Mid-term effects of a thin-only treatment on fuel complex, potential fire behaviour and severity and post-fire soil erosion protection in fast-growing pine plantations

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ABSTRACT

Fuel hazard reduction is an essential component of pine plantation management. In NW Spain, plantation managers assume that thin-only reduces the potential fire behavior and effects by decreasing the quantity and continuity of canopy fuels. Nevertheless, thin-only can alter additional variables than control fire behavior and effects such as surface fuel availability and microclimate conditions. Moreover, the duration of thinning effects could vary and be species-specific. We present an approach linking field-measured fuel variables to well-established models for assessing the mid-term effects (six years) of thin-only on potential fire behaviour and severity and ability of burned stand to protect soil against erosion. Field variables were obtained from 41 thinning trials installed in stands of *P. pinaster* (22 locations) and *P. radiata* (19 locations). Canopy fuel load and canopy bulk density were still significantly lower in treated sample plots for both species six years after treatments, whereas total and fine understory fuel loads were slightly but significantly larger in thinned plots in *P. pinaster*. In a simulation process, different fire danger scenarios were considered through two fire-related weather variables: the 10-m open wind speed and the fine dead fuel moisture content. Results showed that thin-only could significantly reduce the likelihood of active crown fire and its rate of spread for both species, particularly in *P.pinaster,* while passive crown fire probability increased. The potential fire severity, in terms of crown scorch height, scorch volume and tree mortality, hardly worsened by thinning. For fireline intensities lower than 4000 kW m^{-1}, dead fuel moisture content effect on fire severity surpassed the wind speed influence. Moreover, protection of soil against erosion improved only slightly when thinning was previously carried out. The results of the study reveal that, in the mid-term, it is unlikely that thin-only, without intervention in the surface fuels, may have a marked influence on the reduction of the severity of a subsequent fire. The results also highlight the need of a comprehensive assessment of the effects of thin-only on both the whole fuel complex and microclimatic variables for obtaining realistic results.

Keywords: fuel treatment effectiveness, fire severity, dead fine fuel moisture, within-stand wind speed, Maritime pine, Radiata pine

1. INTRODUCTION

Fuel management can be used to reduce fire behaviour potential and fire severity with the aim of providing forest structures that are more resistant to wildfire (Hood et al., 2016; Smith et al., 2016; Vaillant and Reinhardt, 2017). Fuel management treatments typically include thinning and pruning (to manipulate canopy fuels) and prescribed burning or mastication (to manipulate surface fuels). The effectiveness of fire hazard reduction varies depending on whether these methods are used alone or combined with other treatments. In fast-growing commercial pine stands in NW Spain, thinning from below is commonly used to promote diameter growth and mechanical stability of the remaining trees, in order to produce more valuable timber at the rotation age. In addition, managers assume that thinning reduces the potential fire behaviour and severity by decreasing the quantity and continuity of canopy forest fuels (e.g. Ruiz-González et al., 2015; Hevia et al., 2018). In the region, thinning residues are also usually left on site, without being masticated or burned, and the surface fuel layer typically remains untreated.

Thin-only treatments (i.e. thinning without removal of thinning residues) can have different effects on the variables that influence fire behaviour (e.g. Graham et al., 1999). On one hand, thinning even-aged stands from below immediately reduces the canopy fuel load

(CFL) and canopy bulk density (CBD) and increases canopy base height (CBH). Thinning can therefore help to prevent the initiation and spread of crown fires (Van Wagner, 1977) and reduce fire severity. On the other hand, thinning can alter surface fuel and microclimate conditions, via the following effects: (i) by favouring greater incident solar radiation in the understory and forest floor, as well as modifying the availability of nutrients and water in the soil (e.g. Walker et al., 2016). Understory cover and biomass may therefore increase after a thin-only treatment (Navarro et al., 2010; Zhou et al., 2016). The understory stratum represents a critical fire hazard in Southern European regions, including NW Spain (Fernandes and Rigolot, 2007; Arellano-Pérez et al., 2017). Moreover, the higher solar radiation often leads to decreasing the moisture content of surface dead fuel (Ruiz González, 2007; Cruz et al., 2017); (ii) within-stand wind speed usually increases when canopy cover decreases (van Wagtendonk et al., 1996; Weatherspoon, 1996); (iii) thinning can reduce litterfall (Harrington and Edwards, 1999; Jiménez and Navarro, 2016), thus reducing litter and duff layers load; and (iv) the crowns of trees removed during thinning treatments may contribute significantly to increasing woody fuel debris in the surface fuel layer (e.g. Cruz et al., 2017). If these fuels are not removed by burning or treated by mechanical mastication, this can have a major impact on expected surface fire behaviour in the short term, decreasing the reduction in the rate of spread and intensity of a wildfire in the treated area (e.g. Omi et al. 2006; Omi, 2015; Graham et al., 2004; Fulé et al., 2012) or even directly increasing the rate of spread and intensity (e.g. Stephens and Moghaddas, 2005; Raymond and Peterson, 2005).

The numerous studies that have examined the effects of thinning on both surface and canopy fuel complex variables have mainly focused on natural conifer stands in North America (e.g. Fulé et al., 2012; Omi, 2015), and few refer to fast-growing commercial pine plantations (but see Cruz et al., 2008; Fernandes, 2009; Cruz et al., 2017). Because of the particular structural characteristics of these stands (dense, uniform spacing and uniform fuel layers), they are one of the most flammable types of vegetation (e.g. Cruz et al., 2008). Fuel hazard reduction is becoming an essential component of the management of commercial fast-growing pine plantations in NW Spain, and understanding the influence of thin-only treatment on the expected fire behaviour is important. Nevertheless, research on this matter is scarce and has mainly focused on the effects of the canopy fuel layer (Crecente-Campo et al., 2009, Jiménez et al., 2016; Arellano-Pérez et al., 2018).

In crown fires, and high intensity fires in general, post-fire tree mortality usually reaches 100%; however, in fires of low to moderate intensity where crown scorch occurs tree mortality could be only partial. Measures of foliar damage such as crown scorch height and percentage of crown volume scorched have commonly been used in modelling post-fire tree mortality (e.g. Peterson, 1985; Stephens and Finney, 2002). Scorch height (usually defined as the vertical distance from the ground to the mean height of the boundary between dead and live needles in the tree crown) is strongly dependent on the temperature reached in the convection column above the surface fire, which in turn depends on fireline intensity (Van Wagner, 1973). When this temperature reaches or exceeds 60º C for 1 minute, the needles suffer necrosis and the crown becomes scorched (e.g. Van Wagner, 1973; Michaletz and Johnson, 2006). In the study area, post-fire salvage logging is primarily used to recover timber values (Fernández et al., 2008), and estimating the probability of tree survival as a function of potential fire behaviour is advisable in order to decide whether or not logging should proceed.

Needles fall from crowns of partially or totally scorched trees in areas of conifer forest affected by low to moderate burn severity (Pannkuk and Robichaud, 2003). The needles generally fall to the ground shortly after fire and provide a natural ground cover of mulch, thus avoiding the raindrop impact, decreasing overland flow velocity and favouring sediment deposition (Cerdà and Doerr, 2008; Fernández et al., 2019). The benefits of cast needles in protecting burned soil against erosion have been demonstrated in laboratory experiments (Pannuk and Robichaud, 2003) and field studies (Vega and Díaz-Fierros, 1987; Cerdà and Doerr, 2008; Shakesby, 2011; Fernández et al., 2019). However, there is no available means of relating potential fire behaviour and ground cover by needles cast after fire. The ability to identify where dead needles could provide enough ground cover to prevent soil erosion would be useful to forest managers for post-fire rehabilitation.

Most studies of the effect of thinning on fuel complex characteristics, fire behaviour and severity and post-fire soil erosion protection consider the short-term impacts. Study of the mid-term effects is less common and has sometimes led to contradictory results (e.g. Jiménez et al., 2016; Soler Martin et al., 2017).

From the above considerations, we assume that fire behaviour, crown scorch height and post-fire stand resistance (expressed in terms of tree survival probability) will affect soil protection against post-fire erosion. Nevertheless, the directions of relationships are not clear and must be established. On one hand, an increase of crown scorch height to a certain degree could become the stand more fire resistant due to the consequent CBH increase, although if a certain threshold is exceeded, that would imply a higher probability of tree mortality (e.g. Martinson and Omi, 2003; Espinosa et al., 2019). On the other hand, also a higher crown scorch height could increase post-fire needle cast, resulting in higher capacity to protect soil from post-fire erosion. To some extent this effect could be used as an indicator of the effectiveness of fuel treatment to make ecosystem more fire resilient.

This study had two main objectives. First, we aimed evaluate the mid-term effects of thin-only (6 years after treatment) on surface and canopy fuel complex, through field-measured fuel variables, in commercial fast-growing pine stands in NW Spain. We then assessed the effect of thin-only on potential fire behaviour and severity (the latter expressed by crown scorch height and volume and post-fire tree survival) and post-fire soil erosion protection (expressed as cover provided by needles cast after fire).

2. MATERIAL AND METHODS

2.1 Data

2.1.1. Plot network and stand treatments

The study area is located in NW Spain (Figure 1). The data set corresponds to 41 thinning trials established in pure, even-aged stands of maritime pine (*Pinus pinaster*) (22 locations) and radiata pine (*Pinus radiata*) (19 locations). A high density silvicultural regime is usually applied to these species in the region corresponding to initial tree densities of between 2100–2500 trees ha^{-1}, and 3–4 light thinnings to maintain the relative spacing index at values of 0.13–0.15. Rotation ages usually vary from 25 to 35 years in radiate pine and from 35 to 45 years in maritime pine depending on the site quality of the stand and on the purpose of the timber.

The thinning trials were initially established to characterize fuel structure and crown fire potential in the plantations. The experimental design aimed to represent middle-aged and highly stocked pole-size tree stands, which are particularly fire prone (e.g. Fernandes et al., 2008). At the time of plots installation, the stand age ranged from 12 to 32 years (mean age 17.6 years) for maritime pine and from 12 to 22 years (mean age 16.3 years) for radiata pine. Three rectangular plots (25 × 40 m) were established in each location, and a different treatment was randomly applied to each of the three plots: control (C, unthinned), light thinning (LT, 20% of the basal area removed) or heavy thinning (HT, 40% of the basal area removed). The same treatment applied in the plot was also applied in a 5m buffer area around each plot. All plots had been pruned to a minimum height of 2.5 m several years before the study. The trees were measured immediately after plot establishment in 2009-2010, when they were thinned from below. Thinning was carried out manually, with chainsaws, and logs were subsequently harvested using a forwarder or an adapted tractor. In some plots, small diameter logs (usually <10 cm) were left on site, as harvesting was not profitable. Thinning slash was left scattered on site, which is usual practice in the region, again because extraction was not profitable.

Trees in all plots were re-measured in 2011-2012, 2013-2014 and 2015-2016. Surface fuels were only inventoried in 2015-2016 and due to the complexity of the approach used to estimate these fuel loads, the lightly thinned plots were not considered. Therefore, in this study only the extreme treatments (control and heavy thinning) have been analysed, representing 82 sample plots.

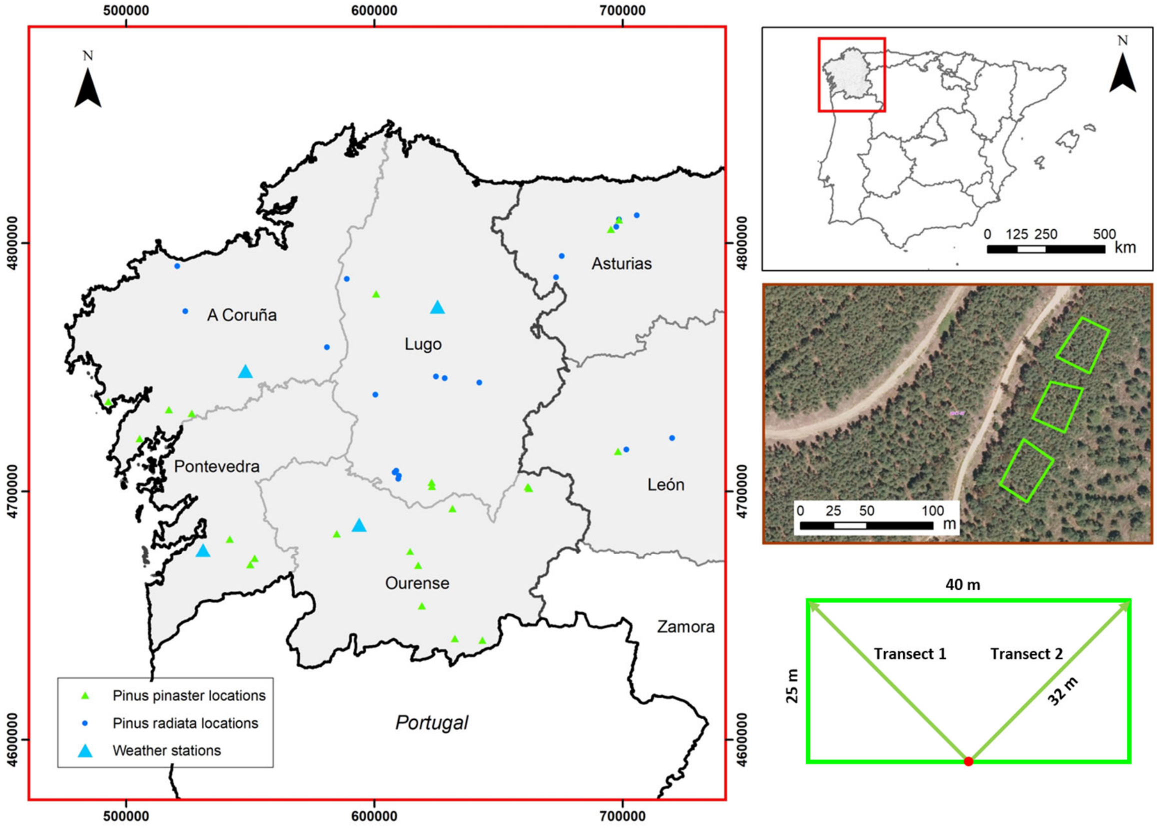


Figure 1. Geographical location of the 41 thinning trials in the study area (left). Example of three sample plots (green polygons) in one of the trial locations (middle right). Arrangement of surface fuel transects in each sample plot (lower right).

2.1.2. Tree and stand variables

Diameter at breast height (d) of all the trees was measured to the nearest 0.1 cm, at two perpendicular angles, with a graduated caliper. Total tree height (h) and height to the base of live crown (h_{blc}), defined as the lower insertion point of live branches in a tree, were measured to the nearest 0.1 m with a digital hypsometer in all trees, except during the last inventory, in which a random sample of 30 trees and an additional sample including all dominant trees (the proportion of the 100-largest diameter trees per hectare) were measured. Generalized h-d models (Diéguez-Aranda et al., 2009) and crown profile models (Crecente-Campo et al., 2009; 2013) developed in the study area for respectively *P. radiata* and *P. pinaster* were used to estimate height (h) and height to the base of live crown (h_{blc}) for the remaining trees.

The number of stems per hectare (N), mean stand diameter ($\bar{d}$), stand basal area (G), mean stand height ($\bar{h}$) and stand dominant height (H) were calculated for each plot and inventory from tree variables.

2.1.3. Canopy fuel variables

Three structural canopy fuel variables were estimated from tree measurements for each plot and inventory: available canopy fuel load (CFL), canopy base height (CBH) and canopy bulk density (CBD). The 'load over depth method' was used to define these variables because it is compatible with the canopy fuel stratum characteristics used in the crown fire initiation and propagation model developed by Van Wagner (1977) and implemented in most fire behaviour simulation systems: BehavePlus (Andrews et al., 2008), Farsite (Finney, 2004), FlamMap (Finney, 2006) and CFIS (Alexander et al., 2006).

According to this method, CBH was calculated as the mean value of the height to the base of live crown per plot; CFL was calculated as the biomass of needles and fine twigs (particles of diameter < 0.6 cm) from all the trees in the plot, which were assumed to be the fuel consumed within the flaming front of a crown fire, divided by surface plot; and CBD was calculated by dividing CFL by the crown length, estimated as the difference between mean stand height ($\bar{h}$) and CBH. The compatible systems of tree biomass equations developed for maritime pine and radiata pine in Galicia (Diéguez-Aranda et al., 2009) were used to estimate CFL. The mean value and standard deviation for the main stand characteristics and canopy fuel variables for each species, treatment and inventory are shown in Table 1.

Table 1. Statistics of the main stand characteristics and canopy fuel variables. Std. dev. = standard deviation; N = stem density; G = stand basal area; $\bar{d}$ = mean stand diameter; $\bar{h}$ = mean stand height; H = stand dominant height; CFL = available canopy fuel load; CBH = canopy base height; CBD = canopy bulk density; BT = before treatment; C = control and HT = heavy thinning.

Species	Variable	Statistic	2009-2010 (BT)		2011-2012		2013-2014		2015-2016	
			C	HT	C	HT	C	HT	C	HT
Pinus pinaster	N	Mean	1521.34	1521.33	1475.95	792.92	1430.01	712.20	1401.22	707.85
	(stems ha^{-1})	Std. dev.	547.92	538.63	530.60	413.77	518.35	218.79	515.01	218.45
	G	Mean	32.99	34.47	37.47	25.51	41.28	28.23	45.93	32.84
	(m^{2} ha^{-1})	Std. dev.	8.98	9.33	8.84	7.67	8.63	5.40	8.31	6.43
	$\bar{d}$	Mean	16.68	17.06	18.10	20.83	19.64	23.13	20.63	24.70
	(cm)	Std. dev.	3.46	3.67	3.70	4.17	3.59	4.04	3.92	4.27
	$\bar{h}$	Mean	10.90	11.13	12.06	12.92	13.52	14.35	14.69	15.20
	(m)	Std. dev.	2.44	2.53	2.45	2.64	2.33	2.51	2.48	2.67
	H	Mean	12.59	12.73	13.75	13.87	15.20	15.33	15.90	15.98
	(m)	Std. dev.	2.52	2.69	2.52	2.69	2.50	2.45	2.53	2.75
	CFL	Mean	0.7702	0.8096	0.8980	0.6300	1.0148	0.7199	1.1474	0.8574
	(kg m^{-2})	Std. dev.	0.2427	0.2478	0.2489	0.2048	0.2489	0.1576	0.2477	0.1903
	CBH	Mean	5.24	5.50	6.47	6.38	7.80	7.50	8.77	8.61
	(m)	Std. dev.	1.90	2.09	2.00	2.27	2.02	2.26	2.19	2.35
	CBD	Mean	0.1376	0.1475	0.1625	0.0974	0.1792	0.1061	0.1964	0.1309
	(kg m^{-3})	Std. dev.	0.0408	0.0501	0.0444	0.0347	0.0462	0.0248	0.0470	0.0274
Pinus radiata	N	Mean	1462.19	1442.85	1327.82	560.67	1254.42	554.77	1207.69	549.29
	(stems ha^{-1})	Std. dev.	445.69	397.31	470.10	187.83	477.67	185.37	500.75	185.07
	G	Mean	31.47	32.19	34.77	21.45	37.90	24.85	41.60	29.03
	(m^{2} ha^{-1})	Std. dev.	7.75	9.25	8.14	5.74	8.92	6.26	10.27	7.17
	$\bar{d}$	Mean	15.83	16.05	17.75	22.01	19.16	23.81	20.49	25.78
	(cm)	Std. dev.	2.35	2.42	2.85	3.61	2.91	3.55	3.11	3.46
	$\bar{h}$	Mean	13.73	14.01	15.78	17.79	17.46	19.31	19.66	20.72
	(m)	Std. dev.	2.29	2.50	2.53	2.89	2.69	2.98	2.45	2.95
	H	Mean	17.60	17.55	19.48	19.35	21.22	20.88	22.69	22.24
	(m)	Std. dev.	2.84	2.88	2.72	2.78	2.79	2.83	2.64	2.92
	CFL	Mean	1.0158	1.0328	1.1006	0.6580	1.1826	0.7501	1.2787	0.8610
	(kg m^{-2})	Std. dev.	0.2466	0.2776	0.2616	0.1670	0.2865	0.1816	0.3277	0.2081
	CBH	Mean	5.85	6.25	7.48	7.42	9.23	8.68	10.73	9.57
	(m)	Std. dev.	2.34	2.53	2.35	2.62	2.00	2.40	2.55	2.78
	CBD	Mean	0.1336	0.1398	0.1354	0.0644	0.1479	0.0719	0.1484	0.0804
	(kg m^{-3})	Std. dev.	0.0421	0.0558	0.0365	0.0181	0.0488	0.0200	0.0465	0.0249

2.1.4. Surface fuel variables

The fuel loads of woody and herbaceous understory, downed woody debris and litter and duff layers were estimated in the last inventory in winter 2015-2016.

For each sample plot, two transects each of 32 m were established from the middle of one of the 40 m sides of the plot to the vertices of the opposite side (see Figure 1). The linear understory cover, differentiated by species, was recorded along each transect. The depth of the litter and duff layers and the understory height were measured for each species every 4 m along each transect. The mean understory cover (COV_{us}) and depth of the litter ($\overline{d_L}$) and duff layers ($\overline{d_F}$ and $\overline{d_H}$) were estimated from these measurements. Moreover, surface fuel depth (FD) was calculated as the sum of $\overline{d_L}$ and the weighted average of the understory fuel depth ($\overline{d_{us}}$), which was calculated by weighting the heights of understory species by the respective cover.

The total understory load (W_{us_total}), the fine understory load (W_{us_1}, particles with diameter < 0.6 cm) and litter and duff layers fuel loads (W_L, W_F and W_H) were calculated using the equations proposed by Arellano-Pérez (2011) for these types of fuels in pine stands in Galicia (equations A.1 to A.5 in appendix A).

The downed woody debris load was estimated by the planar transect method (Brown, 1971; 1974). This is an adaptable technique based on probability-proportional-to-size concepts and has been used extensively in many inventory and monitoring programs because it is relatively fast and simple to apply and is also accurate (Busing et al., 1999; Sikkink and Keane, 2008). The downed woody debris was divided into four commonly accepted size classes corresponding to time-lag fuel classes used in fire behaviour modelling (see e.g. Burgan and Rothermel, 1984): small fine woody debris (FWD) 1-h fuels (particles of diameter <0.6 cm); medium FWD 10-h fuels (particles of diameter 0.6 to 2.5 cm); large

FWD 100-h fuels (particles of diameter 2.5 to 7.6 cm) and coarse woody debris (CWD) 1000-h fuels (fuel components of diameter ≥ 7.6 cm, including all logs). In this study, different segments along each transect were used per size class: 1-h and 10-h fuels were sampled along 2 m segments (n=5), whereas 100-h and 1000-h fuels were sampled along 5 m and 20 m segments, respectively. The downed woody material loads (W_{FWD_1h}, W_{FWD_10h}, W_{FWD_100h}, and W_{CWD_1000h}) were subsequently calculated from relationships that consider the number of pieces intersected, transect length and wood specific gravity (Brown, 1974).

Finally, surface fine fuel load (SFFL) was calculated as the sum of the estimated load of W_{us_1}, W_{FWD_1h} and W_L, and surface fuel load (SFL) was calculated as the sum of the estimated load of all surface fuel layers.

The mean values and standard deviations for the main surface fuel variables measured in the last inventory (2015-2016) are shown in Table 2 for each species and thinning treatment.

During measurements of surface fuels two hemispherical photographs were taken at the middle point of each of the two 32 m transects in the sample plots. These images were then analysed with Gap Light Analyzer software (Frazer et al., 1999) to estimate the canopy cover (CC).

Table 2. Statistics of the main surface fuel variables, canopy cover (CC), wind adjustment factor (WAF) and terrain slope (s) in the 2015-2016 inventory. Std. dev. = standard deviation; C = control; HT = heavy thinning; $\overline{d_{us}}$ = understory fuel depth weighted by species cover; $\overline{d_{LFH}}$ = litter and duff layers depth; FD = surface fuel depth; COV$_{us}$ = understory cover; W_{us_1} = understory fine load (diameter < 0.6 cm); W_{us_tot} = understory total load; W_{L} = litter layer load; W_{FH} = duff layers load; W_{FWD_1h}, W_{FWD_10h}, W_{FWD_100h}, W_{CWD_1000h} = downed woody debris loads for size classes; SFFL = surface fine fuel load and SFL = surface fuel load.

Variable	Statistic	Species			
		Pinus pinaster		*Pinus radiata*	
		C	HT	C	HT
$\overline{d_{us}}$	Mean	18.43	29.55	38.98	44.42
(cm)	Std. dev.	23.12	30.74	29.42	33.20
$\overline{d_{LFH}}$	Mean	9.31	8.99	8.68	8.81
(cm)	Std. dev.	2.09	1.94	1.84	2.01
FD	Mean	33.34	40.17	43.92	53.81
(cm)	Std. dev.	20.17	24.41	25.47	23.29
COV$_{us}$	Mean	28.16	44.55	51.45	55.08
(%)	Std. dev.	26.13	27.70	32.61	32.41
W_{us_1}	Mean	2.63	4.40	3.52	4.78
(Mg ha^{-1})	Std. dev.	1.52	1.97	1.95	2.61
W_{us_tot}	Mean	3.59	5.94	5.54	7.09
(Mg ha^{-1})	Std. dev.	2.53	3.35	3.24	4.13
W_{L}	Mean	0.29	0.29	0.21	0.22
(Mg ha^{-1})	Std. dev.	0.04	0.05	0.05	0.05
W_{FH}	Mean	28.09	27.23	27.24	27.49
(Mg ha^{-1})	Std. dev.	5.27	4.89	4.67	5.20
W_{FWD_1h}	Mean	0.24	0.18	0.40	0.37
(Mg ha^{-1})	Std. dev.	0.14	0.11	0.25	0.20
W_{FWD_10h}	Mean	2.38	2.31	2.28	3.01
(Mg ha^{-1})	Std. dev.	1.32	1.51	1.36	1.87
W_{FWD_100h}	Mean	2.59	3.50	1.73	2.69
(Mg ha^{-1})	Std. dev.	2.32	2.25	1.53	1.00
W_{CWD_1000h}	Mean	0.97	2.55	0.85	2.19
(Mg ha^{-1})	Std. dev.	2.02	3.91	1.53	1.91
SFFL	Mean	5.74	7.49	6.00	7.30
(Mg ha^{-1})	Std. dev.	1.54	2.07	1.98	2.72
SFL	Mean	40.72	44.63	40.12	44.99
(Mg ha^{-1})	Std. dev.	9.10	9.41	8.85	9.22
CC	Mean	72.87	66.64	75.87	66.65
%	Std. dev.	8.16	9.89	6.40	7.88
WAF	Mean	0.15	0.15	0.13	0.12
	Std. dev.	0.02	0.02	0.01	0.02
s	Mean	13.98	14.38	12.43	11.60
(^{o})	Std. dev.	5.91	5.08	7.33	7.44

2.1.5. Wind speed and fuel moisture characterization in the study area

The environmental variables 10-m open wind speed (U_{10}) and the fine dead fuel moisture content (M_s) are strongly related to potential fire behaviour. Because of the wide spatial distribution of the sample plots, extreme percentiles (97th and 3rd) were used to characterize these variables in the study area. The percentiles were estimated on the basis of the daily values of observed air temperature, relative humidity and wind speed at 1400 h (local time) for the fire season (122 days between June and September) at the weather stations in Santiago (42º53′17′′N; 8º24′38′′W), Lugo (43º6′41′′N; 7º27′27′′W), Ourense (42º19′31′′N; 7º51′35′′W) and Vigo (42º14′19′′N; 8º37′26′′W), as the most representative of the study area with the longest data series available (Figure 1). Different recording period lengths were considered between 1961 and 2018, depending on the station record length (AEMET, 2019).

M_s was estimated daily according to Rothermel (1983) due to this approach is compatible with the crown fire rate of spread model that will be used in simulations and it also takes into account the effect of surface fuel exposure degree to solar radiation on moisture content. Since we were dealing with relatively dense plantations (CC > 50 %), it was assumed a sheltered fuel situation. Moreover, because canopy cover (CC) was not significantly different between thinned and unthinned plot six years after thinning, the same M_s was assumed for all treatments. The extreme 3rd percentile of the M_s calculated was 9%, whereas the extreme 97th percentile of U_{10} was 27.7 km h^{-1}.

2.2. Mid-term effect of heavy thinning on the potential fire behaviour

The effects of the thinning six years after treatment, in terms of the potential fire behaviour, were evaluated through simulation of three fire behaviour metrics under different weather scenarios: i) the variation in fire spread rate for a range of wind speed (U_{10}), ii) comparison of fireline intensity (I) and iii) the proportion of different types of fire: surface fire (SF), passive crown fire (PCF) and active crown fire (ACF) according to fireline intensity.

2.2.1. Variation in fire spread rate for a range of wind speed (U_{10})

The response of fire spread rate was simulated for a representative plot of each species and treatment, characterized by the mean values of the stand variables and slope of each species × treatment combination. As already mentioned, U_{10} ranged from 1 to 28 km h^{-1} and M_s extreme percentile was assumed to be equal to 9% for both treatments. Two additional inputs: U_{10} threshold to initiate crown fire (U_{10_init}) and U_{10} threshold to start an active crown fire (U_{10_ACF}) are required to classify the simulated fire in surface fire, passive crown fire or active crown fire and consequently apply the adequate fire rate of spread equation. The thresholds U_{10_init} and U_{10_ACF} were estimated through several interconnected steps shown in Figure 2 (further details in appendix B).

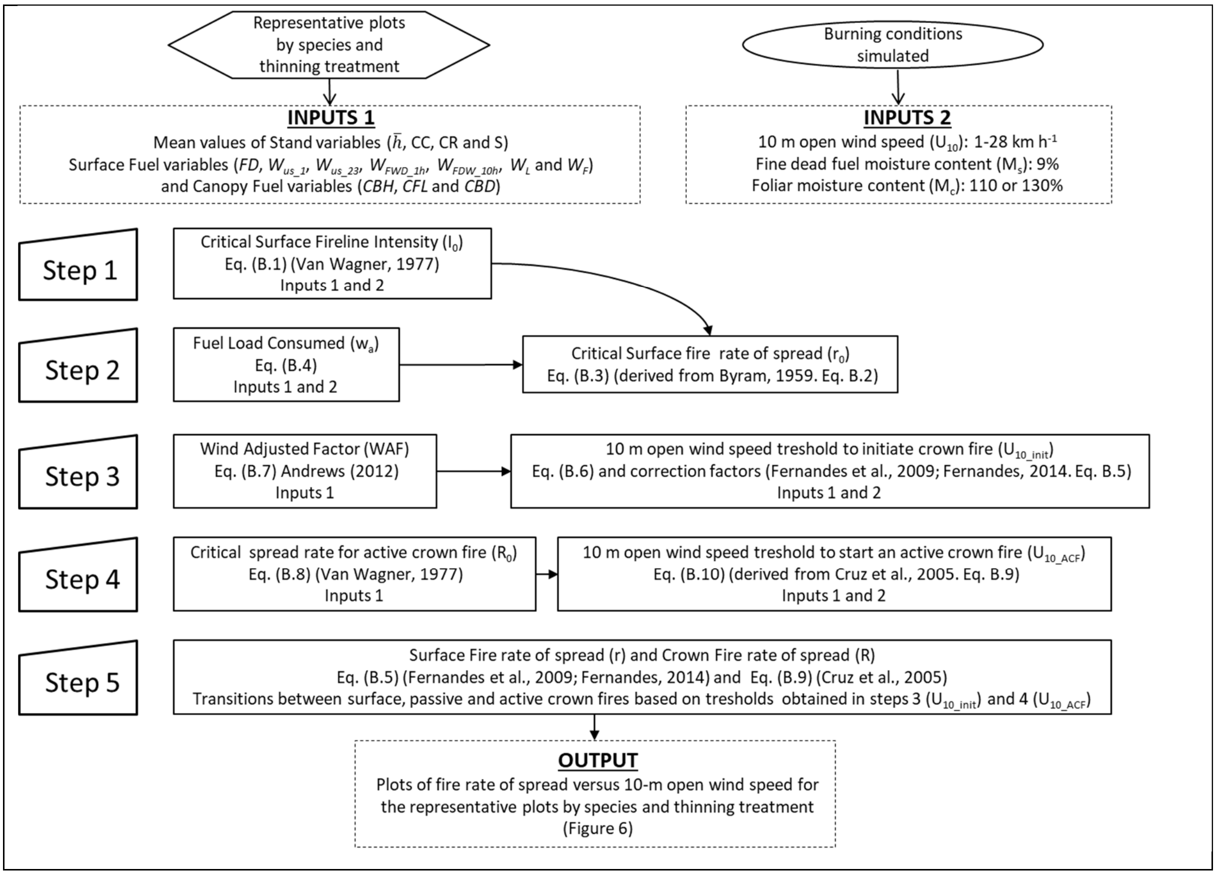


Figure 2. Data sources and workflow components for assessing the mid-term effect of heavy thinning on potential fire behaviour

Plots of fire rate of spread versus 10-m open wind speed were developed for each pine species and treatment by using the surface fire rate of spread (equation B.5) and the crown fire rate of spread (equation B.9) and taking into account the 10-m open wind speed thresholds previously estimated to define transitions between SF, PCF and ACF (Figure 2). Given the uncertainty associated with the prediction of PCF spread rate (Van Wagner, 1993; Scott and Reinhardt, 2001; Cruz et al., 2005), we assumed the spread rate of a passive crown fire between the 10-m open wind speed threshold to initiate crown fire ($U_{10\_init.}$) and the 10-m open wind speed threshold to start an active crown fire (U_{10_ACF}) is equal to that of the surface fire as assumed in some simulators such as Farsite or FlamMap, (Finney, 2004; 2006).

2.2.2. Comparison of fireline intensity (I)

The simulated fireline intensity (I) estimated considering the extreme percentiles of M_s (9%) and U_{10} (27,7 km h^{-1}) for the representative plots of each species and treatments were calculated and compared. Byram's model (equation B.2) was used to estimate I, which depends on fire rate of spread (r or R) above mentioned and fuel load consumed (w_a) varied according to the type of fire (surface, passive crown or active crown fire). For surface fire, w_a was calculated using equation (B.4). For active crown fires, available canopy fuel load (CFL) was also considered as fuel load consumed, and was therefore added to the value obtained from Eq. (B.4). In the case of passive crown fire only a proportion of CFL should be added; this proportion (the crown fraction burned, CFB) was calculated using the model proposed by Van Wagner (1993) for mature stands (equation B.11).

2.2.3. Proportion of fire types according to fireline intensity

Fire rate of spread and fireline intensity were simulated for all the sample plots considering a broad range of M_s and U_{10} values. Subsequently, the percentage of fire types (surface, passive crown and active crown fire) were calculated and compared for four groups of fireline intensity (see, for example Alexander and Lanoville, 1989; Alexander and Cruz, 2012b): group A ($I \leq 500$ kW m^{-1}), group B ($500 < I \leq 2000$ kW m^{-1}), group C ($2000 < I \leq 4000$ kW m^{-1}) and group D ($I > 4000$ kW m^{-1}). M_s ranged from 9% to 20% (by 0.5%), whereas U_{10} varied from 1 to 28 km h^{-1} (by 0.5 km h^{-1}). Overall, 1,265 simulations (55 values of U_{10} combined with 23 values of M_s) were analysed for each of the 82 sample plots, yielding a total of 103,730 simulations.

Van Wagner´s (1977) criteria was followed when classifying the percentage of plots undergoing crown fire in the simulations. First, values of fireline intensity (I, equation B.2) higher than critical surface intensity (I_0, equation B.1) indicated occurrence of crown fire. When the values indicated that a crown fire was likely to occur, if the active crown fire rate of spread (R_c, equation B.9) was higher than critical rate of spread (R_0, equation B.8) an active crown fire occurred, in other case a passive crown fire took place.

2.3. Simulated deferred effect of heavy thinning on fire severity

The effect of thinning treatment on potential fire severity was evaluated via fire simulation, with three metrics: *i*) mean height of tree crown scorch (h_s); *ii*) percentage of crown volume scorched (CVs); and *iii*) mean value of probability of post-fire tree mortality ($p_{tree\_mortality}$), based on individual tree data. The simulation scenario for these metrics was defined for all the sample plots (82) and all combinations of M_s and U_{10} mentioned earlier; i.e. a total of 103,730 simulations.

2.3.1. Crown scorch height

Mean crown scorch height (h_s, m) per plot for different combinations of M_s and U_{10} was calculated using the empirical model (equation C.1) developed by Van Wagner (1973).

Only simulations in groups A, B and C ($I < 4000$ kW m^{-1}) and conditions without active crown fires were used in this part of the study related to fire severity. Group D has not been considered due to two reasons: i) its important percentage of active crown fires and ii) values of I higher than 4000 kW m^{-1} are clearly outside of the empirical values used by Van Wagner to fit the model to estimate h_s (Eq. 2).

2.3.2. Crown volume scorched

The estimated values of h_s for each sample plot and simulation condition were used with the crown profile equations developed for both pine species in the study area by Crecente-Campo et al. (2013) to calculate the scorch crown volume (CV_s) of each tree within each sample plot. The same plot fireline intensity was assumed for each individual tree. The percentage of scorch volume of each sample plot and simulation condition was calculated by dividing the sum of the scorch crown volume of all the trees within the plot by the total crown volume of all the trees.

2.3.3. Post-fire tree mortality

Given the absence of resprouting ability in both pine species considered, tree mortality was assumed for plots affected by passive or active crown fire.

Mean probability of post-fire individual-tree mortality was assessed using the reduced model (equation C.2) proposed by Vega et al. (2011) for *P. pinaster* stands in Galicia. The full model includes as an independent variable the influence of damage to cambium; however, given that a relationship between linear surface fire intensity and the level of damage to the cambium is not available, the reduced model has been used.

An average probability value for each plot for different values of M_s and U_{10} was obtained as the mean probability of mortality of all the trees within the sample plot.

Due to the differences in crown development and structure and other morphological and physiological conifer traits that affect fire resistance of *P. pinaster* and *P. radiata* (Fernandes et al., 2008), only post-fire tree mortality on the sample plots of *P. pinaster* was estimated in this study.

2.4. Effect of thinning on soil protection against potential post-fire erosion

To evaluate the effect of thinning on soil resistance to erosion following wildfire, the potential ground cover provided by dead needles fallen from scorched tree canopies was estimated. The simulation scenario and fireline intensity restrictions were the same as those used in the fire severity section.

We assumed that all the needles below the scorch height fall to the ground, and we estimated the needle load using the vertical profiles of the needle biomass fraction proposed by Hevia (2012) for radiata pine and by Hevia et al. (2017) for maritime pine in the study area. Plot values were calculated by aggregating individual-tree values.

To determine the ability of needles fallen from the scorched stand canopy to provide adequate soil surface cover, the relationship between the load of fallen needles and the corresponding percentage of soil cover was determined. For this purpose, 5 samples of fresh scorched needles from *P. pinaster* and *P. radiata* trees were collected in 5 stands affected by wildfire in Pontevedra province (NW of Spain) in 2013. Needles were transported to the laboratory and spread by hand in regular 20 g increments in a 1 m^2 square frame placed on a firm clean surface. The area of the square frame was divided into 400 squares by a grid (5×5 cm) of tiny threads and was fully lighted to prevent shadows. For each 20 g of needles, the percentage area of each 5×5 cm square covered by needle (at intervals of 10%) was visually estimated. The mean value from the 400 squares was taken as the corresponding 1 m^2 frame cover. Needles were added consecutively in 20g increments until the square frame was almost totally covered. Two different observers evaluated the corresponding cover and the mean value was calculated.

A sigmoid model with a horizontal asymptote equal to 100 was fitted for each species, relating the percent of soil cover (SC) to the fallen dead needle load (W_{dn}, kg m^{-2}):

$$SC(\%) = 100 * (1 - exp(-a * W_{dn})) \tag{1}$$

Figure 3 shows the workflow for assessing the effect of heavy thinning on potential fire severity and ability of a burned stand to protect soil, providing a simple overview of the procedure described in detail in the above sections.

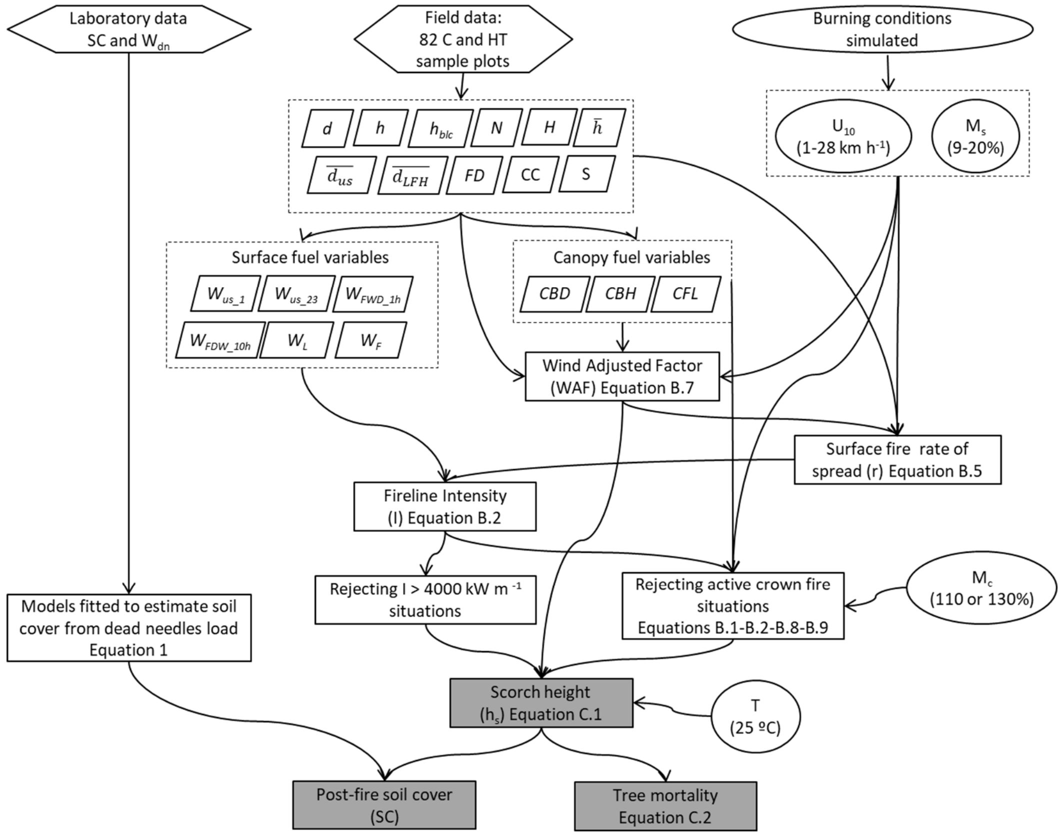


Figure 3. Data sources and workflow components for assessing the effect of heavy thinning on potential fire severity and availability of burn stand to protect soil.

2.5. Statistical analysis

To assess the influence of the thinning treatment on the main stand variables, the canopy and surface fuel variables, the wind adjustment factor (WAF) and the terrain slope (s), a generalized linear mixed model (GLMM) was fitted considering the treatment as a fixed effect and the site as a random effect affecting the intercept of the model. Significant level used was ($\alpha = 5\%$). The value of the variable measured in the previous inventory was included in the model as a covariate for all post-treatment comparisons. The function "lmer" of the package "lme4" of R (R Core Team, 2017) was used to fit the GLMM using restricted maximum likelihood (REML) and the Kenward-Roger approximate F-test was used to approximate inference about fixed effects (Kenward and Roger, 1997).

The sigmoid models used to estimate the percentage surface cover (SC) of dead needles were fitted by ordinary nonlinear least squares in the "nls" function of R (R Core Team, 2017). Model performance was evaluated by graphical analysis, by plotting the observed against predicted values of SC and plotting the studentized residuals against the estimated values and two statistical indices: the root-mean-square error (RMSE) and the model efficiency (ME).

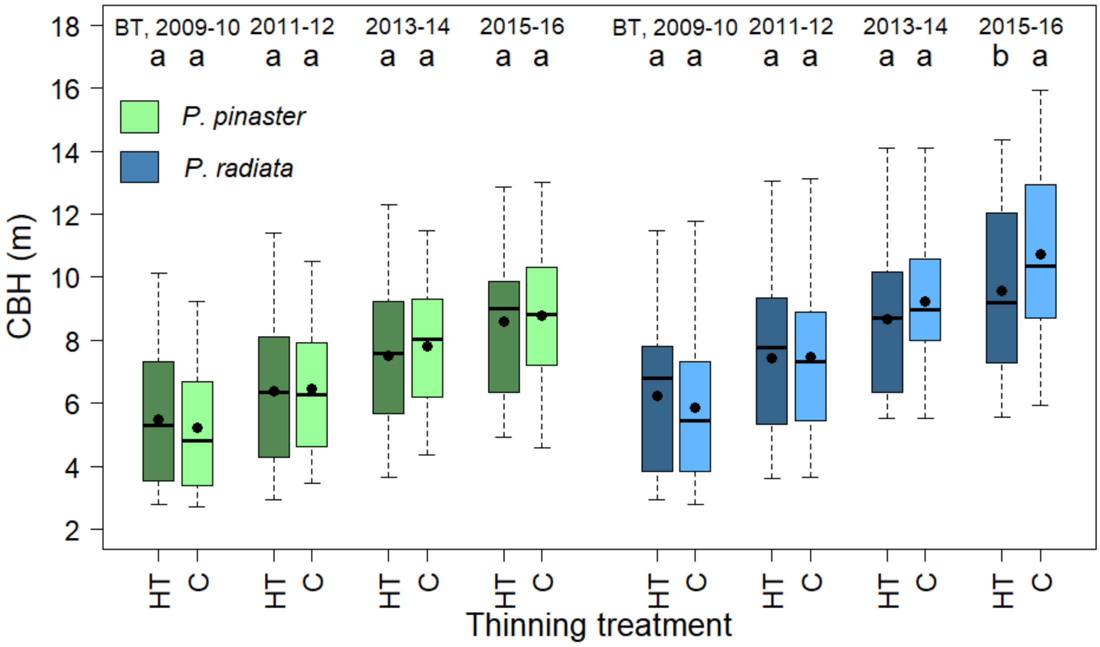
3. RESULTS

3.1. Changes in stand and canopy fuel variables over time

Mean values of the main stand variables (G, $\bar{d}$ and $\bar{h}$) before thinning did not differ significantly between plots assigned to different treatments for both species Mean stand diameter at breast height ($\bar{d}$) increased significantly over the six years after heavy thinning, relative to the control, for both species (Table 1). Mean stand height ($\bar{h}$) did not show any significant response due to treatment in maritime pine but increased significantly relative to the control in radiata pine thinned plots. Six years after treatment, stand basal area (G) was lower in the thinned than in control plots, although the growth pattern during this period was similar (Table 1).

For both pine species before thinning treatments, the values of the three canopy fuel variables (CBH, CFL and CBD) did not differ significantly between plots assigned to different thinning treatments (Figure 4). CBH did not vary between treatments over six years after thinning in *P. pinaster*. However, heavy thinning of *P. radiata* led to significantly lower CBH values six years after the treatment.

The different treatments led to significant difference in CFL and CBD for both species in the first post-thinning remeasurement (2011-2012). Moreover, the differences were maintained throughout the 6-year period considered, and the pattern was similar for both species. The CBD values in the thinned plots at the end of the study period (2015-2016) were similar to those obtained before thinning for maritime pine, but not for radiata pine.



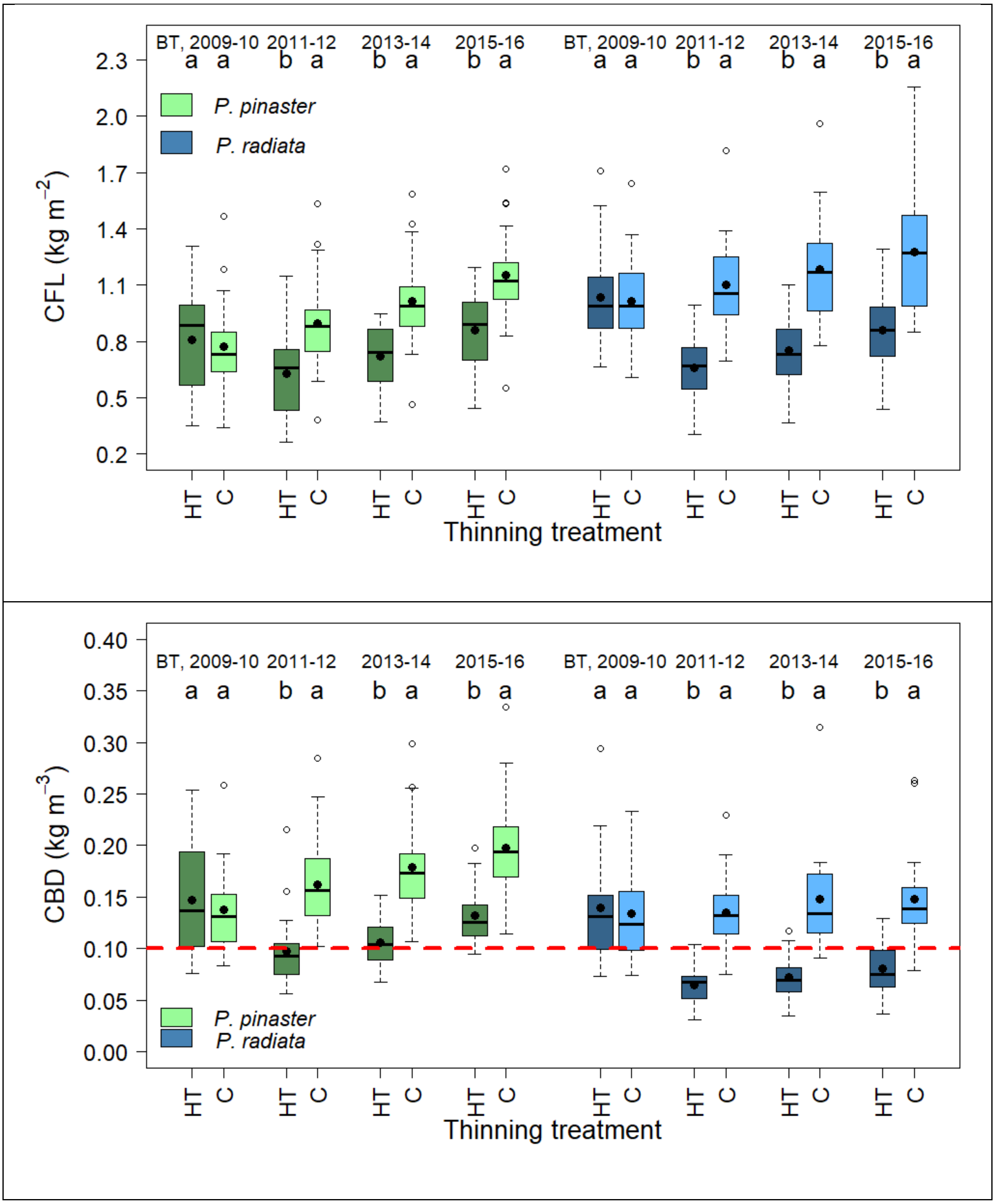
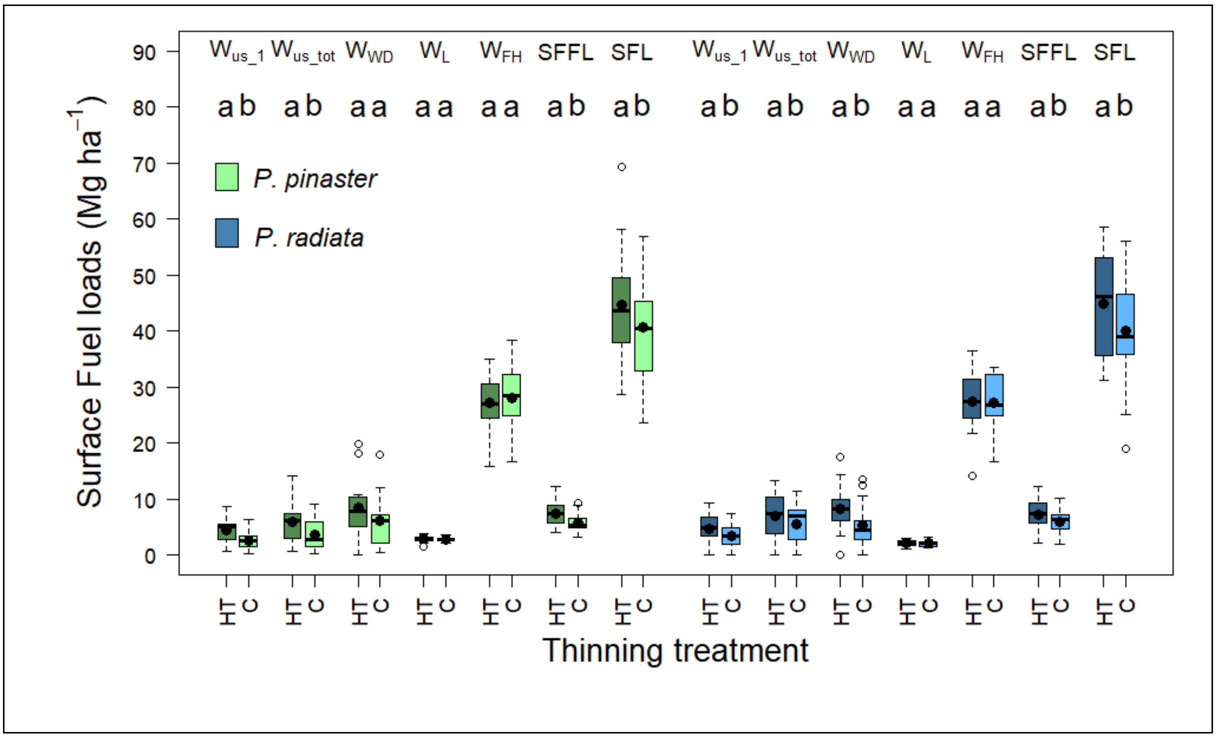


Figure 4. Box plots of CBH (upper), CFL (middle) and CBD (lower) for each species, inventory and thinning treatment: control (C) and heavy thinning (HT). Before treatment (BT). Different letters indicate significant differences between mean values ($\alpha = 5\%$). Black dots represent mean values.

3.2. Surface fuel variables

Surface fuel depth did not differ significantly between treatments for both pine species. Total surface fuel load (SFL) was significantly higher for heavy thinning for both species (Figure 5). Total understory (W_{us_tot}), fine understory (W_{us_1}) and surface fine fuel (SFFL) loads were significantly larger in thinned plots for both species, whereas thinning did not lead to a significant difference in the litter (W_L) and duff (W_{FH}) loads for either species, six years after thinning. Downed woody debris load showed significant differences between treatments only for the two coarser size classes (100h and 1000h) in both species (Figure 5).



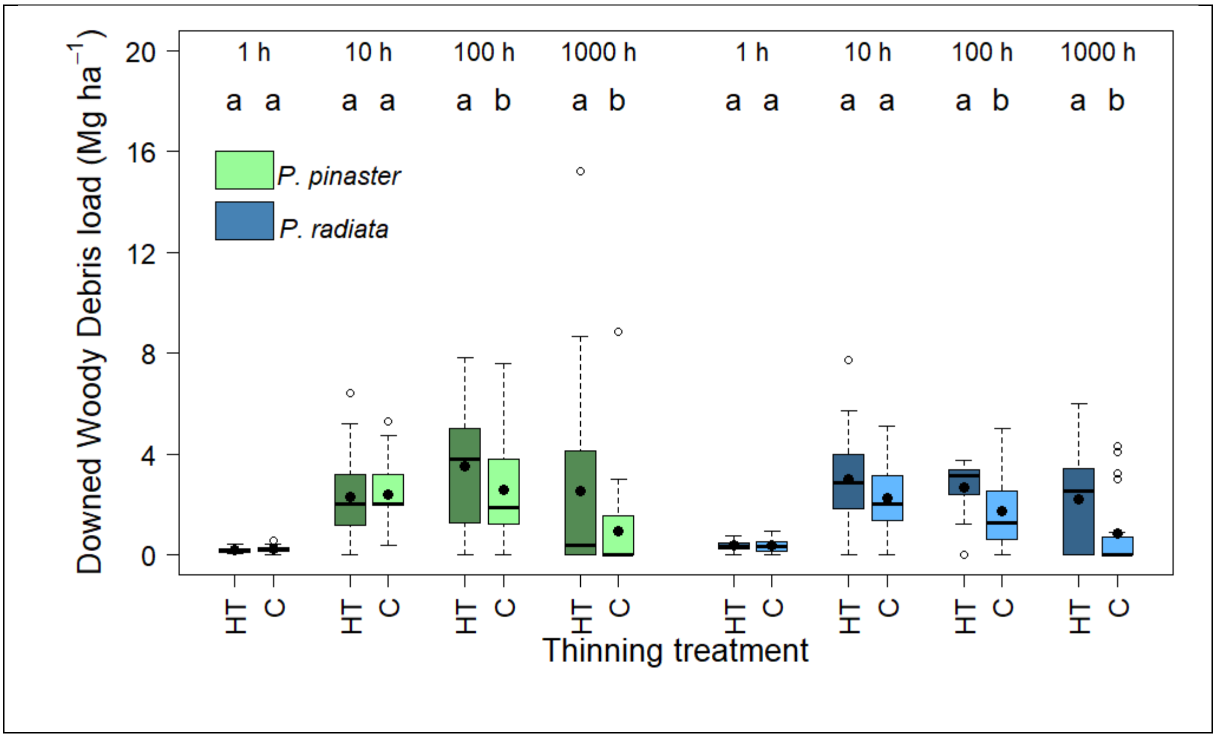


Figure 5. Box plots of the surface fuel load disaggregation (upper) and of the downed woody debris decomposition (lower) six years after thinning for each species and thinning treatment: control (C) and heavy thinning (HT). Different letters indicate significant differences between mean values ($\alpha = 5\%$). Black dots represent mean values. W_{us_1} is the understory fine load; W_{us_tot} is the total understory load; W_{WD} is the total downed woody debris load; W_L is the litter layer load, W_{FH} is the duff layer load; SFFL is the surface fine fuel load; SFL is the total surface fuel load, and 1h (diameter < 0.6 cm), 10h (0.6 cm ≤ diameter < 2.5cm), 100h (2.5 cm ≤ diameter < 7.6 cm) and 1000h (diameter ≥ 7.6 cm) are fractions of downed woody debris.

3.3. Mid-term effect of heavy thinning on the potential fire behaviour

3.3.1 Variation in fire spread rate for a range of U_{10}

Neither the wind adjustment factor (WAF) nor the terrain slope (s) differed between control and treated plots for both pine species. Surface fire rate of spread (r) showed practically the same response to wind speed in the representative thinned and control plots, for U_{10} values lower than 10 km h^{-1} for *P. pinaster* and lower than 14 km h^{-1} for *P. radiata* (Figure 6). For U_{10} values above these limits, fire rate of spread increased markedly in the control plots, directly reaching the threshold to start an active crown fire without a previous passive crown fire phase in both pine species. For thinned plots, the transition from surface fire to crown fire was more gradual, with an intermediate phase of passive crown fire.

Active crown fire started at markedly lower wind speed in the representative control plot than in the thinned plot for both types of pine. The wind speed required to start an active crown fire in the representative thinned plot of *P. radiata* (36.4 km h^{-1}) was even higher than the extreme percentile used as upper limit (27.7 km h^{-1}). In relative terms, the increase in wind speed required to start an active crown fire (U_{10_ACF}) in thinned stands was 88% for maritime pine and 151% for radiata pine, expressed in relation to the respective control values. Once an active crown fire started, rate of spread (R_c) was always higher in the control than in the thinned plots, especially for radiata pine.

3.3.2. Comparison of fireline intensity (I)

For maritime pine, potential fireline intensity for extreme percentiles of M_s and U_{10} was reduced from 31302 kW m^{-1}, in the representative control plot, to 27705 kW m^{-1} in the representative thinned plot. Nevertheless, those differences were more pronounced for radiata pine with values of 31960 kW m^{-1} and 11333 kW m^{-1}, respectively.

3.3.3. Percentage of type of fire according fireline intensity

Overall, the mid-term effect of thinning was a slight increase in the number of simulations within the higher fireline intensity group D ($I > 4000$ kW m^{-1}), especially in maritime pine (Table 3). However, it is important to emphasize that the percentage of active crown fires was significantly lower in both species (62.5% and 90% of reduction for maritime and radiata pine, respectively) in the thinned relative to the control plots. Nevertheless, the percentage of passive crown fires increased (105% and 92%, respectively).

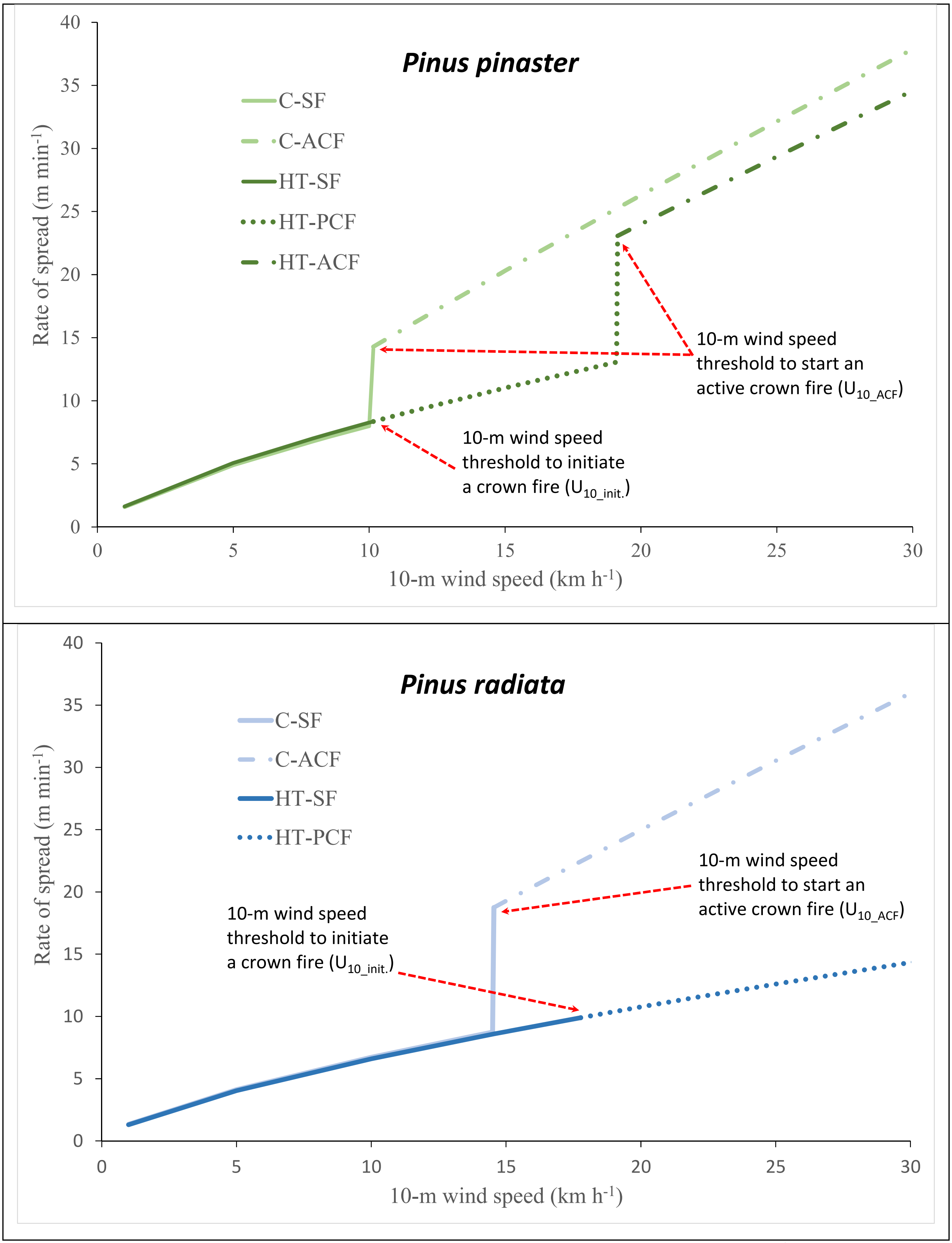


Figure 6. Fire rate of spread as a function of 10-m open wind speed (km h^{-1}) estimated for the extreme percentile of M_s (9%) in the representative plot of each treatment for *P. pinaster* (upper) and *P. radiata* (lower) six years after treatment. C = control treatment; HT = heavy thinning treatment; SF = surface fire; PCF and ACF = passive and active crown fire, respectively.

Table 3. Distribution of number of simulations by species, treatment and fireline intensity ranges six years after treatment. SF = surface fire; ACF = active crown fire; PCF = passive crown fire; C = control and HT = heavy thinning.

Species and Treatment			Group A (I< 500 kW m^{-1})	Group B (500≤I<2000 kW m^{-1})	Group C (2000≤I<4000 kW m^{-1})	Group D (I≥4000 kW m^{-1})	Total
P. pinaster	C	SF	1839 (6.6%)	9353 (33.6%)	6825 (24.6%)	3424 (12.3%)	21441 (77.1%)
		PCF	0	71 (0.2%)	933 (3.4%)	2487 (8.9%)	3491 (12.5%)
		ACF	0	0	237 (0.8%)	2661 (9.6%)	2898 (10.4%)
		Total	1839 (6.6%)	9424 (33.8%)	7995 (28.8%)	8572 (30.8%)	27830
	HT	SF	938 (3.4%)	7861 (28.2%)	6851 (24.6%)	3951 (14.2%)	19601 (70.4%)
		PCF	0	0	1665 (6.0%)	5466 (19.7%)	7197 (25.7%)
		ACF	0	0	8 (0.0%)	1090 (3.9%)	1098 (3.9%)
		Total	938 (3.4%)	7861 (28.2%)	8524 (30.6%)	10507 (37.8%)	27830
P. radiata	C	SF	2219 (9.2%)	8474 (35.3%)	6747 (28.1%)	3399 (14.1%)	20839 (86.7%)
		PCF	0	0	124 (0.5%)	2455 (10.2%)	2579 (10.7%)
		ACF	0	0	0	617 (2.6%)	617 (2.6%)
		Total	2219 (9.2%)	8474 (35.3%)	6871 (28.6%)	6471 (26.9%)	24035
	HT	SF	1722 (7.2%)	8449 (35.1%)	6073 (25.3%)	2770 (11.5%)	19014 (79.1%)
		PCF	0	0	422 (1.7%)	4538 (18.9%)	4960 (20.6%)
		ACF	0	0	0	61 (0.3%)	61 (0.3%)
		Total	1722 (7.2%)	8449 (35.1%)	6495 (27.0%)	7369 (30.7%)	24035

3.4. Simulated deferred effect of heavy thinning on fire severity

The mean scorch height (h_s), for all combinations of M_s and U_{10}, differed significantly between treatments (17.49 and 18.90 m for control and thinned maritime pine plots, respectively, and 16.95 and 17.22 m for control and thinned radiata pine plots, respectively). h_s differed significantly between treatments for all the fireline intensities in *P. pinaster* and only for I < 2000 kW m^{-1} in *P. radiata* (Figure 7).

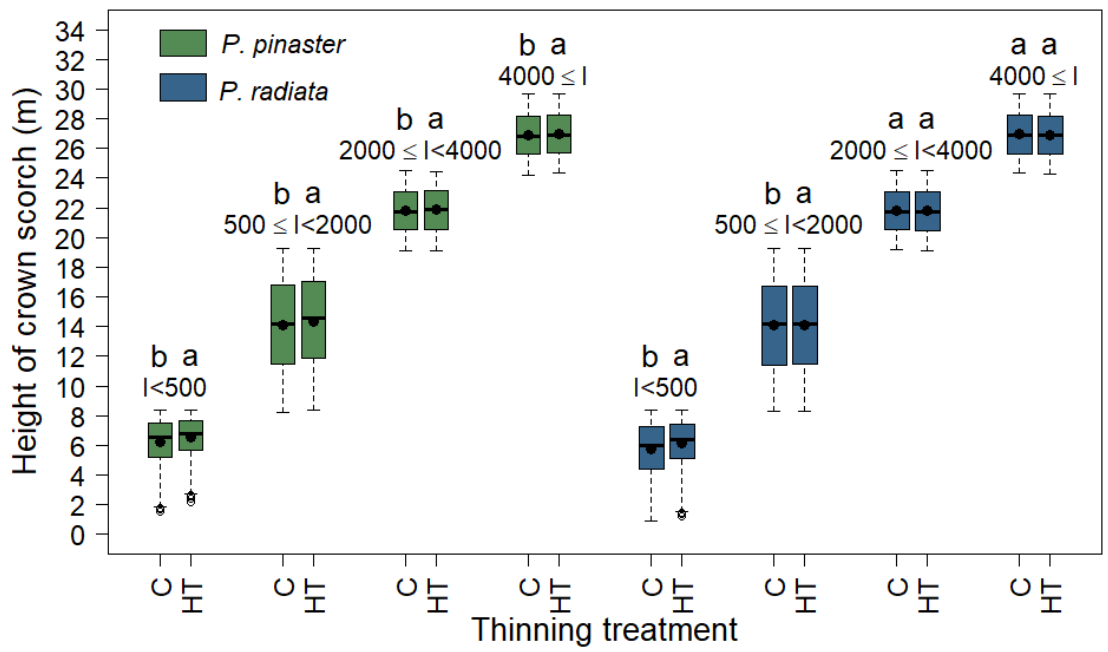


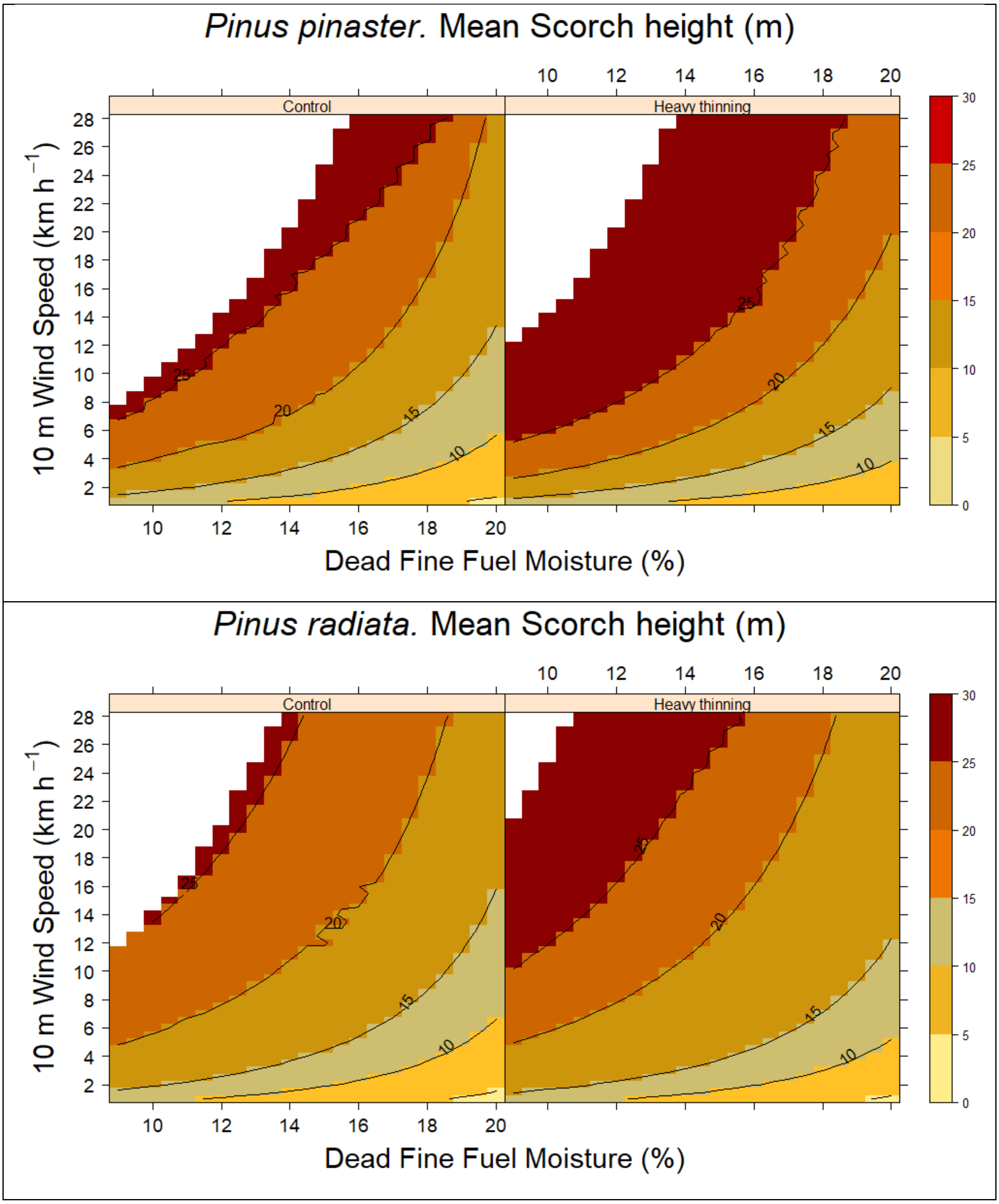
Figure 7. Box plot of the potential crown scorch height for each species, treatment and fireline intensity ranges (kW m^{-1}) six years after thinning. C = control; HT = heavy thinning. Different letters indicate significant differences between mean values ($\alpha = 5\%$). Black dots represent mean values.

Contour plots of the mean value of the scorch height (h_s), percentage of scorch crown volume (CV_s) and mortality ($p_{tree\_mortality}$) are shown in Figures 8, 9 and 10, respectively, enabling visual comparison of the influence of treatments and pine species for each combination of fine fuel moisture (M_s) and 10-m open wind speed (U_{10}).

As expected, the highest mean values of h_s, CV_s and $p_{tree\_mortality}$ corresponded to the lowest fuel moisture content and highest wind speed and all these variables showed more sensitivity to wind for low M_s than for high (Figures 8, 9 and 10). Overall, for the same M_s and U_{10} values, the mean estimates of h_s, CV_s and $p_{tree\_mortality}$ were higher in heavily thinned than in control plots for both maritime and radiata pine. These differences resulted in generally larger areas between isolines for thinning plots for increasingly unfavourable fire danger scenarios.

Regarding the CV_s estimates, the mean values of all the simulations analysed were 81.7% and 90.0% for control and thinned plots of maritime pine, respectively, and 65.4% and 72.2% for control and thinned plots of radiata pine, respectively. Significant differences between treatments were observed for both species.

The mean values of post-fire tree mortality ($p_{tree\_mortality}$) in maritime pine plots were significantly different between treatments in both situations: 0.73 and 0.84 for control and thinned plots without post-fire beetle attack, respectively and 0.81 and 0.90 for control and thinned plots with post-fire beetle attack, respectively. In both cases, the values were above the $p_{tree\_mortality}$ threshold (0.5) proposed by Vega et al. (2011) for the model. In fact, the area below the isoline corresponding to this threshold represented only a small portion of the total area coloured, and the effect was more pronounced in thinned plots.


Pinus pinaster. Mean Scorch height (m)

Pinus radiata. Mean Scorch height (m)

Figure 8. Contour plots of the potential mean scorch height estimates for *Pinus pinaster* (upper) and *Pinus radiata* (lower) for control (left) and heavy thinning (right) six years after treatment. White area corresponds to combinations with fireline intensities higher than 4000 kW m^{-1} and/or at least one sample plot with an active crown fire.

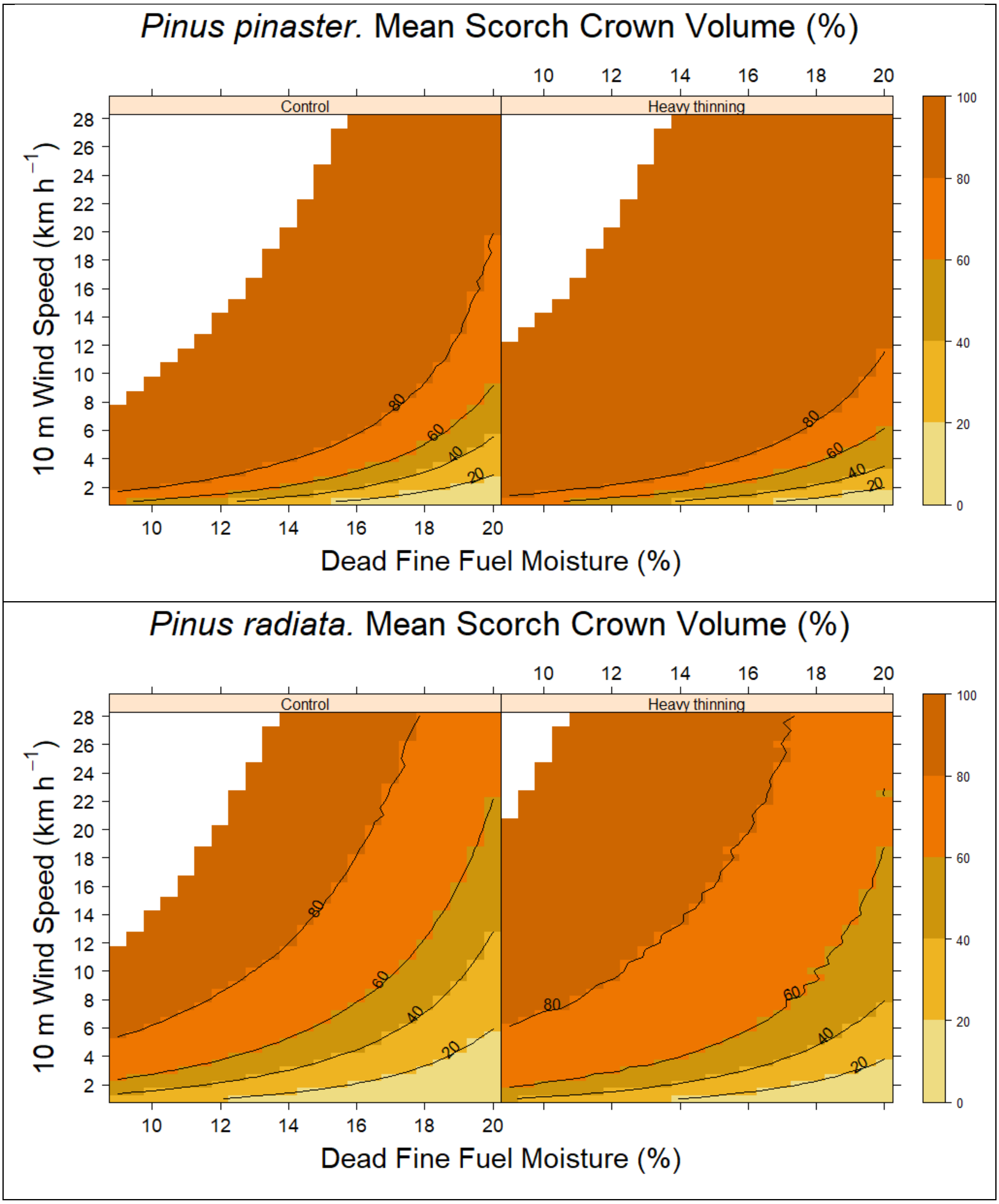


Figure 9. Contour plots of the potential mean scorch crown volume (%) for *Pinus pinaster* (upper) and *Pinus radiata* (lower) for control (left) and heavy thinning (right) six years after treatment. White areas correspond to combinations with fireline intensities higher than 4000 kW m^{-1} and/or at least one sample plot with an active crown fire.

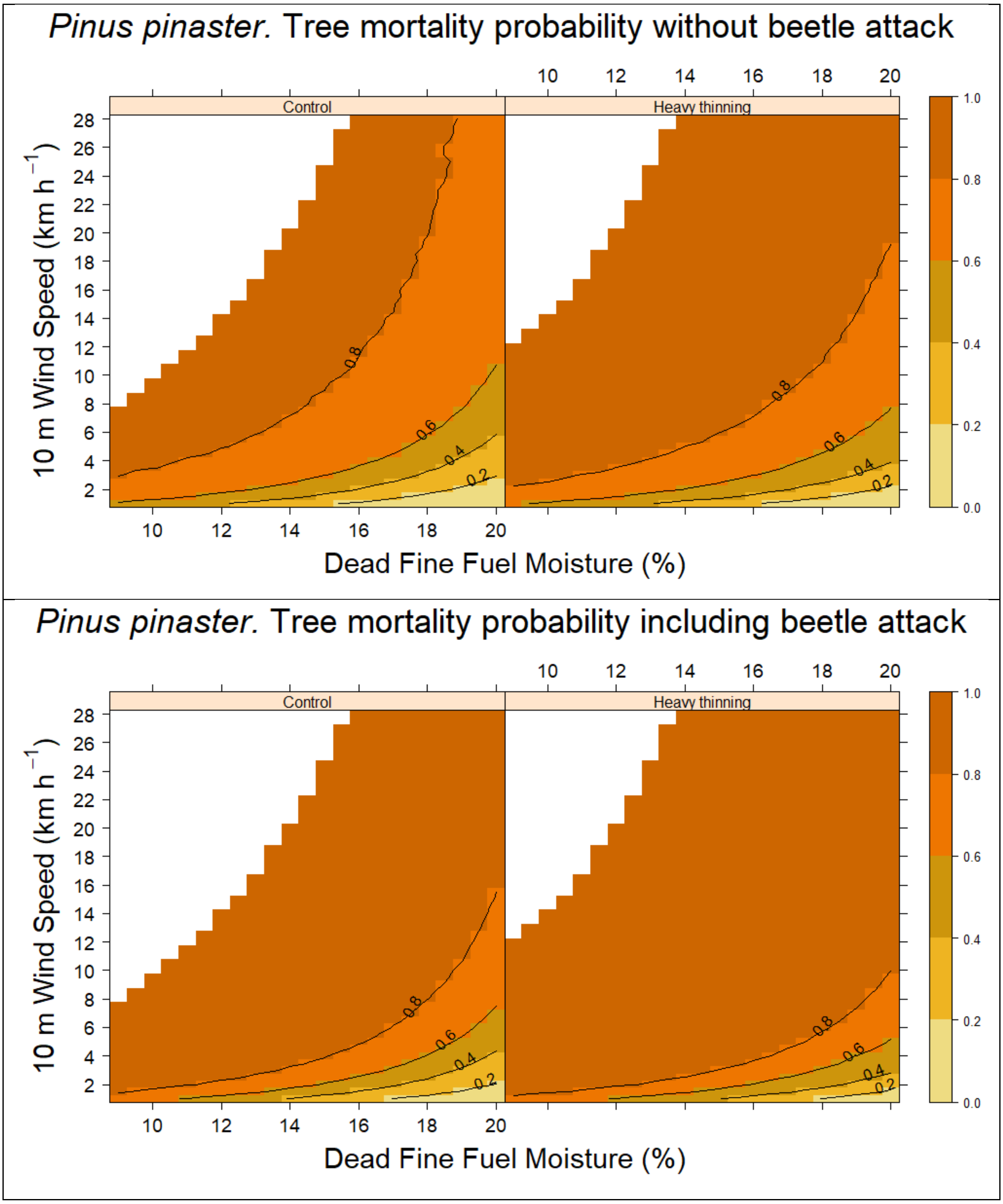


Figure 10. Contour plots of potential three years post-fire tree mortality estimated using equation C.2 for *Pinus pinaster* without post-fire beetle attack (upper) and with post-fire beetle attack (lower) for control (left) and heavy thinning (right) six years after treatment. White areas correspond to combinations with fireline intensities higher than 4000 kW m^{-1} and/or at least one sample plot with an active crown fire.

3.5. Effect of heavy thinning on the protection against potential post-fire soil erosion

The models (based on Equation 1) used to estimate the potential percent soil cover (SC) from the dead needles caused by a fire explained more than 98% of the observed variability (Table 4); all the parameters were significant, and the plots of studentized residuals versus observed values do not show any trend suggesting violations of the assumptions of ordinary nonlinear least squares.

Table 4. Parameter estimates and goodness-of-fit statistics of fitting equation (4) relating the percent soil cover (SC) to the dead needle load (W_{dn}) for each species.

Species	Parameter	Estimate	Std. Error	RMSE	ME
Pinus pinaster	*a*	3.6818	0.0466	2.3252%	0.9920
Pinus radiata	*a*	4.7395	0.0850	2.9117%	0.9867

Once these equations were fitted, contour plots of the mean value of soil cover (SC) by species and treatments for combinations of fine fuel moisture (M_s) and 10-m open wind speed (U_{10}) were obtained (Figure 11).

The mean values of SC, estimated considering all the simulations used**,** were 76.1% and 80.0% for control and thinned maritime pine plots, respectively and 67.2% and 70.2% for control and thinned radiata pine plots, respectively. Significant differences between treatments were found for both species.

Considering a value of 70% of soil cover as a threshold for an effective soil protection **(**Cerdà and Doerr, 2008; Robichaud et al., 2010), this figure was exceeded for a wide number of combinations of M_s and U_{10} for both species and treatments, particularly for maritime pine.

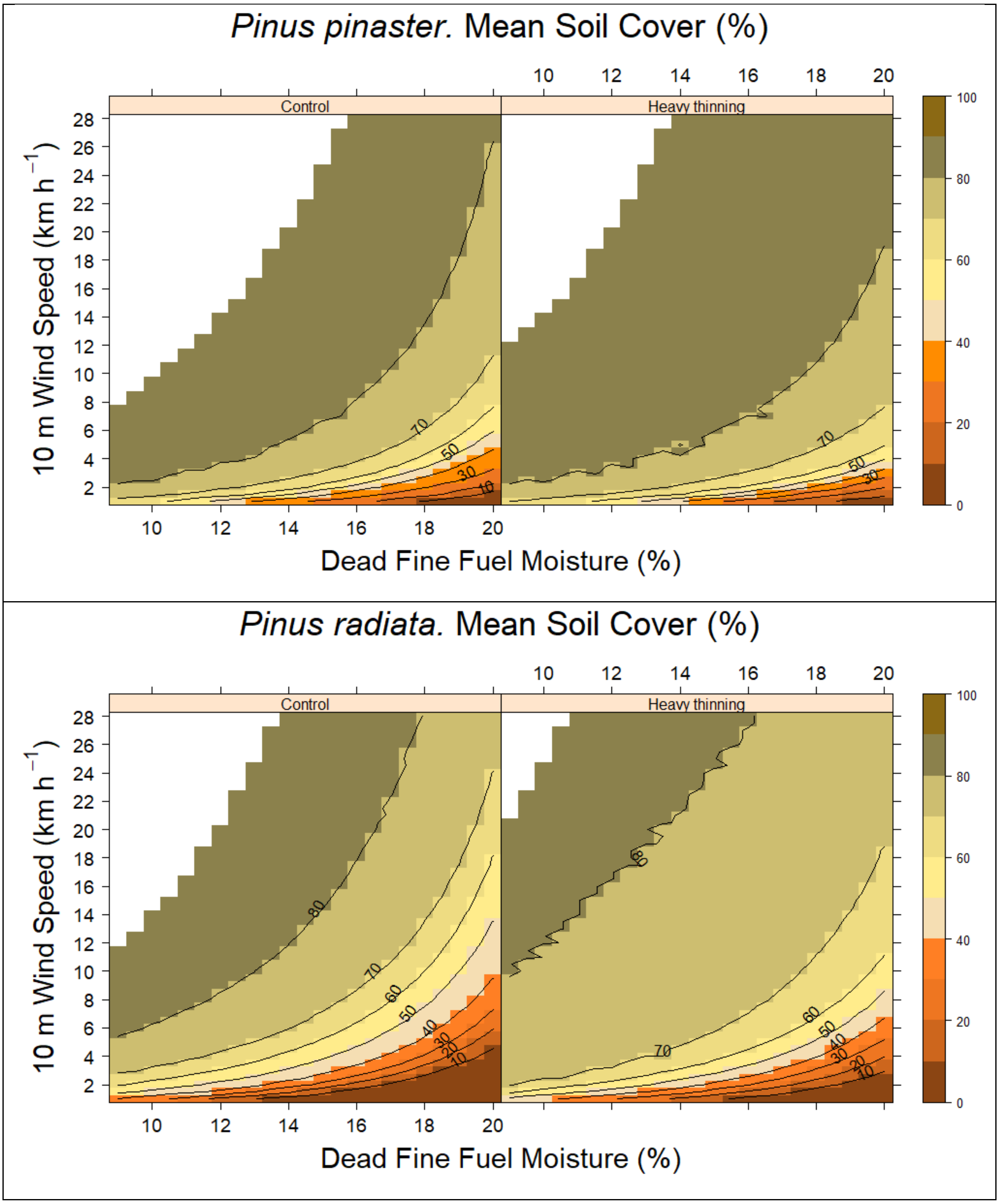


Figure 11. Contour plots of the potential mean percent of post-fire soil cover due to the fall of the dead needles from the scorch canopy volume for *Pinus pinaster* (upper figure) and *Pinus radiata* (lower figure) for control (left column) and heavy thinning (right column) six years after treatment. White areas correspond to combinations with fireline intensities higher than 4000 kW m^{-1} and/or at least one sample plot with an active crown fire.

4. DISCUSSION

4.1. Stand and canopy fuel variables response

The lack of reaction of CBH to thinning in maritime pine in the present study is consistent with the observations of Fernández-Alonso et al. (2013), Gómez-Vázquez et al. (2013) and Ruiz-González et al. (2015) in the same area and was probably enhanced by the marked self-pruning of the species, even at low stocking levels (Fernandes and Rigolot, 2007). The slightly lower CBH in heavily thinned plots of radiata pine six years after the treatment was probably due to enhanced lower branch elongation associated with increased light availability (Mead, 2013).

On the other hand, the smaller CBD and CFL for thinned maritime pine plots six years after treatment disagree with Soler et al. (2017), who did not observe any change in CBD seven years after thinning. Nevertheless, the different stand and environmental characteristics and the type of thinning carried out (systematic thinning, based on the position of the trees) in the latter study preclude direct comparisons. Six years after treatment only the mean value of the CBD for the thinned radiata pine remained below the threshold of 0.10 kg m^{-3} (Figure 4 lower, red dotted line for CBD), recommended for strong reduction in crowning (e.g. Graham et al., 1999; Scott and Reinhardt, 2001; Cruz et al., 2005).

4.2. Surface fuel variables

The higher understory fine fuel load (W_{us_1}) in thinned stands caused an increase in SFFL as W_{FWD_1h} and W_L did not differ between treatments. This result suggests a remaining effect of a probable shrub expansion in the first years following a decrease in canopy cover (CC) in thinned plots. Several factors may have positively and negatively affected the understory response for 6 years after treatment. The increased levels of light, nutrients and water availability following thinning may have favoured understory expansion (Castedo-Dorado et al., 2012). Also, thinning operations may have disturbed understory and thinning slash left on site could partially and temporarily obstruct understory regrowth (Abella and Springer, 2015). In addition, the rapid CC recovery in these fast-growing pine species probably contributed to preventing a marked increase in the understory layer. On the other hand, understory in many plots, particularly in radiata pine stands, was dominated by fern and raspberry, which are not very responsive to changes in light availability (Ricard and Messier, 1996; Gaudio et al., 2011), thus explaining the lower response of the understory load in radiata pine.

The existing literature on the effects of thinning shows that the most frequent response is an increase in understory biomass in different conifer ecosystems (e.g. Son et al., 2004; Zhou et al., 2016), including Mediterranean climate stands (Navarro et al., 2010). The response observed in the present study for maritime pine and, to a lesser extent in radiata pine, supports those results. Regarding the understory cover, a limited thinning impact is the most frequently reported result in different ecosystems for periods ranging from 2 to 19 years (Nelson et al., 2008; Huffman et al., 2013; Abella and Springer, 2015; Willms et al., 2017), as found in the present study.

The absence of significant differences between observed duff loads (W_{FH}) in control and thinned plots suggests that the decomposition rate was not substantially altered by thinning and that the microclimatic conditions in thinned stands were probably not much worse. This would indicate similar smoulder combustion risk six years after thinning in both treatments and for both species, assuming similar duff moisture contents due to the equivalence of CC between treatments.

4.3. Potential fire behaviour

The coincidence of the rate of spread in the surface fire (r) phase in both treatments for the representative plots of maritime and radiata pine (Figure 6) was due to the lack of difference in the independent variables in the prediction equation of r (B.5).

The high 10-m open wind speed threshold for starting an active crown fire (U_{10_ACF}) in both pines in the representative thinned plot is a consequence of the notable reduction in CBD, which affects the balance between the critical spread rate for active crown fire (R_0) and the active crown fire rate of spread (R_c). This was more pronounced for radiata pine and consistent with the greater reduction in CBD in this species over the six-year period. In turn, the decrease in CBD implied lower R_c in thinned than in control plot for both pines. This response agrees with the results obtained by Fulé et al. (2012) in a review of the effects of thinning in western USA pine-dominated forests, although focused on short-term thinning effects.

The response of the potential fireline intensity (I) to thinning for the extreme percentiles of U_{10} and M_s in both species is in line with that reported by Cruz et al. (2017) for *Pinus radiata*, although the differences between treatments were less pronounced in the present study. This may be because of the greater presence of thinning debris on ground in our study.

According to a more comprehensive vision given by a wide range of combinations of U_{10} and Ms (Table 3), the mid-term effects of thinning would not be as favourable, since the number of potential fires in the highest fireline intensity group (group D) would be larger in thinned than in control stands. This response would be caused by a slight increase in FD and w_a.

From the standpoint of the potential environmental impact of fire, the effect of thinning on the reduction in occurrence of active crown fire (ACF) was very important in relative terms but more modest in absolute terms. Given the highly destructive potential of ACF, the extreme effort associated with its suppression and the elevated risk for firefighters, the result is remarkable. The smaller number of ACF in radiata pine plots can be explained by their different structural characteristics (higher CBH, lower CBD), as surface fine fuel characteristics were similar for both pine species. Consequently, the effects of thinning in reducing ACF occurrence were more important in maritime than in radiata pine.

Although there is abundant information available on fuel reduction effects on potential fire behavior, paradoxically there is a gap of information about mid-term effects of thin-only based on field fuel inventory, particularly for maritime and radiata pines. Our findings are consistent with those of Waldrop et al. (2010), who observed only slight differences in simulated fire behaviour characteristics of thinned and control stands five years after thinning. They are also consistent with those of Ziegler et al. (2017), who reported a long-term (ten year) decrease in potential fire behaviour parameters. However, the differences in stand structure and composition and thinning treatment preclude direct comparisons.

While surface fuels were not assessed in the first three inventories after thinning, the changes in the canopy variables suggest possible associated changes in surface fuels as above mentioned. Furthermore, a temporary decrease in litter moisture (M_s) as Ruiz-Gonzalez (2007) found in thinned maritime pine in NW Spain and as also observed in other ecosystems (Cruz et al., 2014; 2017) likely occurred. Also, an increase in wind penetrability due to a larger WAF probably took place. Those three changes may result in an increase in surface fire (SF) behaviour potential in thinned stands in the short term. Overall, although this complex scenario precludes straightforward generalizations, it suggests the worsening of fire behaviour after thin-only in the short-term with: i) more intense SF; ii) lower $U_{10\text{-init.}}$ values; iii) more difficult transition to ACF and iv) higher R_c values, once ACF started, given its greater sensitivity to variations in M_s than in CBD (equation B.9). This is consistent with the findings reported by Cruz et al. (2008) for heavily thinned radiata pine stands and also with findings regarding other species (Raymond and Peterson, 2005; Stephens and Moghaddas, 2005; Waldrop et al., 2010) in which thinning slash was also left on the ground.

4.4. Potential fire severity after thinning

The slightly higher level of damage detected in thinned compared to control plots, for the same combination of U_{10} and M_s, is because the fireline intensity (I) was slightly higher in the treated stands. The latter was due to a somewhat higher available fuel load (w_a) and slight increase in the surface fire rate of spread (r).

Due to the structure of the empirical equation used to estimate crown scorch height (h_s) the I value plays a predominant role in the estimation of this variable. Van Wagner (1973) did not clarify what fuel consumption was used in the I equation. We assumed that fuel consumption included fine fuels and variable proportions of medium fuels and F-layer, depending on M_s values (Cruz et al., 2006; Cruz and Alexander, 2017). Indeed, our approach to fuel consumption as a function of Ms is too simplified since other factors play a role in that process (e.g. Brown et al., 1985; Fernandes and Loureiro, 2013; Prichard et al., 2017). In fact, our modelling underestimated of the F-layer consumption for high values of M_s, with respect to the predictions of Fernandes and Loureiro's (2013) model, particularly when the moisture profile in the forest floor is not very marked. On the other hand, for low M_s, the values obtained in our study were very similar to those predicted by the above-mentioned model. Still, given that the equation proposed by Fernandes and Loureiro (2013) was developed based on prescribed burning carried out from autumn to spring, with a marked moisture profile in the forest floor, that comparison must be taken with caution. Although this raw approximation of the fuel consumed can be clearly improved, we think that it does not substantially alter the results of the comparison between treated and untreated stands, since the same method was used in both cases.

In our case the variability in I depended more on the large variation in w_a, due to the change in M_s, than on wind speed variability, as the mid-flame wind speed was strongly limited by the low values of WAF. Therefore, h_s estimates were ultimately more dependent on M_s than on U_{10}, especially at high values of M_s, whereas for low fuel moisture the influence of both variables was very similar. This same reasoning extends to scorch crown volume (CV_s) and post-fire individual tree mortality ($p_{tree\_mortality}$).

The differences in response in h_s estimates between pine species appear to be primarily related to differences in stand height ($\bar{h}$), FD and wind penetrability in both species The higher values of CV_s in maritime pine were probably due to lower CBH and crown length values in this species.

The values of h_s should be considered as a first approximation and taken with caution, mainly because the Van Wagner´s model of h_s (equation C.1) does not directly consider the effect of terrain slope (neither do any of the currently available equations for estimation of h_s: Alexander and Cruz, 2012a). On steep terrains, hot convective gases flow up the slope closer to the surface than on flat terrain (Cheney and Sullivan, 2008), and overestimation of h_s is thus expected.

The high post-fire tree mortality ($p_{tree\_mortality}$) in maritime pine for most wind and moisture conditions considered was due to the simulated CV_s values were frequently higher than the two-third threshold for tree survival usually considered for this species (Vega et al., 2011; Catry et al., 2010). Regarding radiata pine some authors consider that this species is more sensitive to fire than *P. pinaster* (Luke and McArthur, 1978; Fernandes et al., 2008) although no model has yet been developed for predicting post-fire mortality.

Low-intensity surface fires can also kill the cambium of thin bark trees, since fire-caused tree mortality results from injuries not only to the crown, but also to the bole and roots (Hood et al., 2018). Nevertheless, mortality from convective and radiative heating from surface fires is more challenging to predict than from crown scorch height (Hood et al., 2018).

Information about the effect of thinning only on the severity of a subsequent fire is very limited. Some studies have reported significantly lower canopy CV_s in thinned conifer stands than in untreated ones (Omi and Martinson, 2002; Cram et al. 2006; Ritchie et al., 2007), while others have revealed a higher level of canopy damage (Raymond and Peterson, 2005; Omi et al., 2006).

The tree mortality after wildfire affecting thinned only and unthinned areas showed a complex response. In some cases there was no difference in mortality (Prichard et al., 2010), while in other cases the mortality was lower in thin-only stands (Prichard and Kennedy, 2012; Safford et al.; 2009; 2012).

4.5. Soil protection against potential post-fire erosion

The estimated value of parameter “a” for maritime pine (3.7) in the equation fitted to relate needle fall mass and soil cover was almost the same as those reported for different pine species (Gilley et al., 1991) and also for ponderosa pine (Pannkuk and Robichaud, 2003), a species with similar needle dimensions to maritime pine. The higher estimated value of “a” for radiata pine resulted in a slightly higher SC capacity (15%) for the 0.2-0.8 kg m^{-2} needle load range. However, given that the mean CVs was much lower in radiata pine than in maritime pine, the combined result was a reduction in the capacity to protect burned soil in radiata pine stands.

Six years after thinning, most fires potentially occurring in a wide range of U_{10} and M_s would generate enough needle cast to effectively reduce post-fire erosion in both treatments and species. This is important from the ecosystem resilience perspective and mitigation of wildfire impacts on potentially threatened human communities. Our results are compatible with the predictions reported by Vega et al. (2013) for the same species, On the other hand, the slightly higher capacity of thinned stands to cover soil appears irrelevant from a practical standpoint.

5. CONCLUSIONS

Our results showed that, relative to fuel hazard reduction, the thin-only treatment significantly and moderately increased the load of the fine surface fuels even in the mid-term. However, the treatment was still effective in reducing CBD. These effects on the fuels resulted in an increase in the fireline intensity of a potential surface fire, and therefore in greater capacity for crown fire initiation, although lower risk and rate of spread of active crown fire once this it started.

Overall, the potential severity (in terms of crown scorch height and volume and tree mortality) caused by hypothetical post-thinning fire was hardly altered by the treatment. In addition, protection of soil against erosion improved only slightly when thinning has previously been carried out, although again the differences were unimportant in practical terms.

Although our study did not evaluate surface fuels in the first years after thinning, our data suggests that it is possible that the situation from a surface fuel hazard reduction point of view was more unfavourable than in the mid-term. This point needs to be further investigated.

On the whole our results show that thin-only is not an effective treatment to reduce the intensity and effects of a possible fire affecting the treated area. Since its main limitation is due to its effect on surface fuels, its reduction is critical from the point of view of fire management. Consequently, treatments such as prescribed burning, mastication or surface fuel removal for energy could clearly improve their effectiveness and are strongly recommended.

The results also highlight the need of a comprehensive assessment of the effects of thin-only on both the whole fuel complex and microclimatic variables for obtaining realistic results.

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APPENDIX A

Equations used to estimate surface fuel loads

The total understory load (W_{us_total}, kg m^{-2}), the fine understory load (W_{us_1}, particles with diameter < 0.6 cm, kg m^{-2}) and litter and duff layers fuel loads (W_L, W_F and W_H, kg m^{-2}) were calculated using the equations proposed by Arellano-Pérez (2011) for these types of fuels in pine stands in Galicia:

$W_{us\_total} = 0.0052 * \overline{d_{us}} + 0.2095 * \left(\frac{100}{H * \sqrt{N}}\right)^{0.7035} * \overline{d_{us}}^{0.4514}$	(A.1)
$W_{us\_1} = 0.2095 * \left(\frac{100}{H * \sqrt{N}}\right)^{0.7035} * \overline{d_{us}}^{0.4514}$	(A.2)
$W_L = 0.02166 + 0.1998 * \overline{d_L}$	(A.3)
$W_{LF} = 0.2992 + 0.1549 * \left(\overline{d_L} + \overline{d_L}\right)$	(A.4)
$W_{LFH} = 0.5374 * \left(\overline{d_L} + \overline{d_F} + \overline{d_H}\right)^{0.787}$	(A.5)

where $\overline{d_{us}}$, $\overline{d_L}$, $\overline{d_F}$ and $\overline{d_H}$ are the depth (cm) of understory, litter and duff layers, respectively; H is the stand dominant height (m) and N is the number of stems per hectare.

APPENDIX B

Mid-term effect of heavy thinning on the potential fire behaviour

The approaches used to estimate the fire behaviour metrics were as follows:

i) Variation in fire spread rate for a range of wind speed (U_{10})

The first step was to estimate the critical surface intensity (I_0) needed to initiate crowning. The model proposed by Van Wagner (1977) was applied:

$$I_0 = [0.01 * CBH * (460 + 25.9 * M_c)]^{1.5} \tag{B.1}$$

where I_0 is the critical fireline intensity (kW m^{-1}), CBH is the mean canopy base height (m) and M_c is the foliar moisture content (%). M_c was assumed to be equal to 130% for plots located in areas strongly affected by the Atlantic ocean climate influence, where summer drought is frequently low (Pontevedra, A Coruña, Lugo and Asturias) according to the mean values observed for radiate pine in the study area (Ruiz-González et al., 2010) and 110% for areas characterised by typical Mediterranean climate (Southern Lugo, Ourense and Leon) and usually affected by intense summer drought (Míguez-Castro, 2010).

Once I_0 was obtained, the second step was to estimate the critical surface fire rate of spread (r_0) by substituting the critical fireline intensity (I_0) in the model proposed by Byram (1959) to estimate fireline intensity (I, kW m^{-1}) (Eq. B.2) and solving for r (m s^{-1}):

$$I = H_{comb} * w_a * r \tag{B.2}$$

$$r_0 = \frac{I_0}{H_{comb} * w_a} \tag{B.3}$$

where H_{comb} is the net low heat of combustion (kJ kg^{-1}) and w_a is the fuel load consumed in the active flaming front (kg m^{-2}).

Net low heat of combustion (H_{comb}) was fixed at 18,828 kJ kg^{-1} (Van Wagner, 1973). Fuel load consumed (w_a ,kg m^{-2}) was computed as follows:

$$w_a = W_{us\_1} + W_{FWD\_1h} + W_L + \frac{\left(W_{FWD\_10h} + W_F + W_{us\_23}\right) * (20 - M_s)}{11} \tag{B.4}$$

where W_{us_23} is the difference between total understory (W_{us_total}) and fine understory loads (W_{us_1}).

The third step consisted of estimating the 1.5-m in-stand wind speed threshold to initiate crown fire ($U_{1.5\_init.}$) from the r_0 value obtained in Eq. (B.3). The empirical model proposed by Fernandes et al. (2009) was used together with the initial multiplicative parameter modification proposed by Fernandes (2014) (Eq. B.5). This model was used to estimate the surface fire rate of spread for maritime pine stands in Portugal. Given the similarities in fire behaviour in radiata pine and maritime pine plantations (Cruz et al., 2008; Cruz and Alexander, 2017), the model is assumed to be appropriate for the study area and the tree species analysed.

$$r\ (m\ s^{-1}) = 0.034 * U_{1.5}^{0.707} * \exp(0.062 * S - 0.039 * M_s) * FD^{0.188} \tag{B.5}$$

$$U_{1.5\_init.} = \left(\frac{r_0}{0.034 * \exp(0.062 * S - 0.039 * M_s) * FD^{0.188}}\right)^{1/0.707} \tag{B.6}$$

where $U_{1.5}$ is the 1.5-m in-stand wind speed (km h^{-1}), S is the terrain slope (º), M_s is the moisture content of fine dead surface fuels (%) and FD is the surface fuel depth (cm).

The 1.5-m in-stand wind speed $U_{1.5\_init.}$ was then converted to open wind velocity, measured at 6 m height (U_6), by dividing by the sheltered wind adjustment factor (WAF) per plot obtained using the model proposed by Andrews (2012) (Eq. B.7):

$$WAF = \frac{0.555}{\sqrt{1.0936 * CC * CR * \bar{h} * ln\left(\frac{20 + 1.1811 * \bar{h}}{0.4265 * \bar{h}}\right)}} \tag{B.7}$$

where CC is the plot canopy cover and CR is the plot crown ratio, calculated for each plot by dividing average crown length ($\bar{h}$ - CBH) by mean stand height ($\overline{h}$). Finally, each value of $U_{6\_init.}$ was divided by 0.87 to estimate $U_{10\_init.}$ (Turner and Lawson, 1978).

The 10-m open wind speed threshold to start an active crown fire (U_{10_ACF}) was obtained in two steps. Initially, the critical minimum spread rate for active crown fire (R_0, m min^{-1}) was estimated from canopy bulk density values (CBD, kg m^{-3}) by applying the criterion proposed by Van Wagner (1977) (Eq. B.8):

$$R_0 = \frac{3}{CBD} \tag{B.8}$$

Once R_0 was obtained, U_{10_ACF} was estimated by substituting R_0 in the model of active crown fire rate of spread (R_c, m min^{-1}) developed by Cruz et al. (2005) (Eq. B.9):

$$R_c = 11.02 * U_{10}^{0.9} * CBD^{0.19} * e^{-0.17 * M_s} \tag{B.9}$$

$$U_{10\_ACF} = \left(\frac{R_0}{11.02 * CBD^{0.19} * e^{-0.17 * M_s}}\right)^{1/0.9} \tag{B.10}$$

where U_{10} is the 10-m open wind speed (km h^{-1}) and M_s is the moisture content of fine dead surface fuels (%).

ii) Comparison of fireline intensity (I)

The crown fraction burned (CFB) was calculated using the model proposed by Van Wagner (1993) for mature stands:

$$\mathrm{CFB} = 1 - e^{-0.108 \cdot (\mathrm{r} - \mathrm{r_0})} \tag{B.11}$$

where r is the surface fire rate of spread (m min-1) and r0 is the critical surface fire rate of spread (m min-1), estimated by equations B.5 and B.3, respectively. For passive crown fires, the CFL partial load, obtained by multiplying CFB by CFL, was added to the values of w_a obtained from Eq. (B.4).

APPENDIX C

Simulated deferred effect of heavy thinning on fire severity

The equations used to estimate the potential fire severity were:

i) mean height of tree crown scorch (h_s)

Mean crown scorch height (h_s, m) per plot was calculated using the empirical model developed by Van Wagner (1973):

$$h_s = \frac{0.7418 * I^{7/6}}{\sqrt{0.0256 * I + 0.0214 * U_{1.2}^3} * (60 - T)} \qquad \text{(C.1)}$$

where I is the Byram's fireline intensity (kW m^{-1}, equation B.2), T is the ambient air temperature (ºC) and $U_{1.2}$ is the 1.2 m in-stand wind speed (km h^{-1}). The ambient air temperature (T) was fixed for all simulations to 25ºC corresponding to the 75th percentile of temperature at 1400 h (local time) for the fire season in the study area. The values of $U_{1.2}$ were calculated by multiplying U_{10} values by 0.87 to estimate 6-m wind speed (Turner and Lawson, 1978) and these values were subsequently converted to 1.5-m in-stand wind speed by multiplying by the sheltered wind adjustment factor (WAF) obtained using equation (B.7) and then assuming that in-stand wind speed is the same at 1.2 and 1.5 m.

ii) mean value of probability of post-fire tree mortality ($p_{tree\_mortality}$)

Mean probability of post-fire individual-tree mortality per plot, based on individual tree data, was assessed using the reduced model proposed by Vega et al. (2011) for *P. pinaster* stands in Galicia:

$$p_{tree\_mortality} = \frac{1}{1 + exp(1.444 - 0.052 * CV_s + 1.601 * X_{dummy})} \qquad \text{(C.2)}$$

The model estimates the probability that a tree will die ($p_{tree\_mortality}$) in the third post-fire year, by using as independent variables the total crown volume damaged (CV_s,) and a dummy variable (X_{dummy}), which takes a value of 0 when the tree was attacked by beetles post-fire and 1 otherwise (in this study, both situations were simulated).