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Article

Assessing the effect of pruning and thinning on crown fire hazard in young Atlantic maritime pine forests

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Abstract

Management of fuel to minimize crown fire hazard is a key challenge in Atlantic forests, particularly for pine species. However, a better understanding of effectiveness of silvicultural treatments, especially forest pruning, for hazard reduction is required. Here we evaluate pruning and thinning as two essential silvicultural treatments for timber pine forests. Data came from a network of permanent plots of young maritime pine stands in northwestern Spain. Vertical profiles of canopy bulk density were estimated for field data and simulated scenarios of pruning and thinning using individual tree biomass equations. Analyses of variance were conducted to establish the influence of each silvicultural treatment on canopy fuel variables. Results confirm the important role of both pruning and thinning in the mitigation of crown fire hazard, and that the effectiveness of the treatments is related to their intensity. Finally, models to directly estimate the vertical profile of canopy bulk density (*CBD*) were fitted using the Weibull probability density function and usual stand variables as regressors. The models developed include variables sensitive to pruning and thinning interventions and provide useful information to prevent extreme fire behavior through effective silviculture.

Keywords: silviculture, vertical canopy fuel distribution, canopy bulk density, canopy base height, wildfires, *Pinus pinaster*.

1. Introduction

The risk of wildfires in temperate southwestern European forest is expected to increase as a result of severe weather conditions and the high accumulation of flammable fuels (EEA, 2016). Changes in traditional forests practices (Pérez, 1990) and land-use activities have changed forest composition, structure and stocking density (Gómez-Vázquez et al., 2013). Fuels reduction treatments help lessen the risk of high intensity and severe wildfires by decreasing both quantity and continuity of forest fuels (Agee and Skinner, 2005; Chiono et al., 2012). Silvicultural interventions such as pruning and thinning not only improve wood quality, but also break up the continuity of fuels. Specifically, pruning affects canopy base height and thus reduces vertical fuel continuity (e.g. Scott and Reinhardt, 2007), while thinning alters canopy bulk density and decreases the horizontal fuel continuity (e.g. Hevia et al., 2016b; Prichard et al., 2010). This fuel modification hinders the vertical development of surface fires burning through treated stands and reduces the probability of canopy fuels ignition (Graham et al., 2004), hence limiting the potential for high intensity crown fires (Cruz et al., 2008).

Crown fires are the most intense type of fire, they spread fast and are thus difficult and dangerous to contain (Ruiz-González and Álvarez-González, 2011; Scott and Reinhardt, 2001). Moreover, in managed forests, they cause severe damage (Alexander and Cruz, 2011; Ruiz-González and Álvarez-González, 2011) in terms of economic value and forest productivity (Rodríguez y Silva et al., 2012), as well as the ecology of the forest (Turner et al., 1999), wildlife habitat, recreational use, and human health through the effects of smoke (Dale et al., 2001). For these reasons, there is great interest in silviculture interventions to reduce forest susceptibility to crown fires (e.g. Reinhardt et al., 2006; Ruiz-González and Álvarez-González, 2011).

Two key variables that influence the initiation and spread of crown fires are canopy base height (*CBH*) and canopy bulk density (*CBD*) (Van Wagner, 1977). The quantification of these canopy fuel variables is therefore necessary in fire behavior simulation systems for modelling crown fire (Reinhardt et al., 2006). Measurements of many canopy fuel characteristics, such as *CBH* and *CBD* are not possible by direct methods (e.g. Carey and Schumann, 2003; Cruz et al., 2003; Hevia et al., 2016b; Reinhardt et al., 2006) and most indirect methods proposed (e.g. Gómez-Vázquez et al., 2013; Jiménez et al., 2013; Ruiz-González and Álvarez-González, 2011) require the determination of the available fuel which might be consumed in an active crown fire (Hevia et al., 2016b). In this respect, although there is some disagreement over what exactly constitutes available fuel, or the best way to estimate *CBH* and *CBD* (Fernández-Alonso et al., 2013), the use of data from destructive sampling and the development of biomass equations has been described as the most accurate method for estimating canopy fuel variables related to crown fire (Fulé et al., 2004; Reinhardt et al., 2006).

In the Atlantic region (northwestern Spain and Portugal) wildfires are the most destructive type of forest disturbance (e.g. Gómez-Vázquez et al., 2013; 2014) and maritime pine (*Pinus pinaster* Aiton) has historically been one of the species most prone to crown fire (Jiménez et al., 2013) due to its flammability (Fernandes and Rigolot, 2007), particularly when pruning and thinning are not applied, and forests carry high surface fuel loads (Cruz et al., 2008; Fernandes, 2009; Pinto and Fernandes, 2014). Indeed, in Atlantic forests it is possible to find high levels of fuel build-up which are probably not reached in temperate pine stands elsewhere (Vega, 2001), making fuel management to minimize fire risk a key challenge.

Recent studies for the main Atlantic conifer species have demonstrated that a better understanding of canopy fuel complex characteristics in forests and their relation to crowning potential can be obtained by combining classic forest inventory data with models which estimate those fuel characteristics. To date, however, most work in the Atlantic region has not considered the influence of silviculture (e.g. Fernández-Alonso et al., 2013; Gómez-Vázquez et al., 2013; Jiménez et al., 2013; Ruiz-González and Álvarez-González, 2011), while those that do have principally only taken into account thinning interventions (e.g. Crecente-Campo et al., 2009; Gómez-Vázquez et al., 2014; Hevia et al., 2016b; Ruiz-González et al., 2015) and studies focused on pruning or its combination with thinning remain scarce.

The first goal of this research is, therefore, to evaluate the effect of pruning and thinning on the potential initiation and propagation of crown fire in managed Atlantic maritime pine forests using a data set from permanent plots of this species in northwestern Spain. In addition to field data for pruning interventions, four simulated scenarios were considered: (1) untreated (control); (2) pruning only; (3) thinning only; and (4) pruning combined with thinning. Field data and simulated scenarios were used to estimate *CBH* and *CBD* as well as changes (%) in both canopy fuel variables.

The second aim is to develop equations for predicting the canopy fuel profile from easily measurable stand descriptors, using classic inventory data and variables related to silvicultural treatments. Field data from the permanent maritime pine plots and pruning interventions were considered in this respect.

2. Material and methods

2.1. Study Area

The study area encompasses the western region of Asturias, Spain (Figure 1) where pure and even-aged maritime pine forests abound. This area has an Atlantic climate with mild temperatures (annual average 12-14 ºC) and abundant rainfall (930-1500 mm) throughout the year. The network of experimental plots used in the present study was chosen because they represent the range of forest conditions occurring within young maritime pine Atlantic forests which are suitable for silviculture. Mean elevation of the plots ranges between 101 and 536 m above sea level, soils are acid (pH from 3.8 to 4.3), and slope often greater than 15%.

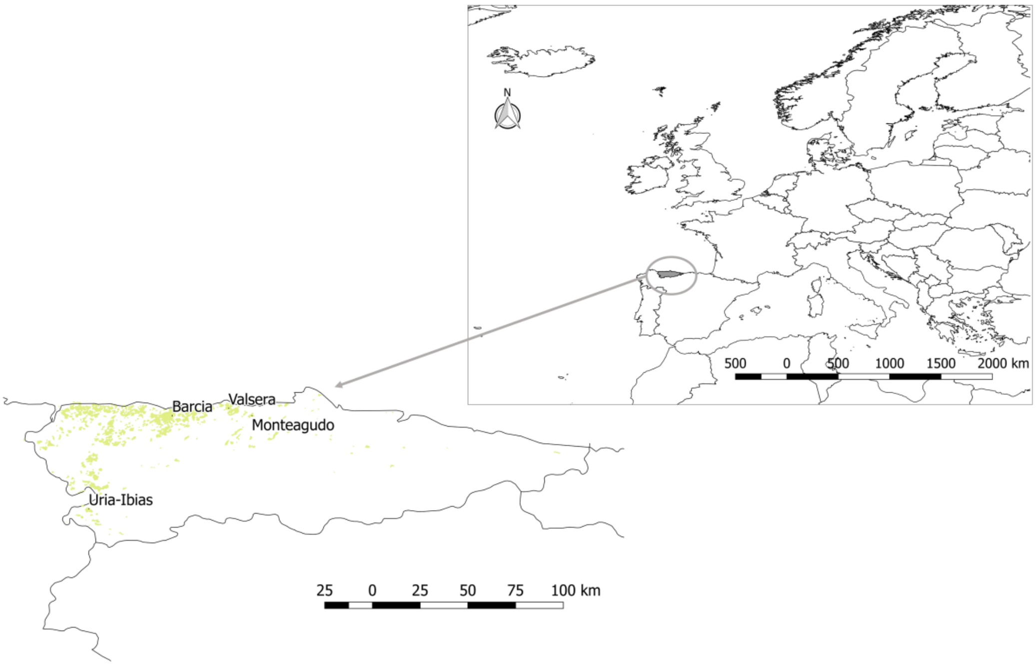


Fig. 1. Location of the study area within Europe (top right) and distribution map of *P. pinaster* (green) showing location of the network of research plots used to obtain the canopy fuel data (below, location names cross the centroid of each individual plot studied).

2.2. Data collection

This study was performed in four young stands of *P. pinaster* (7-11 years) from the network of permanent plots established in northwestern Spain in winter 2005-2006. The experimental design consisted of dividing each 1 hectare stand into 64 subplots (average area, 156 m^2) and randomly allocating each to one silvicultural regime. These were either unpruned control (C, none of the live crown was removed), or ‘‘variable lift pruning” (i.e. dictated by individual tree parameters) at one of two intensities: light pruning (LP, the percentage of live crown removed ranged from 12% to 15%) or heavy pruning (HP, 29–37% of live crown removed). In order to facilitate fieldwork, the lower and dead branches were removed from each tree crown for all the treatments. More detailed descriptions of the study sites, silviculture applied and experimental design can be found in Hevia (2013) and Hevia et al. (2016a).

Forest inventories were carried out in the winters of 2005-2006 (both before and after pruning), 2008-2009 and 2010-2011. All trees were measured for each inventory. Diameter at breast height (d, 1.3 m above ground level, cm), total tree height (h, m), crown base height (h_{base}, m) –defined as the height from the ground to the point on the stem of the lowest live branch– and crown length (L_{crown}, m) –from the lowest live branch to the top of the tree– were recorded. Crown ratio, CR, was determined as the ratio between crown length and total tree height (L_{crown}/h). In addition, number of trees per hectare (N, stems ha^{-1}), quadratic mean diameter (D_g, cm), stand basal area (G, m^2 ha^{-1}), mean height (H_m, m), and dominant height (H_0, m) –defined as the mean height of the 100 largest diameter trees per hectare– were calculated. Table 1 presents summary statistics for some of the above-mentioned variables.

Table 1. Summarized tree and stand data (mean and standard deviation in brackets) from the permanent plots used.

Inventory	Tree variables		Stand variables					
	d (cm)	h (m)	t (years)	N (stems ha^{-1})	D_g (cm)	G (m^2 ha^{-1})	H_m (m)	H_0 (m)
Inv 0 - Inv 1	7.47 (3.03)	5.02 (1.34)	8.48 (1.51)	1558.54 (192.53)	7.71 (1.86)	7.52 (3.15)	5.03 (0.89)	6.4 (1.12)
Inv 2	11.57 (3.26)	7.15 (1.38)	11.48 (1.51)	1543.69 (176)	11.32 (1.74)	15.84 (3.96)	7.13 (0.86)	8.49 (1.05)
Inv 3	13.71 (3.79)	9.26 (1.61)	13.48 (1.51)	1528.34 (165.25)	13.7 (1.86)	23.15 (5.08)	9.19 (1.02)	10.33 (1.25)

[a] Inventory 0 (Inv 0) is prior to pruning and Inventory 1 (Inv 1) is post-pruning in the same year. Here they are combined, as these parameters did not change after pruning.

2.3. Estimating structural canopy fuel variables

Different approaches can be used to define and estimate *CBH* and *CBD* (Scott and Reinhardt, 2001; Keyser and Smith, 2010). A review of previous research (Fernández-Alonso et al., 2013; Gómez-Vázquez et al., 2013; Hevia et al., 2016b; Ruiz-González and Álvarez-González, 2011) provides detailed information of these approaches. In the present work, *CBH* and *CBD* were calculated following the canopy fuel profile method of the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS, Reinhardt and Crookston, 2003) based on Sando and Wick (1972). However, the current study assumed that fine crown biomass and canopy fuel load is not equally distributed within the tree crown. This provides a more realistic approach with a lower source of error than assuming a homogeneous distribution of crown fuels (Ruiz-González and Álvarez-González, 2011).

According to this method, *CBD* is defined as the maximum 4.5 m running mean of canopy bulk density in the vertical distribution of this variable for layers 0.3 m thick, and *CBH* is defined as the height at which a *CBD* value of 0.037 kg/m^3 is reached in that vertical distribution (Sando and Wick, 1972) (Figure 2). This *CBD* value was selected from the many that exist, as it falls between the highest estimate of 0.067 kg m^{-3} (Williams, 1978), and the lowest of 0.011 kg m^{-3} (Beukema et al., 1997), and several other studies have used the same threshold with this species in northwestern Spain (e.g. Hevia et al., 2012; Ruiz-González and Álvarez-González, 2011; Vega et al., 2009), allowing comparisons with previous studies (Ruiz-González and Álvarez-González, 2011).

The vertical profile of canopy fuel was determined by sectioning each subplot into layers 0.3 m depth from the ground to the top of the tallest tree (Sando and Wick, 1972). The value of *CBD* for each layer was calculated as the ratio between the available fuel load and the layer depth (0.3 m). For modelling purposes, and according to Scott and Reinhardt (2001), needles and fine twigs less than 6 mm thick were considered as the available fuel consumed in crown fires.

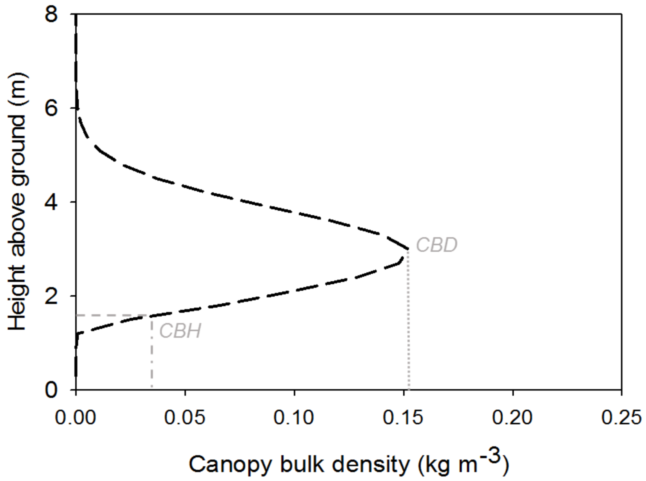


Fig. 2. Canopy bulk density profile (*CBD*, kg m^{-3}) in a representative young maritime pine stand. *CBD* is defined as the maximum *CBD* value in the profile, and *CBH* is the lowest height at which the value of *CBD* is 0.037 kg m^{-3} (Sando and Wick, 1972).

The values of available fuel load for each layer were calculated for each subplot using the dendrometric variables obtained from the forest inventories carried out in the plots and the biomass equations developed by Hevia et al. (2017) for young trees of this species in Asturias which relate fine crown biomass components (needles and fine twigs$\leq$ 0.6 cm thick) to easily measured individual tree variables (i.e. *d*, *h* and *CR* as input variables).

2.4. Modelling the vertical profile of CBD

A two-parameter Weibull probability density function (pdf) was used to characterize the vertical profiles of *CBD* for each experimental subplot. This function was selected after a preliminary study revealed it to be the best option (Hevia, 2013):

$$CBDrel = \left(\frac{c}{b}\right) \cdot \left(\frac{h_i - a}{b}\right)^{c-1} \cdot \exp^{-\left(\frac{h_i - a}{b}\right)^{c}} + e \qquad (3)$$

where *CBDrel* is the ratio between the canopy bulk density at the specific height above ground h_i (m) and the total area limited by the vertical *CBD* distribution; *a*, the minimum height above ground which values of the function are higher than 0 (in this study, *a* was defined as 0.3 m, the height of the first layer); *b* and *c* are the scale and shape parameters to be estimated, and *e*, the error term. The Weibull parameters were estimated by using the NLIN procedure of SAS/STAT® (SAS Institute Inc., 2009).

An analysis of variance (ANOVA) was used to assess possible significant differences in the two parameters (*b* and c) with respect to each inventory or silvicultural intervention (at the 95% significance level) using the MIXED procedure of SAS/STAT® (SAS Institute Inc., 2009). Finally, models to estimate the Weibull function parameters from stand variables that are easy to measure in field were fitted. Previous studies have demonstrated that Weibull function parameters can be linearly related to stand variables (e.g. Gómez-Vázquez et al., 2013; Hevia, 2013). Therefore regressive variables were selected by the "*stepwise*" method, using the REG procedure of SAS/STAT® (SAS Institute Inc., 2009).

The model performance was evaluated by graphical analysis of residuals. Moreover, the goodness-of-fit statistic of root mean squared error (*RMSE*) and the adjusted coefficient of determination (*Adjusted* R^2) were determined for each model.

Finally, the Kolmogorov–Smirnov test (K-S) was used to compare the estimated and the observed *CBD* distributions. As indicated by Lilliefors (1967), as the estimated *CBD* distribution parameters were recovered from empirical information (observed tree canopy fuel distribution), an approximation of the K-

S statistic distribution for each subplot was obtained by generating 10,000 independent pseudo-random samples and computing the corresponding K-S statistic for each sample.

2.5. Silvicultural scenarios

In addition to the field data from pruning, the effect of thinning combined with pruning was explored by simulating different silvicultural scenarios. The situation of unmanaged forests (i.e. field data at the time the experiments were established in winter 2005-2006 before pruning) was defined as the starting point for each simulated scenario and 6 different pruning scenarios (from 0% to 60% of L_{crown} removed) along with 6 different thinning from below scenarios (from 0% to 60% of *G* removed) and 36 combined scenarios (i.e. all combination of pruning and thinning intensities) were considered. For field data and each simulated silvicultural scenario the canopy fuel profile and values of *CBH* and *CBD* were estimated.

Analyses of variance were conducted to establish the influence of each silvicultural treatment (observed data and simulated scenarios) on *CBH* and *CBD* using the MIXED procedure of SAS/STAT® (SAS Institute Inc., 2009). Silvicultural treatments and plot were considered as fixed factors while subplot was defined as a random factor.

Finally, the results obtained in the simulations were graphically represented using *CBD* profiles for each silvicultural scenario, and data from a representative average subplot (in terms of fuel characteristics) are presented here. In addition, *CBH* and *CBD* values were graphically represented in relation to the remaining stand density (N_{remain}) and basal area (G_{remain}) for each thinning scenario simulated (this work provides, as an example, data for two plots, one located on the coast and one inland).

3. Results

3.1. Structural canopy fuel variables (CBH, CBD)

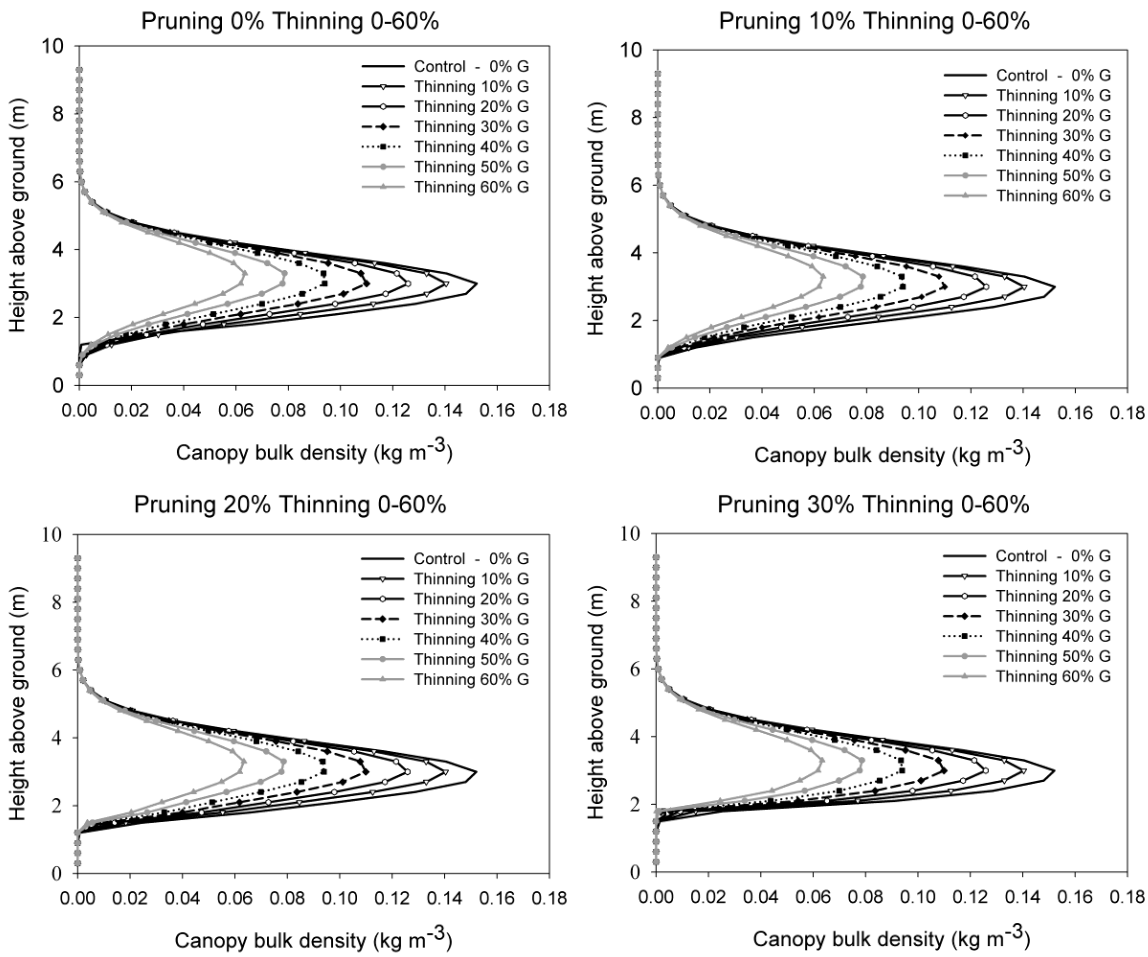
The results of the analysis of field data from the network of maritime pine plots (pruning from 0% to 37% of L_{crown}) showed, as was expected, significant differences for *CBH* not only immediately after treatment, but also 3 and 5 years later. However, there were no evident effects of these intensities of pruning on *CBD* immediately after intervention, and only a very weak influence of treatment on this variable 3 and 5 years later (Table 2).

Table 2. Mean values and standard deviation (in brackets) of the canopy fuel variables for the field data, in each inventory (Inv) before and after pruning, in the permanent plots of *P. pinaster*. Means with the same letter represent no-significant differences (Tukey´s adjusted pairwise comparisons; α = 95%).

Silvicultural treatment (field data)	*CBD* (kg m^{-3})	*CBH* (m)	Δ *CBD* (%)	Δ *CBH* (%)
Inv 0 (winter 2005-2006) – Before Pruning				
Control	0.164 (0.061) [a]	1.657 (0.249) [a]	-	-
Light Pruning	0.158 (0.061) [a]	1.678 (0.265) [a]	-	-
Heavy Pruning	0.158 (0.068) [a]	1.668 (0.214) [a]	-	-
Inv 1 (winter 2005-2006) – After Pruning				
Control	0.164 (0.061) [a]	1.744 (0.275) [c]	-	-
Light Pruning	0.157 (0.062) [a]	1.997 (0.367) [b]	-4.3	14.5
Heavy Pruning	0.149 (0.068) [a]	2.284 (0.397) [a]	-9.1	31.0
Inv 2 (winter 2008-2009) – After Pruning				
Control	0.260 (0.071) [a]	1.739 (0.270) [c]	-	-
Light Pruning	0.219 (0.068) [b]	1.992 (0.366) [b]	-15.8	14.5
Heavy Pruning	0.196 (0.063) [c]	2.278 (0.394) [a]	-24.6	31.0
Inv 3 (winter 2010-2011) – After Pruning				
Control	0.325 (0.079) [a]	1.739 (0.270) [c]	-	-
Light Pruning	0.277 (0.068) [b]	1.992 (0.366) [b]	-14.8	14.5
Heavy Pruning	0.254 (0.055) [b]	2.277 (0.393) [a]	-21.8	31.0

Silvicultural treatment = intensity of pruning (% of L_{crown} removed) applied in the network of experimental plots; *CBD* = canopy bulk density in the stand; *CBH* = lowest height of the crown where *CBD* equals 0.037 kg m^{-3} (Sando and Wick, 1972); Δ*CBD* = increment in *CBD* at each treatment intensity with respect to the untreated scenario (control); Δ*CBH* = increment in *CBH* for each treatment with respect to the untreated scenario (control).

The vertical profiles of *CBD* for each simulated silvicultural scenario for a representative maritime pine subplot are shown in Figure 3. The shape of the profiles is typical of single strata stands as indicated in Keane (2015). It reveals changes in *CBD* profiles after each silvicultural strategy, with greater influence apparent when the intensity of the intervention was higher. These changes in the vertical profiles of *CBD* impacted on the canopy fuel variables, as Supplemental Material S1 demonstrates.



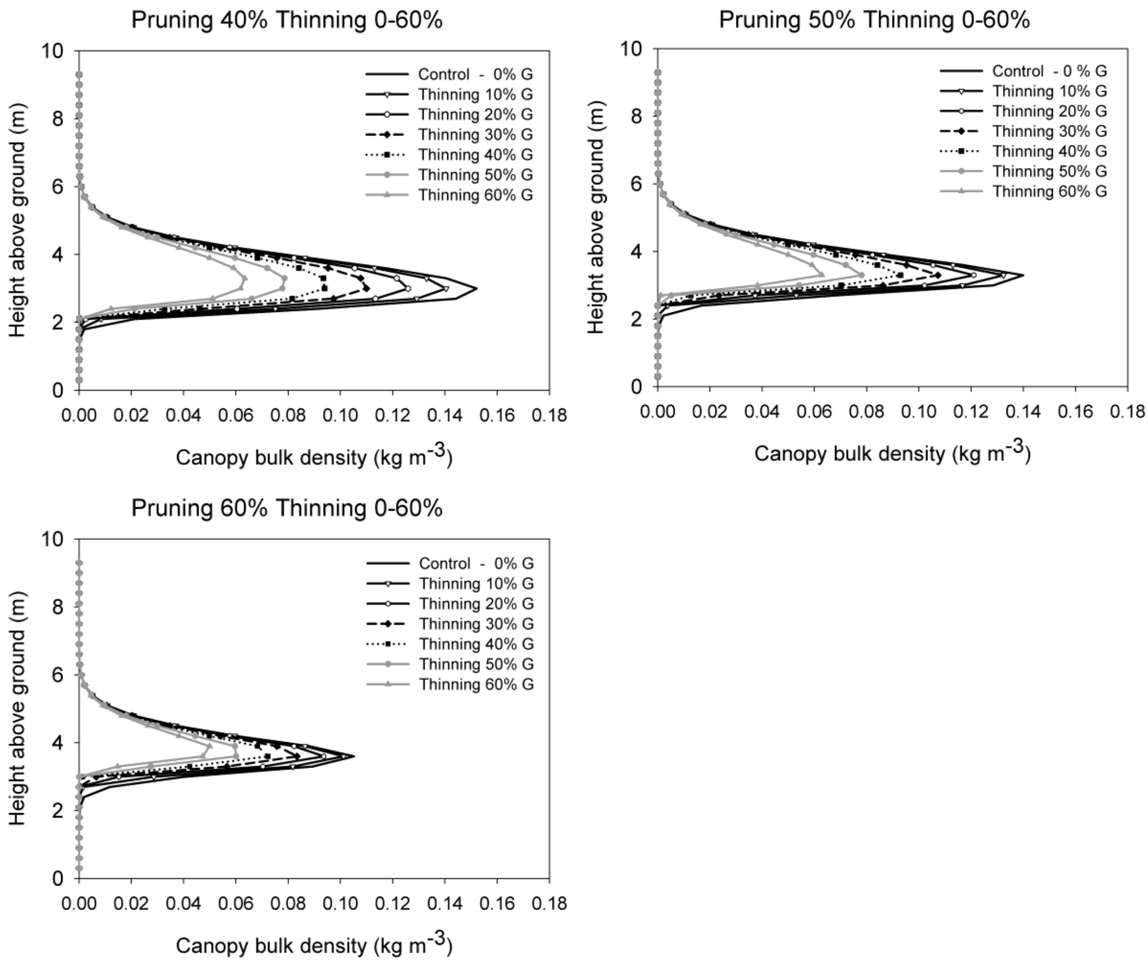


Fig. 3. Available canopy fuel profiles showing *CBD* in a representative mean subplot in the network of maritime pine plots for each simulated silvicultural scenario: (1) untreated scenario (control); (2) pruning; (3) thinning; (4) pruning combined with thinning. Intensities of pruning and thinning from 0% to 60% are shown in bands of 10%.

Pruning scenario had more influence on *CBH* than on *CBD*, and both pruning and thinning showed a significant increase in *CBH* for treatment intensities above 20% (% of L_{crown} for pruning scenario and % of *G* removed for thinning scenario).

The mean values obtained in this work for *CBH* ranged from 1.67 m in the untreated scenario, to 3.83 m for the pruning scenario, 2.54 m for the thinning scenario, and 4.49 m for the combined pruning and thinning scenario. The *CBD* values ranged from 0.158 to 0.048 kg m^{-3} for the simulated scenarios. The highest value of *CBD* (0.158 kg m^{-3}) was obtained for the untreated scenario while the lowest (0.048 kg m^{-3}) was when the heaviest pruning and thinning were combined (60% of L_{crown} and 60% of G removed). More specifically, for the pruning scenarios, CBD values ranged from 0.158 to 0.090 kg m^{-3}, while lower values were observed for thinning (from 0.147 to 0.068 kg m^{-3}) or thinning combined with pruning (0.147 kg m^{-3} and 0.048 kg m^{-3}), with the greatest reduction being seen in the latter treatment (Supplemental Material S1). Reductions in CBD values were shown to be statistically significant when at least 50% of L_{crown} was removed for the pruning scenario. However, the stronger effect of thinning was confirmed by the fact that reduction in CBD was statistically significant even at the lowest intensity (10% of G removed), and also in all intensities of the combined pruning and thinning scenarios.

3.2. Modelling canopy fuel profile

The final models constructed to relate Weibull function parameters and the main stand variables are shown in Table 3. The mean crown length (L_{crown_m}) and mean height (H_m) were included as regressors for models of both scale (b) and shape (c) parameters (Equations (6) and (7)). In addition, the equation for parameter c included stand stocking (N) (Eq. (7)).

Table 3. Parameter estimates, standard errors and goodness-of-fit statistics of the linear models relating Weibull parameters and stand variables.

Model (Weibull parameters)	Eq.	Param.	Estimate	Std. Dev.	RMSE	Adjusted R^2
$b = \alpha_1 + \beta_1 \cdot L_{crown\_m} + \gamma_1 \cdot H_m$	(6)	α_1	0.0955	0.0440	0.1865	0.9797
		β_1	-0.2039	0.0195		
		γ_1	0.8871	0.0170		
$c = \alpha_2 + \beta_2 \cdot L_{crown\_m} + \gamma_2 \cdot H_m + \theta_2 \cdot N$	(7)	α_2	4.7880	0.1493	0.2914	0.5860
		β_2	0.1272	0.0268		
		γ_2	-0.3560	0.0305		
		θ_2	-0.00017	0.0001		

b and c = Weibull function parameters (defined in Eq. 3) ; α_i, β_i, γ_i and θ_i = parameters of the linear model; L_{crown_m} = mean crown length (m); H_m = mean stand height (m); N = stand stocking (trees ha^{-1}).

The percentage of variability explained by the models defined in this study varied between 59% (parameter c) and 98% (parameter b) (see Table 3). No evidence of heterogeneous variance or systematic patterns of the residuals of the models finally selected for each Weibull function parameter was observed in the graphical analysis.

In this work, we compared the vertical distribution of observed *CBD* and those values of *CBD* estimated by Weibull function, using the parameters estimated (Table 4) in each subplot and inventory carried out in the network of maritime pine plots before and after pruning (Table 4).

Although the model for estimating parameter *c* was less accurate, the results of the Kolmogorov-Smirnov test at a 20% significance level showed no differences between observed and modelled distributions in the pruning subplots, except one for the inventory of winter 2008-2009, which was rejected.

For parameter *c*, there were significant differences between light and heavy pruning intensities in both inventory 2 and inventory 3 (winters 2008-2009 and 2010-2011 after pruning) although for each inventory neither treatment was significantly different to the control. For parameter *b*, differences between heavy pruning for inventory 1, and light and heavy pruning for inventory 3 were significant with respect to control (see Table 4).

Table 4. Mean values and standard deviation (in brackets) of Weibull parameters for the vertical distribution of *CBD* in each inventory (Inv) of pruning subplot in the permanent of plots of maritime pine. Means with the same letter represent no-significant differences (Tukey´s adjusted pairwise comparisons; α = 95%).

Silvicultural scenario (field data)	parameter *b*	parameter *c*
Inv 0 (winter 2005-2006) - Before Pruning		
Control	3.7030 (0.6297) [a]	3.5392 (0.1542) [a]
Light Pruning	3.6930 (0.6143) [a]	3.5267 (0.1417) [a]
Heavy Pruning	3.7149 (0.6322) [a]	3.5020 (0.1503) [a]
Inv 1 (winter 2005-2006) - After Pruning		
Control	3.7308 (0.6386) [b]	3.6659 (0.1867) [a]
Light Pruning	3.8118 (0.6584) [b]	3.9974 (0.2422) [a]
Heavy Pruning	3.9750 (0.7283) [a]	4.4001 (0.2908) [a]

Inv 2 (winter 2008-2009) - After Pruning		
Control	5.1076 (0.6151) [a]	3.3475 (0.2677) [ab]
Light Pruning	5.1875 (0.6001) [a]	3.3392 (0.3325) [b]
Heavy Pruning	5.2865 (0.6030) [a]	3.4770 (0.3483) [a]
Inv 3 (winter 2010-2011) - After Pruning		
Control	6.2418 (0.7214) [c]	3.0729 (0.2344) [ab]
Light Pruning	6.4567 (0.7566) [b]	3.0510 (0.3387) [b]
Heavy Pruning	6.6426 (0.7525) [a]	3.1526 (0.3602) [a]

Variables explained above (see Equation 3).

4. Discussion

4.1. Structural canopy fuel variables (CBH, CBD)

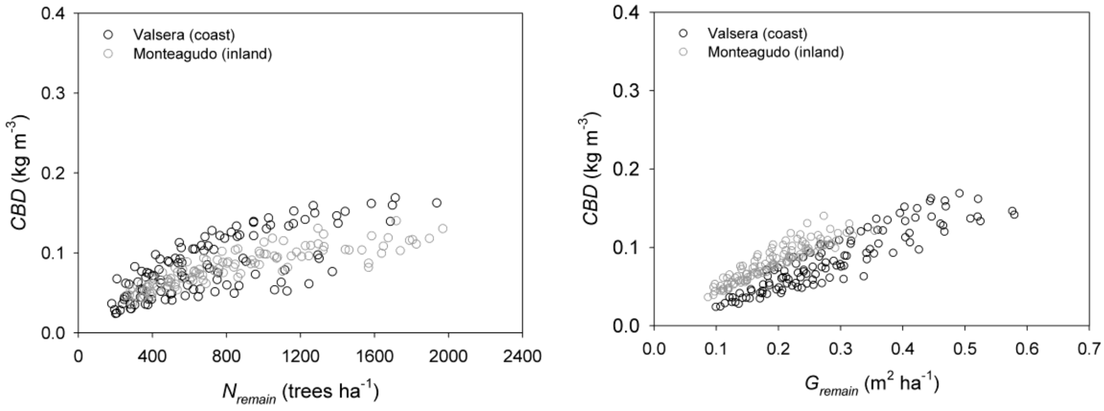
The shape of the vertical profiles of *CBD* obtained for each simulated silvicultural scenario is typical of single strata stands as indicated in Keane (2015). It reveals changes in *CBD* profiles after each silvicultural strategy, with greater influence apparent when the intensity of the intervention was higher. In general, profiles were smooth, the same as Ruiz-González and Álvarez-González (2011) observed for radiata pine (*Pinus radiata* D. Don) in northwestern Spain.

The influence of silviculture on *CBH* estimates observed is especially noteworthy, as young maritime pine forests are likely candidates for crown fire. For example, the early stages of this species have been documented to be susceptible to this type of fire due to their low *CBH* and low mean height (Fernandes and Rigolot, 2007). In addition, a comparative study of maritime pine and radiata pine in northwestern Spain indicated that crowning is more likely in maritime pine forests, not only due to the lower *CBH* but also because of their higher *CBD* values (Gómez-Vázquez et al., 2013).

The mean values obtained in this work for *CBH* (from 1.67 m in the untreated scenario to 4.49 m for the combined pruning and thinning scenario), except when pruning removed over 50% (Supplemental Material S1), are, in general, lower than those observed in other studies. For example, Fernández-Alonso et al. (2013) reported values ranging from 5.11 to 6.36 for different pine species in Galicia. In the same region, Gómez-Vázquez et al. (2013) observed

CBH average values of 5.36 m for maritime pine and 9.78 m for radiata pine. However, in our study such high values are not achieved, probably due to the age of the stands and the influence of site conditions. As an example, the clear difference in *CBH* between a coastal and an inland plot (of similar age) can be seen in Figure 4.

(a)



(b)

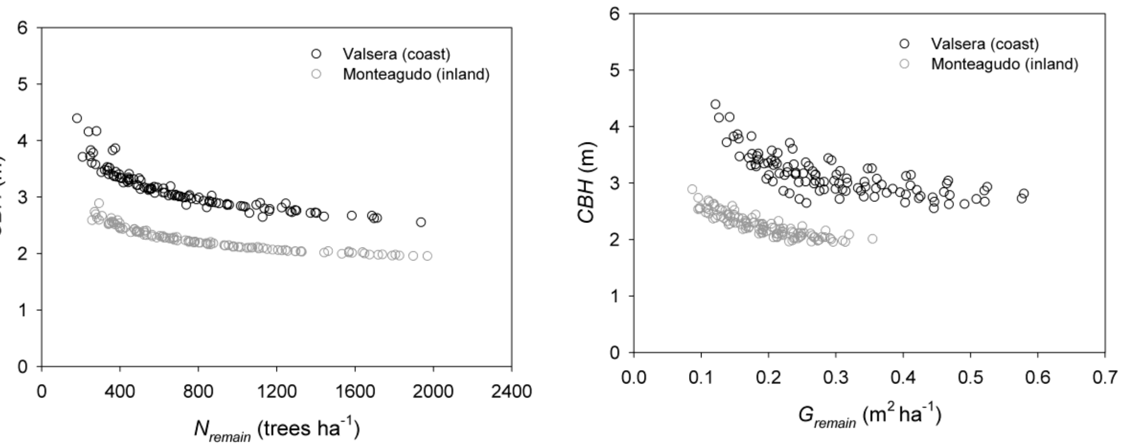


Fig. 4. (a) *CBD* in relation to the remaining stocking (N_{remain}, trees/ha) (left) and basal area (G_{remain}, m^2 ha^{-1}) (right), and (b) *CBH* in relation to the remaining stand stocking (N_{remain}, trees ha^{-1}) (left) and basal area (G_{remain}, m^2 ha^{-1}) (right) in two maritime pine subplots (one inland and one on the coast) for simulations of thinning from below (from 0% to 60% of *G* removed).

The mean values of *CBD* from our study were similar to those obtained in northwestern Spain by Gómez-Vázquez et al. (2014) for maritime pine (0.08 kg m^{-3}), or Fernández-Alonso et al. (2013) for maritime and radiata pine in the same region (0.11 kg m^{-3} and 0.08 kg m^{-3}, respectively). In contrast, our mean values were clearly lower than the value of 0.21 kg m^{-3} obtained in northwestern Spain for radiata pine (Ruiz-González and Álvarez-González, 2011); the value of 0.23 kg m^{-3} obtained for Douglas fir (*Pseudotsuga menziessii* Mirb. Franco) stands in the same region (López-Sánchez and Rodríguez-Soalleiro, 2009) or those observed for thinned and unthinned stands of Scots pine (*Pinus sylvestris* L.) in northwestern Spain by Crecente-Campo et al. (2009) (0.50 kg m^{-3} -unthinned-, 0.30 kg m^{-3} -4 years after heavy thinning- and 0.22 kg m^{-3} -4 years after very heavy thinning-). *CBD* values in our study were also lower than those obtained in studies carried out outside Spain, such as Cruz et al. (2003) for Douglas fir and ponderosa pine (*Pinus ponderosa* P. & C. Lawson) stands (0.18 kg m^{-3}), lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) stands (0.28 kg m^{-3}) and mixed conifers (0.32 kg m^{-3}) in western North America.

However, comparisons should be made with caution due to the different approaches which are used to estimate canopy fuel characteristics. In addition, factors such as forest species, age and site conditions are also important. Indeed, one reason for the differences in mean *CBD* values in the Atlantic region studies could be related to the ages of the forests involved, a notion supported by the fact that the younger trees in our study presented a lower fuel load and height of the base of the crown.

Silvicultural interventions to reach *CBD* values lower than 0.10 kg m^{-3} has been recommended in order to reduce crown fire hazard (Agee, 1996; Graham et al., 1999) since the likelihood of active crown fire is strongly reduced below this empirical *CBD* threshold value (e.g. Agee, 1996; Cruz et al., 2005; Scott and Reinhardt, 2001). The mean value obtained for *CBD* in the treatment scenarios when at least 60% of L_{crown} (pruning scenario), 40% of *G* (thinning scenario) or 60% of L_{crown} combined with 20% of *G* (pruning and thinning scenario), were lower than this threshold of 0.10 kg m^{-3}.

The results obtained in our simulations should be considered with caution since in this study the fuel, weather and topography parameters that affect surface and crown fire behavior have been considered invariants, regardless of the silvicultural scenario. It is of particular note that optimal planning of silvicultural management for fuel hazard reduction should also take into account the impact of factors such as surface fuel load, surface fuel moisture, midflame wind speed and slope (e.g. Andrews, 2012; Pinto and Fernandes, 2014; Reinhardt et al., 2006; Scott and Reinhardt, 2001). While even in rather dense forests, pruning and reducing surface fuels could reduce the likelihood of crown ignition (e.g. González-Ferreiro et al., 2017; Graham et al., 1999; Omi and Martinson, 2002; Pollet and Omi, 2002), thinning could be less effective due to its effect on other factors influencing potential fire behavior such as increasing surface fuel load for heliophilous species, the reduction of surface fuel moisture content and the increment in midflame wind speed (Graham et al., 2004; Scott and Reinhardt, 2007). Changing crown structure without the management of surface fuels will reduce the probability of active crown fires but not necessarily change the hazard of surface fires, which can be intense enough to reach the canopy (e.g. Pinto and Fernandes, 2014; Stephens, 1998). It is, therefore, necessary to manage all fuel strata in order to minimize the harmful effects of wildfires (Graham et al., 2004). What is more, even though a silvicultural scenario may be implemented to reduce crown fire hazard, it may also meet other objectives. For example, if management is focused on timber quality, a silviculture of pruning and thinning could be defined for both mitigating crown fire hazard and improving wood quality.

4.2. Modelling canopy fuel profile

To date, most equations developed to estimate *CBH* and *CBD* have included stand variables more related to stand density management, such as number of stems per ha (*N*), stand basal area (*G*) or dominant height (H_0) (e.g. Crecente-Campo et al. (2009) for Scots pine; Fernández-Alonso et al. (2013) for different pine stands; Gómez-Vázquez et al. (2014) for maritime pine; López-Sánchez and Rodríguez-Soalleiro (2009) for Douglas fir; and Ruiz-González and Álvarez-González (2011) for radiata pine) rather than consider variables related to other interventions which strongly affect the crown of trees, such as pruning. This work goes some way to filling this gap, and the inclusion of variables affected by pruning provides an essential step in addressing the fire prevention silviculture of maritime pine in the Atlantic region.

The approach proposed to model the Weibull pdf allows the determination the vertical profile of available fuel load from easily measured stand descriptors, providing greater flexibility in comparing results from past, present and future research since it means *CBH* can be estimated for any desired *CBD* threshold.

The models developed in this work provide researchers and forest managers with useful tools for describing the canopy fuel characteristics of *CBH* and *CBD*, which in turn are related to crown fire potential, and they could be used to define effective preventive silviculture for reducing crown fire hazard. The accurate estimation of these canopy fuel variables is important as a basic requirement of crown fire behavior empirical models but also because of their close relationship with physiological and environmental (e.g. carbon accounting) aspects of the forest ecosystem (Jiménez et al., 2013).

4.3. Management implications

Mitigation of the effects of crown fires requires the implementation of different strategies. One key and effective strategy is silvicultural intervention that intensifies the fire protection afforded to a stand through its active management. The main interest of this study is that the actual weight that the silvicultural management can have in the mitigation of crown fire potential in young Atlantic maritime pine forests in northwestern Spain has been evaluated quantitatively. It is suggested than similar outcomes could be achieved in other pine forest types, especially in timber production, where the silvicultural interventions of pruning and thinning are already recommended to improve wood quality. In general, the results from our simulations are consistent with other previous studies that have indicated that stocking management (e.g. Crecente-Campo et al., 2009; Gómez-Vázquez et al., 2014; Hevia et al., 2016b) and pruning of trees (e.g. Graham et al., 2004) could considerably change structural stand variables and reduce crown fire hazard. Our analysis further establishes a simple tool to easily estimate canopy fuel variables that any forest manager could use to evaluate the effect of silvicultural activities on crown fire hazard. However, any decision about the best strategy for forest fuel reduction should also take into consideration other essential variables such as changes in the surface fuel layer due to the treatments (e.g. residual biomass accumulation following interventions, variations on regeneration, growth rates or fuel moisture) and the influence of meteorological and topographical conditions on fire behavior.

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Supplemental Material

S1. LS-Mean values of the canopy fuel variables for the different simulated silvicultural scenarios: (1) untreated scenario (control); (2) pruning only; (3) thinning only; (4) pruning combined with thinning. Means with the same letter represent no-significant differences with control (Tukey´s adjusted pairwise comparisons; α = 95%).

Silvicultural scenario (simulated)	*CBD* (kg m^{-3})	*CBH* (m)	Δ *CBD* (%)	Δ *CBH* (%)
Untreated scenario				
Control 0%	0.158 [a]	1.672 [b]	-	-
Pruning scenario				
Pruning 10	0.158 [a]	1.673 [b]	-	0.1
Pruning 20	0.158 [a]	1.821 [a]	-	8.9
Pruning 30	0.158 [a]	2.182 [a]	-	30.5
Pruning 40	0.156 [a]	2.629 [a]	-1.27	57.24
Pruning 50	0.135 [b]	3.159 [a]	-14.56	88.94
Pruning 60	0.090 [b]	3.829 [a]	-43.04	129.01
Thinning scenario				
Thinning 10	0.147 [b]	1.785 [b]	-6.96	6.76
Thinning 20	0.132 [b]	1.892 [a]	-16.46	13.16
Thinning 30	0.116 [b]	2.011 [a]	-26.58	20.28
Thinning 40	0.100 [b]	2.148 [a]	-36.71	28.47
Thinning 50	0.084 [b]	2.292 [a]	-46.84	37.08
Thinning 60	0.068 [b]	2.542 [a]	-56.96	52.03
Pruning and Thinning scenario				
Thinning 10 Pruning 10	0.147 [b]	1.785 [b]	-6.96	6.76
Thinning 10 Pruning 20	0.147 [b]	1.901 [a]	-6.96	13.70
Thinning 10 Pruning 30	0.147 [b]	2.266 [a]	-6.96	35.53
Thinning 10 Pruning 40	0.146 [b]	2.731 [a]	-7.59	63.34
Thinning 10 Pruning 50	0.129 [b]	3.254 [a]	-18.35	94.62
Thinning 10 Pruning 60	0.089 [b]	3.884 [a]	-43.67	132.30
Thinning 20 Pruning 10	0.132 [b]	1.892 [a]	-16.46	13.16

Thinning 20 Pruning 20	0.132 [b]	1.975 [a]	-16.46	18.12
Thinning 20 Pruning 30	0.132 [b]	2.333 [a]	-16.46	39.53
Thinning 20 Pruning 40	0.131 [b]	2.811 [a]	-17.09	68.12
Thinning 20 Pruning 50	0.119 [b]	3.348 [a]	-24.68	100.24
Thinning 20 Pruning 60	0.084 [b]	3.974 [a]	-46.84	137.68
Thinning 30 Pruning 10	0.116 [b]	2.011 [a]	-26.58	20.28
Thinning 30 Pruning 20	0.116 [b]	2.067 [a]	-26.58	23.62
Thinning 30 Pruning 30	0.116 [b]	2.403 [a]	-26.58	43.72
Thinning 30 Pruning 40	0.116 [b]	2.881 [a]	-26.58	72.31
Thinning 30 Pruning 50	0.107 [b]	3.430 [a]	-32.28	105.14
Thinning 30 Pruning 60	0.077 [b]	4.066 [a]	-51.27	143.18
Thinning 40 Pruning 10	0.100 [b]	2.148 [a]	-36.71	28.47
Thinning 40 Pruning 20	0.100 [b]	2.183 [a]	-36.71	30.56
Thinning 40 Pruning 30	0.100 [b]	2.488 [a]	-36.71	48.80
Thinning 40 Pruning 40	0.100 [b]	2.958 [a]	-36.71	76.91
Thinning 40 Pruning 50	0.093 [b]	3.518 [a]	-41.14	110.41
Thinning 40 Pruning 60	0.068 [b]	4.167 [a]	-56.96	149.22
Thinning 50 Pruning 10	0.084 [b]	2.292 [a]	-46.84	37.08
Thinning 50 Pruning 20	0.084 [b]	2.312 [a]	-46.84	38.28
Thinning 50 Pruning 30	0.084 [b]	2.567 [a]	-46.84	53.53
Thinning 50 Pruning 40	0.084 [b]	3.041 [a]	-46.84	81.88
Thinning 50 Pruning 50	0.079 [b]	3.607 [a]	-50.00	115.73
Thinning 50 Pruning 60	0.059 [b]	4.295 [a]	-62.66	156.88
Thinning 60 Pruning 10	0.068 [b]	2.542 [a]	-56.96	52.03
Thinning 60 Pruning 20	0.068 [b]	2.548 [a]	-56.96	52.39
Thinning 60 Pruning 30	0.068 [b]	2.713 [a]	-56.96	62.26
Thinning 60 Pruning 40	0.068 [b]	3.150 [a]	-56.96	88.40
Thinning 60 Pruning 50	0.064 [b]	3.718 [a]	-59.49	122.37
Thinning 60 Pruning 60	0.048 [b]	4.493 [a]	-69.62	168.72

All the variables have been described in Table 2.