is an algorithm that splits a data set into segments that differ with respect to the response variable (Kass, 1980). The segments are defined by a tree structure of a number of independent variables, the predictors.

The CHAID method is an alternative to CaRT (classification and regression trees) analysis for analyzing prediction-type problems on the basis of a set of categorical or continuous predictor variables. The CHAID uses a different algorithm (than CaRT) to determine a final hierarchical classification tree in which each node can produce multiple branches (unlike CaRT, in which all nodes are binary). The result of the CHAID algorithm is a decision tree structure with a split at each node. The final nodes – called leaves – are defined as combinations of the predictor variables. More details on the CHAID procedure are available in van Diepen and Franses (2006) and Álvarez-Álvarez et al. (2011). The main advantage of using CHAID to analyse our data is that no assumptions on data distribution are needed (van Diepen and Franses, 2006).

In the present study, SPSS software (SPSS, 2007) was used to carry out the analysis. A significance level of 5% was used in the F-test (used in the splitting process), the maximum number of levels was set as 3, and the minimum number of cases in a node for being a child node was set as 30 plots.

In the analysis, potential predictor variables were all those mentioned above (which are usually used by foresters for describing a stand), whereas the resulting response variables were shrub cover, shrub height and shrub fine fuel load.

2.2.2. Maximum response models

The relationship between forest overstory and understory can be viewed as a limiting factor case, where changes in biological response variables (e.g., Y = shrub characteristics) does not exceed limits imposed by some limited factors that are measured (e.g., X = overstory stand variables), but can be reduced by other limited factors that are unknown or were not measured.

For selecting the overstory stand variables that constrain shrub development, the predictor variables corresponding to the first branch level of the CHAID regression trees were used. Only first-split level variables where considered because they are expected to be the most significant for explaining general tendencies in the response variable.

Historically, several regression methods have been used to deal with this type of data distribution (Zhang et al., 2005). However, as Thomson et al. (1996) pointed out, commonly used standard statistical methods such as correlation and regression are inappropriate for estimating or testing limiting relationships in ecology. Alternatively, Scharf et al. (1998) and Cade et al. (1999), applied quantile regression to model limiting relations and account for the unmeasured ecological factors by estimating changes near the upper extremes of data distributions. Basically, the τth quantile ($0 \leqslant \tau \leqslant 1$) of a random variable Y, is the inverse of the cumulative distribution function $F^{-1}(\tau)$, which is defined as the smallest real value Y such that the probability of obtaining smaller values of Y is greater than or equal to τ. Mathematical details on regression quantiles are available in Cade et al. (1999) or Koenker (2005).

The main advantages of quantile regression are (Zhang et al., 2005): (i) robustness to distribution assumptions; (ii) equivalency to monotonic transformation; (iii) the random error ε can change as a function of the limited factor, accommodating both homogeneous and heteroscedastic error models; and (iv) the estimates are insensitive to extreme values of outlying dependent variables. However, there are several concerns about quantile regression: (i) the statistical inference is very difficult (Zhang et al., 2005); (ii) the variance of quantile regression estimator is

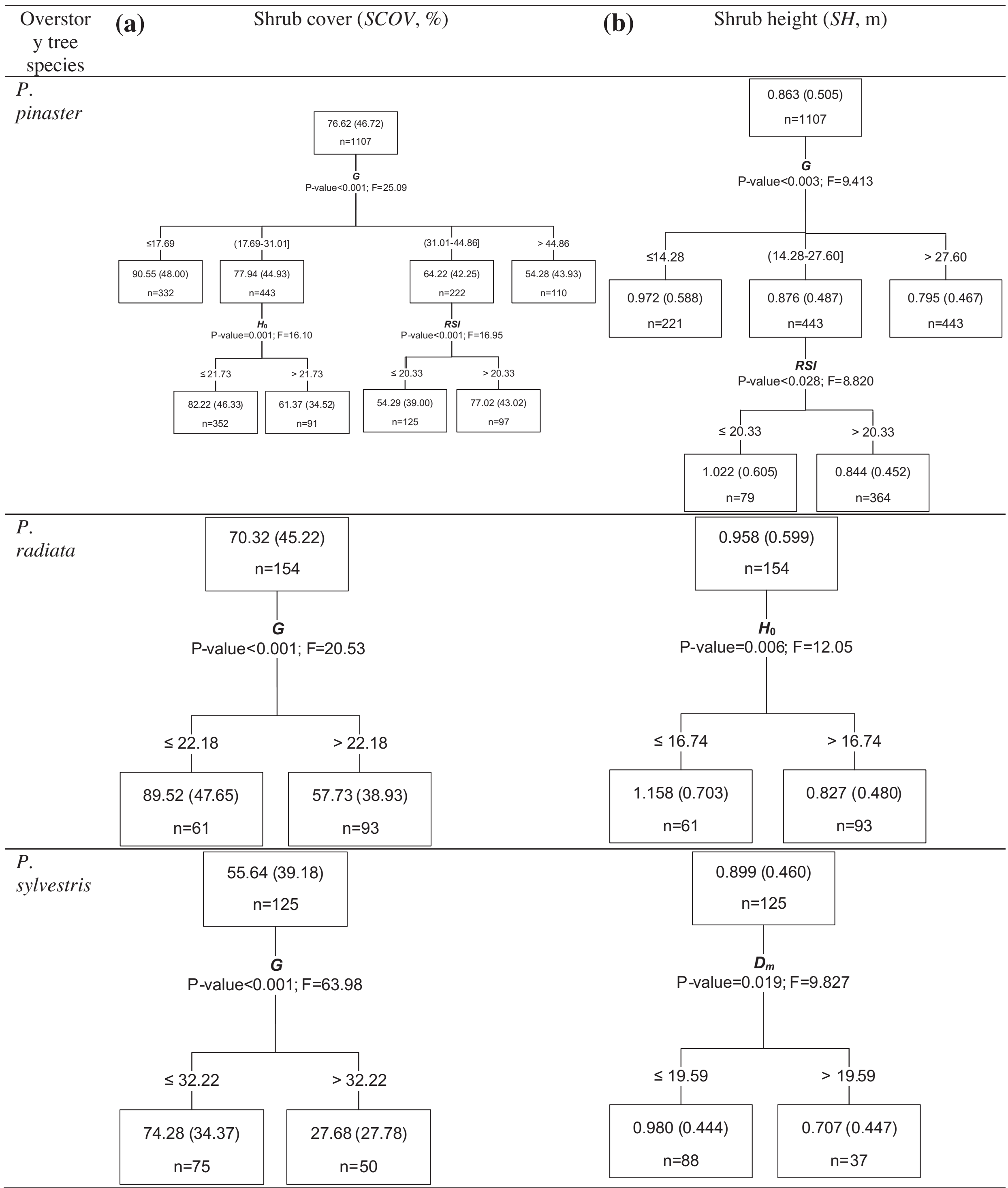

Fig. 2. Regression tree in which the CHAID algorithm is used for estimating shrub cover (a) and shrub height (b). Note: G = stand basal area (m^2 ha^{-1}); H_0 = dominant height (m); RSI = relative spacing index (%); D_m = average stand diameter (cm).

U-shaped with τ changing from zero to one, and therefore the estimated boundary line can be variable even with a very small change in τ. The variability is particularly high when the number of data points under analysis is small (Scharf et al., 1998; Cade and Noon, 2003); and (iii) in heteroscedastic distributions, several quantiles must be evaluated before selecting the most appropriate, and this depends on sample size and distribution of the data (Cade et al., 1999). Appropriate values of τ must allow confidence intervals calculation and have to exclude zero, and must adequately characterize the changes in the quantiles of interest (Cade et al., 1999).

The quantile regression analysis was carried out using the SAS/STAT® PROC QUANTREG procedure (SAS Institute Inc., 2008). The simplex algorithm was used for regression quantile estimates, because the data sets contain less than a few thousand observations (Koenker, 2005, p. 300). The confidence intervals were computed by the rank-score test, which is robust for data that are not independently and identically distributed (Chen, 2005).

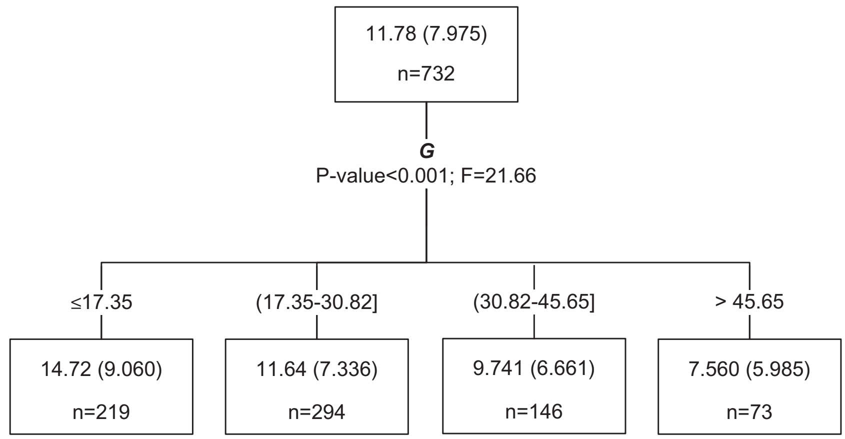

Fig. 3. Regression tree in which the CHAID algorithm is used for estimating shrub fine fuel load (*SWa*, t ha^{-1}) in stands where overstory is dominated by *P. pinaster* and understory is dominated by species of genera *Erica*, *Calluna*, *Ulex* and *Genistella*. Note: Overstory variables defined in Fig. 2.

2.2.3. Model applications to fire behaviour prediction

Stand management against wildfire can benefit from the combined use of the results of quantile regression models and fire behaviour equations. An empirical surface fire behaviour model is available for *P. pinaster* stands (Fernandes et al., 2009). In addition, *P. pinaster* is the only species for which quantile regression models can be developed for *SCOV*, *SH* and *SWa*. Accordingly, applications of the models developed in this study were exemplified only for *P. pinaster*. Applications for the remaining overstory species or different understory vegetation will be possible in the future when equations for estimating fuel load by fuel size class are available.

Two basic fire behaviour variables were estimated: forward rate of spread and fire intensity. The former was calculated from the following empirical equation developed by Fernandes et al. (2009):

$$R_f = 0.773 \cdot U^{0.707} \cdot \exp(0.062 \cdot S - 0.039 \cdot Ms) \cdot FD^{0.188} \quad (R^2 = 0.75;\ n = 90) \tag{1}$$

where R_f = forward rate of spread (m min^{-1}), U = wind speed (km h^{-1}, measured inside the stand at 1.7 m above ground level), S = terrain slope (°); Ms = moisture content of fine dead surface fuel (%), and FD = surface fuel depth (m).

Fire intensity was calculated as per Byram (1959):

$$I_B = R_f \cdot Ws \cdot H \tag{2}$$

where I_B = Byram's fire intensity (kW m^{-1}); R_f = forward rate of spread (m s^{-1}), Ws = amount of fuel consumed in the flaming front (kg m^{-2}), which for summer conditions is assumed to be the surface fine fuel load; H = net heat of combustion or heat yield (kJ kg^{-1}), which was fixed at 18,000 kJ kg^{-1} (Forestry Canada Fire Danger Group, 1992). Although an empirical equation for estimating fire intensity is available in Fernandes et al. (2009), it was not used in order to decrease the uncertainty in the simulation process (in the empirical model, I_B depends on the prediction of flame length), and to make it more compatible with Van Wagner (1977) crown fire initiation model.

Both Eqs. (1) and (2) depend on fuel variables, but some of these cannot be directly estimated from quantile regression models. Fuel depth (*FD*) and surface fine fuel load (*Ws*) are the sums of litter (L-layer) and understory vegetation depths and loads, respectively. Taking into account that SNFI does not provide data on litter, litter fuel load had to be estimated from the following equation developed by Fernandes et al. (2002):

$$Wl = 1.108 \cdot G^{0.473} \cdot (1 - \exp(-0.871 \cdot t) \quad (R^2 = 0.93;\ n = 28) \tag{3}$$

where Wl = litter L-layer fuel load (t ha^{-1}); G = stand basal area (m^2 ha^{-1}); t = stand age (in the absence of fuel treatments) or time since the last prescribed burning (years). For simulation purposes, we assumed steady-state accumulation of litter L-layer fuel (t = 4 years) (Fernandes et al., 2002). It follows that both *Wl* and *Ws* (the sum of *SWa* and *Wl*) depend only on *G*.

As there is no equation available for estimating L-layer depth from stand variables, it was assumed to be equal to 3 cm, corresponding to the average L-layer depth observed in *P. pinaster* stands (Fernandes et al., 2002). Accordingly, *FD* was computed as the sum of shrub height (*SH*) plus 3 cm. The reported L-layer depth range varies from 1.2 to 5.5 cm (Fernandes et al., 2002), representing a small percentage of *SH* height (mean = 86.2 cm). Therefore, this assumption is not expected to significantly affect the results of fire behaviour simulations.

Surface fire behaviour was modelled under two fire weather scenarios, respectively: U = 7 km h^{-1}, S = 10° and Ms = 20% (i.e., mild weather conditions); and for 50% increases in U and S and a 50% decrease in Ms, resulting in a more flammable situation: U = 10.5 km h^{-1}, S = 15° and Ms = 10% (dry weather conditions). The average and minimum *Ms* summer values for Galician maritime pine stands are respectively 20% and 10% (Ruiz-González and Vega, 2001). The values of these input variables were all within the experimental conditions used for developing Fernandes et al. (2009) model; for the same reason, more extreme environmental conditions were not simulated.

Simulation for both median (i.e., 50th regression quantile) and maximum (the quantile selected as the more appropriate for the near-upper extremes of data distributions) response models were compared. The former can be considered an alternative to OLS estimates of conditional means for modelling central tendency (e.g., Cade and Richards, 1996), i.e., it represents the "average" effect of the limited factor on surface fire behaviour, whereas the latter characterizes the potential effects, i.e., the thresholds to which overstory variables constrain fire behaviour.

Additionally, the model of Van Wagner (1977) was used for assessing crown fire initiation for different fuel and environmental conditions. Canopy ignition occurs when the thermal energy supplied from the surface fire attains or exceeds a minimum threshold. The critical fire intensity that will initiate a crown fire in a conifer stand is dependent on foliage moisture content and canopy base height (Van Wagner, 1977):

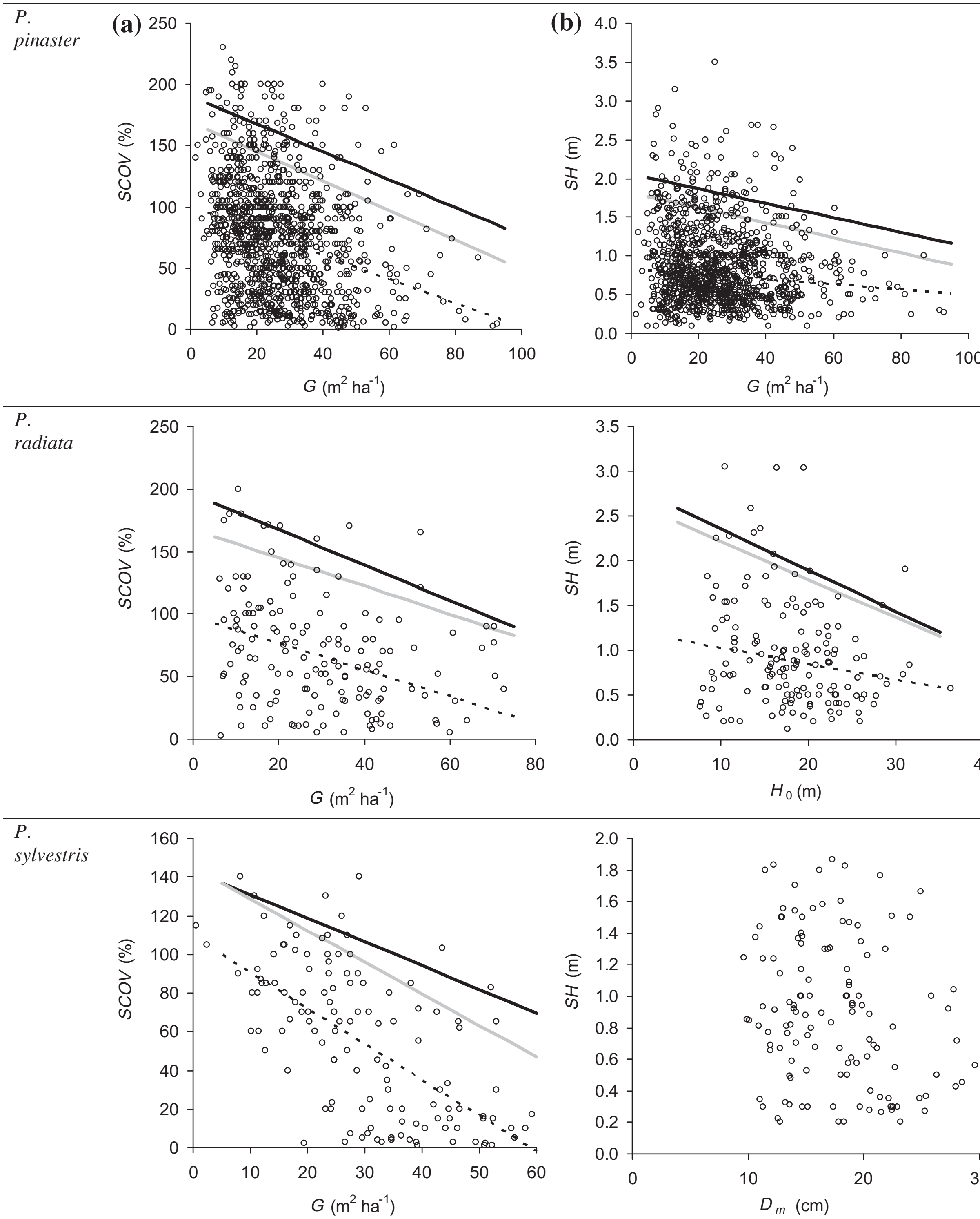

Fig. 4. Distribution of shrub cover (a) and shrub height (b) with respect to overstory variables corresponding to the first branch level of the CHAID regression trees. Black solid line, grey solid line and black dashed line correspond to the 95th, 90th and 50th regression quantile estimates, respectively. Note: Overstory variables defined in Fig. 2.

$$I_0 = [0.01 \cdot CBH(460 + 25.9 \cdot FMC)]^{1.5} \quad (4)$$

where I_0 is the critical Byram's fire intensity (kW m^{-1}), *CBH* is the canopy base height (m) and *FMC* is the foliage moisture content (%).

CBH, in turn, depends on stand variables (e.g., Cruz et al., 2003; Ruiz-González and Álvarez-González, 2011). For *P. pinaster* stands in NW Spain, *G* and H_m explained more than 80% of *CBH* variability (Gómez-Vázquez et al., submitted) using the following model:

$$CBH = 0.126 \cdot G^{0.111} \cdot H_{\mathrm{m}}^{1.42} \quad (R^2 = 0.84; n = 82\,plots) \quad (5)$$

where *CBH* = canopy base height (m); *G* = stand basal area (m^2 ha^{-1}); H_m = average stand height (m).

The positive parameter estimate for *G* in Eq. (5) indicates that denser stands usually have higher canopy base heights, owing to self-pruning in limited light-conditions (Reinhardt et al., 2006). In addition, the large positive parameter estimate for H_m ensures that the effect of thinning from below (the most usual thinning option in *P. pinaster* stands) in increasing H_m is much larger than the effect of the decrease in G in reducing *CBH* (Cruz et al., 2010).

If Eq. (5) is used to derive the *CBH* input for the model of Van Wagner (1977), then the critical fire intensity I_0 (Eq. (3)) can be estimated from G and H_m, given constant foliar moisture content. Crown foliar moisture is roughly steady during the fire risk season, around 100% in central Portugal (Viegas et al., 1992). In conifers, crown fire potential increases whenever the live foliage moisture content is below 100% (Van Wagner, 1967), and this value was assumed for the simulation.

Fernandes et al. (2009) and Van Wagner (1977) models were jointly used for simulations to assess the importance of overstory–understory relationship to fire behaviour and to stand management.

3. Results and discussion

3.1. Data characterization

Mean shrub cover varied substantially among species, ranging from 56.6% in *P. sylvestris* to 76.6% in *P. pinaster*, through 70.3% in *P. radiata*. The Mann–Whitney *U* test found these differences to be significant ($\alpha = 0.05$) for the three sample pairs. Higher shrub cover and biomass under *P. pinaster* stands has been also observed by other authors, and is attributed to higher canopy light transmission (Coll et al., 2011; Porté et al., 2000; Rodríguez-Soalleiro and Madrigal, 2008). Lower canopy leaf area indices generally result in greater canopy light transmission, which in turn is associated to more drought-tolerant or shade-intolerant species (e.g., Légaré et al., 2002), as is the case of *P. pinaster*.

Therefore, the relatively lower shrub cover found in *P. radiata* and *P. sylvestris* stands could be partially explained by higher light canopy interception and consequent lower understory incident radiation. However, this result can be somewhat masked by the effect of altitude, since mean shrub cover is usually inversely correlated with elevation in temperate forest (e.g., Coll et al., 2011; Gràcia et al., 2007). According to the Mann–Whitney *U* test, plots of *P. sylvestris* are established at significantly higher altitude (1022 m on average) than those of *P. radiata* (484 m) and *P. pinaster* (310 m), which are also significantly different.

On average, mean shrub cover values were higher than those reported for the same species in other regions of the Iberian Peninsula (Coll et al., 2011; Fernandes et al., 2002, 2009; Rodríguez-García et al., 2011), and can be partially attributed to the high net primary productivity of NW Spain.

On the other hand, mean shrub height was not significantly different ($\alpha = 0.05$) among the three pine species. For *P. pinaster*, both mean shrub height and mean shrub fine fuel load are higher than those reported by Fernandes et al. (2002); the range of variation was also much wider.

3.2. Mean response models

The CHAID procedure revealed that mean *SCOV* is significantly and inversely related to G for the three species (P-value <0.001) (Fig. 2a). This confirms that shrub cover in pine stands is negatively affected by overstory (e.g., González-Hernández et al., 1998; Kerns and Ohmann, 2004; O'Brien et al., 2007), probably through light availability. The second level in intermediate G groups for *P. pinaster* is also consistent with this assumption: shrub cover was higher in stands with lower H_0 and higher *RSI*.

It must be emphasized that when describing overstory–understory relationships in forest ecosystems, G is commonly used as a surrogate for canopy cover, theoretically the preferred overstory cover descriptor (Mitchell and Popovich, 1997). In addition, G has the advantage of being relatively simple to obtain in the field or to be estimated by a growth and yield model, e.g., Barrio Anta et al. (2006), Castedo-Dorado et al. (2007) and Diéguez-Aranda et al. (2006), respectively for *P. pinaster*, *P. radiata* and *P. sylvestris* in NW Spain.

Most pine references for the Iberian Peninsula (e.g., Fernandes et al., 2002; González-Hernández et al., 1998; Rodríguez-García et al., 2011) also implicitly or explicitly found a negative effect of G on shrub development. One exception is Godinho-Ferreira et al. (2005), which, using NFI data, indicate that closed *P. pinaster* forests in Portugal typically have higher shrub cover than open stands. For this species, Porté et al. (2009) did not found any significant relationship between overstory stand variables and understory cover in south-western France.

The CHAID procedure showed no agreement on the variable playing the most important role in explaining mean shrub height for the three pines in the region (Fig. 2b): G, H_0 and D_m were selected for *P. pinaster*, *P. radiata* and *P. sylvestris*, respectively. The groups established by the CHAID procedure were less significant in comparison with shrub cover (P-value $\geqslant$0.003), but the behaviour seems logical: the three overstory variables (which take into account stand development stage and the level of competition within the stand) had a negative effect on mean shrub height. This weaker correlation could be expected because shrub height development is mainly driven by local physiographic or edaphic conditions (e.g., Fernandes and Rego, 1998).

Concerning shrub fine fuel load in *P. pinaster* stands, the CHAID procedure revealed that this variable is significantly related to G (P-value <0.001) (Fig. 3), with the highest fuel loads related to the lowest G values. The four leaves finally considered are consistent with this general trend. This result suggests that the shrub layer is responsive to management practices such as thinning (Ares et al., 2010; Whitehead et al., 2008).

3.3. Maximum response models

A clear limit at maximum levels of the response variables (Fig. 4) is indicated by the analysis of the two-dimensional plots of *SCOV* and *SH* with respect to the overstory stand variables corresponding to the first branch level in the CHAID regression trees. This "wedge-shaped" distribution for *SCOV* with respect to G was more evident than for *SH* with respect to the corresponding stand variables. This is especially true for the *SH* distribution with respect to D_m in *P. sylvestris* stands, where no obvious pattern is visually detected. A "triangular" distribution for *SWa* with respect to G is also easily observed in *P. pinaster*, producing a clear linear decline of maximum fine shrub fuel load over G (Fig. 5a).

These distributions indicate that shrub variables do not exceed the limits imposed by overstory stand variables, which is consistent with the hypothesis that a high-level control of overstory on understory vegetation may override the controlling influence of local factors (Brosofske et al., 2001), especially in areas where major growth constraints (dryness, coldness) are absent. Data points in the interior of these distributions indicate that shrub development is reduced by environmental factors or the management history of the plots (shrubby vegetation clearing, past wildfires, etc.). At this point, it must be emphasized that human activity is a major driving force on shrubby vegetation structure in NW of Spain.

The overstory variable selected for modelling maximum shrub development (G, for most of the cases) can be considered a surrogate for the relative availabilities of light, nutrients, water or growing space. Coll et al. (2011) also found a good relationship between G and the maximum development of the shrub strata for pine species located at intermediate altitudes in Catalonia (NE Spain). Other authors found that the stand density index (McKenzie et al., 2000) or canopy cover (Cole et al., 2010) were better stand predictors.

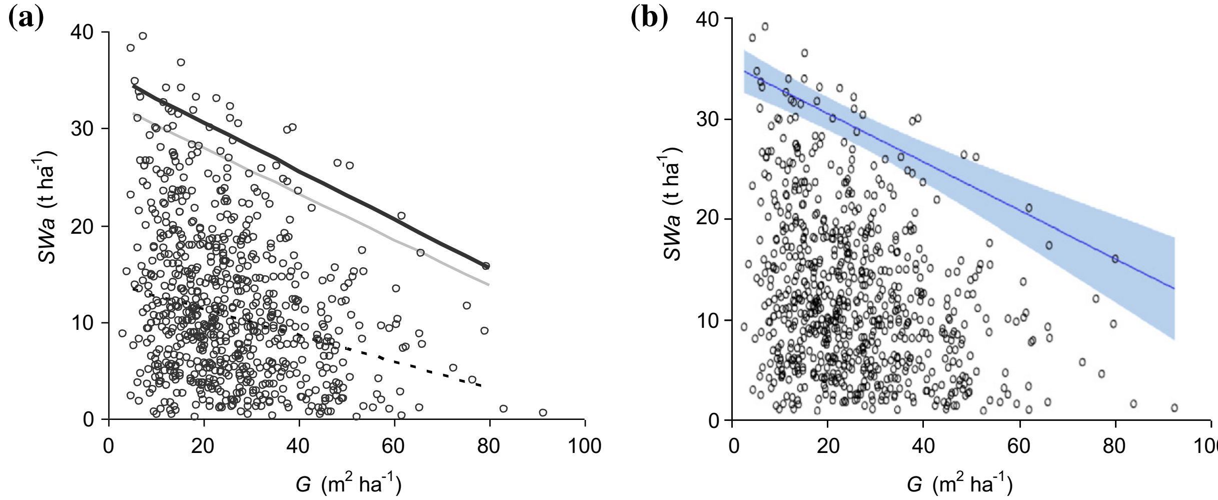

Fig. 5. Distribution of shrub fine fuel load with respect to stand basal area for *P. pinaster* data. Black solid line, grey solid line and black dashed line correspond to the 97.5th, 95th and 50th regression quantile estimates, respectively (a). Ninety-five percent confidence intervals for the 97.5th regression quantile (b).

Table 2
Parameter estimates for four selected regression quantiles for predicting *SCOV*, *SH* and *SWa*. Significant uppermost quantiles are highlighted in bold.

Overstory species	Shrub variable	Parm.	Regression quantiles (100τth)			
			97.5th	95th	90th	50th
P. pinaster	*SCOV*	b_0	202.6	**190.4**	169.4	99.91
		b_1	−0.8541	**−1.136**	−1.208	−0.981
	SH	b_0	–	**2.054**	1.818	0.8358
		b_1	–	**−0.00935**	−0.00974	−0.00336
	SWa	b_0	**35.61**	32.70	28.94	14.07
		b_1	**−0.2507**	−0.2369	−0.2342	−0.1364
P. radiata	*SCOV*	b_0	192.5	**196.0**	167.8	98.21
		b_1	−1.109	**−1.417**	−1.131	−1.067
	SH	b_0	–	**2.818**	2.642	1.208
		b_1	–	**−0.0462**	−0.0426	−0.0180
P. sylvestris	*SCOV*	b_0	–	**143.2**	145.0	108.9
		b_1	–	**−1.227**	−1.638	−1.852
	SH	b_0	–	–	–	–
		b_1	–	–	–	–

Note: Shrub variables defined in Table 1.

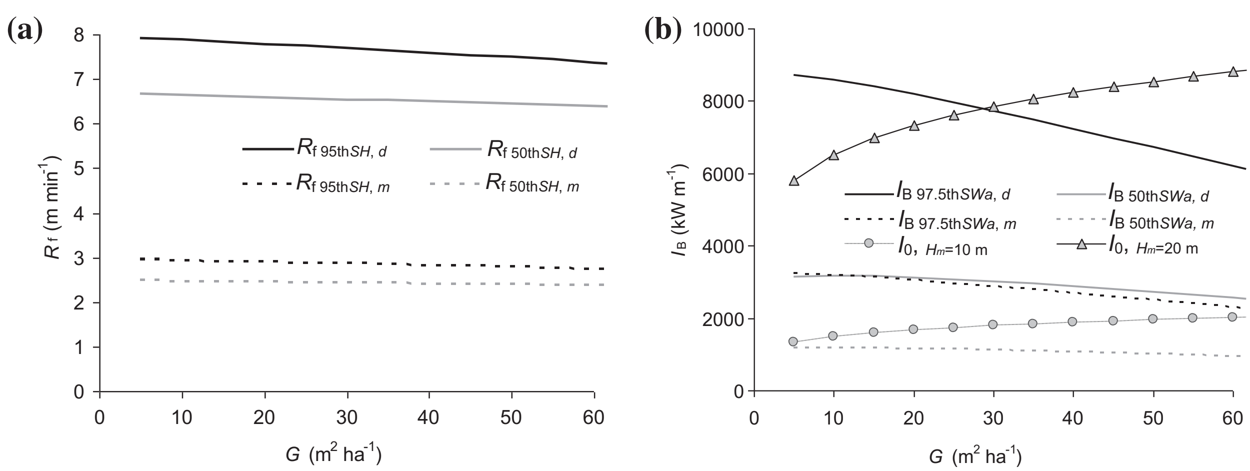

Fig. 6. Surface fire behaviour simulations using Fernandes et al. (2009) model in two contrasting weather scenarios [U = 10.5 km h^{-1}, S = 15°, Ms = 10% (dry –*d*– solid lines) and U = 7 km h^{-1}, S = 10°, Ms = 20% (mild –*m*– dashed lines)] and for two shrub fuel response models [maximum response model (black lines) and median response models (grey lines)]. Variables simulated: forward rate of spread (R_f, a) and Byram's fire intensity (I_B, b). Critical Byram's fire intensity (I_0) estimated using Van Wagner (1977) model for two contrasting H_m values (10 m and 20 m), and considering a foliar moisture content of 100%.

Table 2 shows the estimates for the 50th, 90th and 95th regression quantiles. Both *SCOV* and *SH* decrease with increasing overstory stand variables, and the decreases are greater for higher quantiles (see b_1 estimates) than for median quantiles. The only exception is *P. sylvestris*, where the opposite occurs, suggesting that other unknown variables (e.g., elevation-related coldness) are more active limiting constraints. Moreover, the comparable b_1 estimates obtained for *SCOV* for *P. pinaster* and *P. radiata* suggests that *G* limits maximum shrub development in a similar manner.

The 95th regression quantile was the most extreme quantile that could be estimated with reasonable precision for *SCOV* and *SH* (as indicated by 95% confidence intervals, values not shown). For upper quantiles (e.g., 97.5th and 99th), the confidence intervals of the estimates included zero, and therefore the former cannot be estimated precisely. Therefore, the 95th quantile was selected as the best approximation for changes in *SCOV* and *SH* when overstory stand variables (H_0 in *P. radiata* stands and *G* in the other species) are active limiting factors. *P. sylvestris* confidence intervals of parameter estimates for *SH* included zero for all regression quantiles, and therefore a predictive model could not be obtained. This result could be expected because of the mentioned absence of any significant trend in the graphical distribution of SH–D_m pairs of data (Fig. 4). No other overstory stand variable was a *SH* limiting factor in *P. sylvestris* stands.

Fig. 4 also shows the lines corresponding to the 95th, 90th and 50th quantile estimates. The 50th regression quantile estimates suggest increases in *SCOV* and *SH* with respect to the overstory variables lower than those indicated by the 90th and 95th regression quantiles. Moreover, the fact that the latter regression quantiles were almost parallel indicates that a large proportion of the sample is not impacted by interactions with unmeasured or unknown factors (Cade et al., 1999), such as environmental local factors or past management. Larger sample sizes would be required to determine whether higher slopes of more extreme regression quantiles are better approximations of changes in these shrub variables when *G* or H_0 are the active limiting factors.

The previous considerations in relation to *SCOV* and *SH* hold for *SWa* in *P. pinaster* stands when *G* is the major active limiting factor, but in this case the 97.5th regression quantile seems a reasonable approximation of the expected decrease in *SWa* (Table 2 and Fig. 5a). Fig. 5b shows the 95% confidence intervals for the 97.5th regression quantile. The reason for the wide confidence interval observed is that quantile regression is estimating parameters describing changes near the extremes of biological response distributions, which are inherently less precise than central tendency estimates (Cade et al., 1999).

The estimation of the effects of limiting factors has been discussed for describing the understory–overstory relationship (e.g., Coll et al., 2011; McKenzie et al., 2000), but OLS regression after subjectively grouping the data to calculate summary values was used. Regression quantiles used in this study have the advantage of estimating linear models without subjectively selecting a subset of data points based on predefined criteria and considering minimal assumptions about the form of the error distribution (Cade et al., 1999; Zhang et al., 2005). In addition, regression quantiles provide an approximation that is more consistent with the ecological theory of limiting factors.

3.4. Model applications to fire behaviour prediction

Fig. 6 shows the surface fire behaviour and crown fire initiation simulations based on models by Fernandes et al. (2009) and Van Wagner (1977), respectively, for the two contrasting fire environments. Surface fire spread rate was weakly influenced by surface fuel height (Fig. 6a). For the same environmental conditions and fuel moisture, considering the 95th quantile regression model for *SH* (b_0 = 1.96 and b_1 = −0.0111, considering only the 732 plots where understory is dominated by species of genera *Erica*, *Calluna*, *Ulex* and *Genistella*) implied a difference in R_f equal to or less than 1.2 m min^{-1} comparing to a 50th quantile regression model (b_0 = 0.758 and b_1 = −0.00285 for the above-mentioned plots). This small difference is due to the fact that fuel depth accounted for a minor portion of the total variance in fire spread rate in Fernandes et al. (2009) study. Moreover, the rate of spread variation for certain *SH* quantile estimates for the simulated range of *G* is almost negligible. Hence, the decreasing trend in fire rate of spread is unsubstantial. Therefore, the impact of managing overstory layer (implicitly, *G*) on the shrub layer is expected to have no significant influence on surface fire spread rate.

Fig. 6b shows the results for the simulated Byram's fire intensity. This variable was very responsive to both environmental conditions and quantile models for *SWa* and, to a lesser extent, to stand basal area. For a 5–60 m^2 ha^{-1} *G* range, the average reduction in fire intensity exceeds 30% only for the 97.5th *SWa* quantile model and the most favourable fire environment. This reduction is lesser than 15% for the remaining situations.

Fire intensity (closely related with flame length) determines fire suppression difficulty. Several authors suggest fire intensity thresholds that relate to the effectiveness of different types of fire suppression equipments (e.g., Alexander and Lanoville, 1989). According to these authors the difficulty in controlling fire varies from very high (>4000 kW m^{-1}) to moderate (500–2000 kW m^{-1}) for a *G* range of 5–60 m^2 ha^{-1}. The latter class is associated to effective suppression by ground suppression crews, whereas the former class implies that direct control of the headfire by either ground or airborne suppression resources is unlikely. High (2000–4000 kW m^{-1}) to very high fire control difficulty is expected over the *G* range for the more flammable scenario, and even for mild weather conditions if the 97.5th *SWa* quantile model is considered. Moderate fire control difficulty is predicted for the less flammable scenario only, and when *SWa* is given by 50th quantile model. Moreover, except for the latter case, dominant trees are likely to be killed by a surface fire (Fernandes and Rigolot, 2007).

Fig. 6b also shows the critical fire intensity I_0 trend over *G* for two predetermined H_m values: 10 and 20 m. For a stand where H_m = 10 m, crowning is expected to occur under all environmental conditions and *SWa* quantile models considered in the simulations, except for the less flammable scenario, and when *SWa* is estimated by the median response model. Nevertheless, for a stand where H_m = 20 m, crown fire initiation is expected only under higher fire potential conditions, when the maximum response model of *SWa* is considered, and *G* is <30 m^2 ha^{-1} (corresponding to an estimated *CBH* of 10.1 m). These results suggest that crowning is driven mainly by average stand height, and that stand basal area (although it affects both surface fine fuel load and canopy base height) plays a secondary role.

Results from Fig. 6b imply that the control of understory shrub development by maintaining a dense overstory layer can decrease the intensity of a potential surface fire, especially when fire-prone weather occurs and maximum development of the shrub stratum for a given *G* is expected. Nonetheless, shrub control is unlikely to assist in decreasing the likelihood of crown fire, regardless of environmental conditions, at least for low (young) stands. In addition, crown fire propagation is more likely in denser stands because of the higher mass of fuel per unit of canopy volume (i.e., canopy bulk density – *CBD*). In fact, using a preliminary equation developed by Gómez-Vázquez et al. (submitted), ($CBD = 0.0126 \cdot G^{0.775}$; R^2 = 0.56; n = 82), the estimated *CBD* exceeds the threshold of 0.10 kg m^{-3} for G > 15 m^2 ha^{-1}. This threshold is usually assumed as a prerequisite for active crowning, i.e., a form of fire propagation where canopy combustion dominates fire spread (Agee, 1996; Alexander, 1998; Cruz et al., 2005).

In NW Spain, owing to high forest productivity and the demand for pulpwood and board-wood, it is common to follow silvicultural schedules that maximize yield through the maintenance of high stocking over stand development (Pasalodos-Tato et al., 2010). In addition, some silvicultural prescriptions (especially where fire risk is higher) recommend high plantation density and low-intensity thinning from below in order to avoid rapid shrub development (e.g., Rodríguez-Soalleiro and Madrigal, 2008). However, as Alexander (1998), Cruz et al. (2005) or Van Wagner (1977) pointed out for other conifer species, silvicultural regimes that maintain denser stands (i.e., higher *G*) will sustain faster-spreading, higher-intensity fires if the combination of *CBH* and surface fire intensity results in crowning. Therefore, the deliberate option for these stands should be aggressive and early tree pruning.

Fire behaviour simulations indicated that shrub control through overstory management does not prevent fires from crowning, at least in low (young) stands. Fire-preventive measures, to be effective, should address the whole fuel complex, including the forest canopy (Agee and Skinner, 2005; Fernandes and Rigolot, 2007). Case studies and fire reports provide evidences that maritime pine stands without proper canopy fuel management are prone to high-intensity crown fires – even under relatively mild weather (Fernandes and Rigolot, 2007). As an example, Fernandes et al. (2004) report an experimental summer fire with incipient understory vegetation and *CBH* = 5.4 m where surface fire behaviour was just below the threshold for crown fire development.

The critical importance of decreasing the canopy vertical and horizontal continuity is well-known in the context of fuel management (e.g., Graham et al., 2004; Agee and Skinner, 2005). According to the results of this study, low density in young stands decreases the likelihood of crowning provided that surface fire intensity is not increased significantly by shrubs, and reduces active crowning by decreasing *CBD*. In adult stands, since *CBH* is driven mainly by H_m, canopy fuel management through thinning is expected to be less relevant to decrease crowning hazard. Other authors (e.g., Alexander, 1998) also found that fire hazard is especially high at an early age. Therefore, when a significant fire threat exists, early thinning should be scheduled, assuming it is conducive to understocking and loss of stand growth (Keyes and O'Hara, 2002). Additionally, thinning increases the remaining trees growth rate and accelerates the acquisition of fire tolerance features (Fernandes and Rigolot, 2007).

Simulation results are conditioned by limitations in the fire behaviour models, by assumptions about the fuel complex, and by simplifications in regards to the effect of overstory characteristics on micrometeorological conditions. Empirical fire behaviour models such as Fernandes et al. (2009) are a flexible tool for predicting fire behaviour, offering a valuable framework for fire risk analysis. Nevertheless, their use is limited to the range of environmental conditions inherent to their development. Fernandes et al. (2009) model was developed from a substantial number of experimental fires, but the prevailing environmental conditions were mild and make it especially adequate for use under low to moderate fire danger. Therefore, the model is expected to underestimate fire spread if extrapolated to simultaneously dry and windy weather (Fernandes et al., 2009).

Only the fuel layers corresponding to litter, understory vegetation and canopy where considered in this study simulations. Nonetheless, ladder fuels (especially suspended needles and twigs in the lower canopy) can be important in maritime pine stands (Fernandes and Rigolot, 2007). In highly-stocked stands, these ladder fuels might contribute with substantial fuel quantities, significantly increasing crown fire hazard (de Ronde et al., 1990). SFI does not provide information on this type of fuels.

Overstory canopy characteristics affect local fire weather, specially dead fine fuel moisture content and within-stand winds, which in turn affect surface fire behaviour and crowning potential (Rothermel, 1983). Moisture content of surface fine fuels is influenced by microclimatic factors (e.g., canopy interception of rainfall and solar radiation, near surface air temperature, relative humidity and within-stand wind speed) that are expected to be responsive to overstory stand variables (Rothermel, 1983). Some studies (e.g., Whitehead et al., 2008; Faiella and Bailey, 2007) found no conclusive evidence for a *G* effect on the moisture content of fine fuels. In a maritime pine stand in NW Spain a modest fuel moisture content decrease of about 2% on average was reported after comparing two nearby plots, respectively unthinned and heavily thinned (Ruiz-González, 2007). Nevertheless, the study is very local and does not allow generalization for a wide *G* range, as it would be necessary to be considered in our simulations. Within-stand wind speed changes with stand structure and decreases with canopy density even more consistently than fine fuel moisture content (van Wagtendonk et al., 1996). However, this effect was not included in the simulations because wind adjustment factors cannot be inferred from *G*.

4. Conclusions

The relationship between overstory variables and understory shrub characteristics was studied for three pine species in NW Spain based on data from the National Forest Inventory. Results showed that mean shrub development (assessed by cover, height and biomass) responds directly to overstory variables (primarily stand basal area). Moreover, maximum shrub development was also limited by overstory variables for *P. pinaster* and *P. radiata* stands. This is not valid for *P. sylvestris*, suggesting that altitude or other environmental factors are more active limiting constraints for shrub development in this case. The use of quantile regression models of shrub development as inputs to simulate surface fires and crown fire initiation was exemplified for *P. pinaster* stands. Fire behaviour outputs revealed that the control of understory shrub development through the maintenance of high overstory basal area can decrease the intensity of a potential surface fire. Nonetheless, the effect of basal area on crown fire initiation is negligible, and it is unlikely to result in more effective fire suppression, at least in young stands. Moreover, and because of higher canopy bulk density, crown fire spread is more likely in dense stands if the critical surface fire intensity for crowning is attained. In summary, a growing stock that limits shrub development does not avoid crown fire initiation and spread, overriding the decrease in surface fire intensity. This general conclusion is expected to be valid for forest management decision-making, despite not considering overstory effects on micrometeorological conditions and some simplifications in regards to the whole fuel complex. Data collected during and after future wildfire events should be used to test these study findings.

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