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Wind and Snow Damage in the Pyrenees Pine Forests: Effect of Stand Attributes and Location

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Wind and snow-induced damage have been analyzed at stand level for three pine forests in the Central-Eastern Pyrenees (*Pinus nigra* Arn. *salzmanii*, *Pinus sylvestris* L. and *Pinus uncinata* Ram.). Stand-level models have been then developed for the most affected two species, *Pinus sylvestris* L. and *Pinus uncinata* Ram., to describe damage severity. The models were based on data from national forest inventory plots. They included variables related to the spatial location and structure of the stands, being validated using a sub-set of the database (25% of the plots randomly selected). Mountain pine forests (*Pinus uncinata* Ram.) were the most heavily affected by wind and snow disturbances. For both mountain and Scots pine species, topographic exposure and the severity of the local storm regime had an important effect on the degree of damage. Stand's resistance to wind and snow was found to be dependent on the combined effect of basal area and mean slenderness of the dominant trees. For a given slenderness ratio, damage increased strongly in lower-density stands, particularly in stands with basal areas below 15 m^2/ha. Stand structure was particularly important to define the resistance of Scots pine stands, which presented a higher vulnerability to wind and snow under higher degree of even-agedness. The models presented in this study provide empirically-based information that can be used to implement silvicultural practices to minimize the risk of those forests to suffer wind and snow-related damages.

Keywords conifers, models, Pyrenees, snow damages, stability, stand structure, wind damages
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1 Introduction

Natural forest disturbances caused by abiotic factors like wind and snowstorms are an integral part of forest ecosystem functioning and one of the main forces driving forest dynamics (Attiwill 1994, Ulanova 2000, Lieffers et al. 2003, Papaik and Canham 2006). The natural disturbances on the dominant forest strata can help the system to naturally regenerate, increase its biodiversity, and provide food and shelter for a large number of living organisms that benefit from the presence of deadwood (Angers et al. 2005). However, in many forested areas, wind and snow-induced damage can seriously compromise the productive and protective function assigned by forest managers. Europe has seen an increasing number of forest areas affected by snow and windstorms in recent decades (Doll 2000, Schelhaas et al. 2003). The occurrence and effects of these disturbances in any given forest generally depend on the climatic regime of the local area (Quine 2000), the topographical position and soil properties of the stand (Ruel et al. 1998, Mayer et al. 2005), and the stand structure and composition (Jalkanen and Mattila 2000, Mason 2002, Dhôthe 2005, Jactel et al. 2009).

Two different empirical approaches have been used to study the effects of wind and snowstorms in forest ecosystems: analyses based on a single catastrophic event (Canham et al. 2001, Cucchi and Bert 2003, Mayer et al. 2005) and analyses based on the study of disturbances occurring over a given period of time and in a defined area (Valinger and Fridman 1999, Jalkanen and Mattila 2000, Ni Dhubhain et al. 2001). The factors determining the magnitude of forest damage related to weather disturbances act at different levels (i.e. regional, landscape and stand level) (Ruel 2000). While climatic regime acts at a broad scale (Quine et al. 1995, Valinger and Fridman 1999), other factors, such as those related to stand characteristics, can be partially controlled through adequate forest practices.

Analysing forest damage caused by the natural regime of wind and snowstorms represents a big challenge for mountain ranges like the Pyrenees. These areas are characterized by sharp variations in the climatic conditions across the territory due to its topographical complexity and strong Mediterranean influence (Whiteman 2000, Lopez-Moreno et al. 2008). In addition, forest stands in the Spanish side of the Pyrenees present high structural and species composition variability (DGCN 2005), in contrast with the characteristic structures of most even-aged stands in other forests where the effects of wind and snowstorms have already been assessed (Lohmander and Helles 1987, Valinger and Fridman 1999, Jalkanen and Mattila 2000, Ni Dhubhain et al. 2001).

The present study aims to advance our understanding of the factors regulating the extent of wind and snowstorm damage on different conifer stands distributed across an altitudinal range in North-East Spain where this topic has never before been investigated. We first examined how factors related to the geographical position of the stands have influenced the degree of damage occurring in these systems over the last decade. We then developed regression models to analyze whether stand-associated attributes significantly determine the proportion of wind and snowstorm-damaged trees in forests dominated by the two most affected pine species.

2 Material and Methods

2.1 Description of the Study Area

The study area is located in the north-eastern part of the Iberian Peninsula. It occupies an area of over 22 620 km^2 and includes the southern slopes of the Eastern Pyrenees (Fig. 1). In this region, the strong Mediterranean influences and the complex topography (i.e. elevation ranges from sea level to over 3000 meters a.s.l.) cause important spatial variations in climatic conditions (del Barrio et al. 1990). Wind and snow damages to forests in this region are generally caused by winter storms centred on the mountain areas, which are normally dominated by coniferous forests (DGCN 2005).

Our study focused on stands in the Mediterranean-influenced Pyrenees region dominated by the three coniferous species most representative of montane and sub-Alpine belts (*Pinus nigra* Arn. *salzmanii*, *Pinus sylvestris* L. and *Pinus*

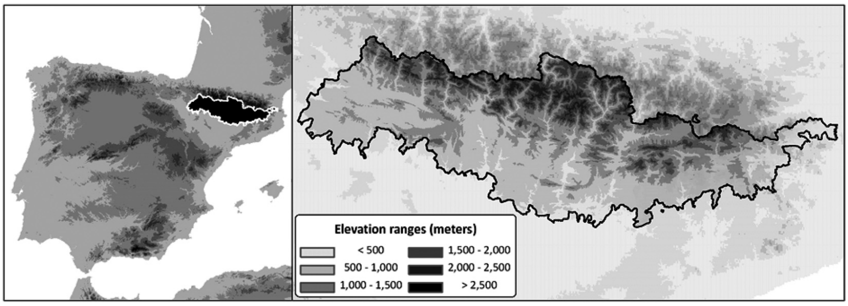

Fig. 1. Localization of the study area in north-eastern Spain.

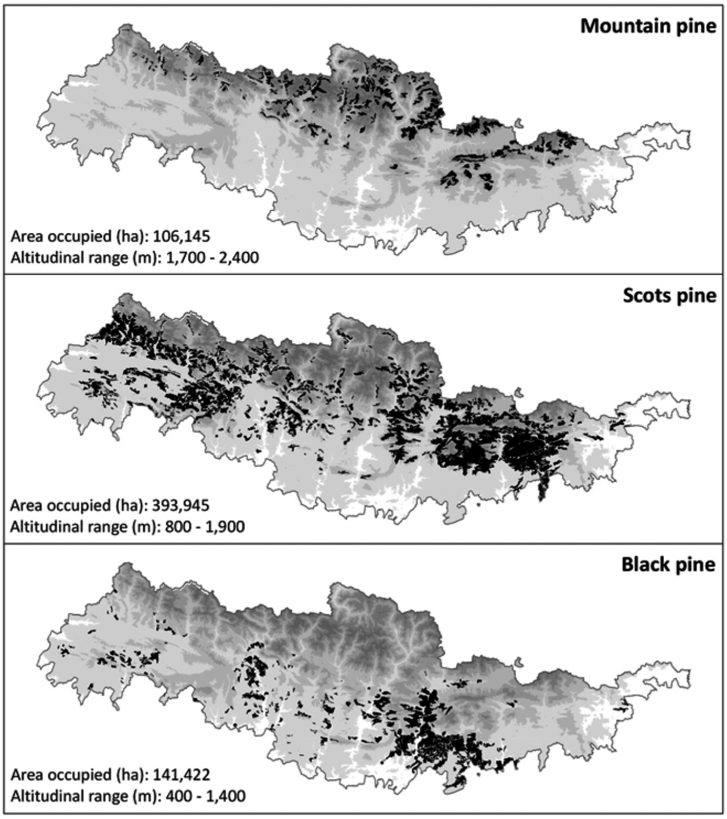

Fig. 2. Distribution area of mountain, Scots and black pines in the study area.

uncinata Ram.). The total forest area dominated by these species covers approximately 641 500 ha, mainly located in the Pyrenees and Pre-Pyrenees mountain ranges (Fig. 2).

A recent survey by Martín-Alcón and Coll (2008) highlighted that the forests most affected by wind and snow damage (hereafter termed 'WS-damage') at regional level in Catalonia were mountain pine (*P. uncinata*) and Scots pine (*P. sylvestris*). According to the mentioned study, around 36% of the forest surface dominated by mountain pine showed signs of WS associated damages, against 11.5% and 3.5% of the forest dominated by Scots pine and black pine (*P. nigra* Arn. *salzmanii*), respectively.

Table 1. Summary of the main continuous variables used for modelling obtained from the NFI database.

Group	Variable	Mountain pine (n = 155) Mean	S.D.	Scots pine (n = 187) Mean	S.D.	All species (n = 342) Mean	S.D.
RESPONSE	*PDAM* (%)	18.7	21.7	11.1	14.6	14.6	18.6
SITE	*Elevation* (*m a.s.l.*)	1896	180	1386	289	1617	353
	Slope (%)	34.3	14.5	35.0	12.8	34.7	13.6
	Soil pH	5.5	1.1	5.7	1.1	5.6	1.1
STAND	*TCC* (%)	63.4	17.3	76.5	12.6	70.5	16.2
	N ($trees{\cdot}ha^{-1}$)	719.2	482.0	728.6	451.1	724.3	464.7
	BA ($m^2{\cdot}ha^{-1}$)	24.0	11.6	23.5	12.5	23.7	12.1
	NC_{BA} (%)	1.2	4.5	3.7	8.8	2.5	7.3
	D_q (cm)	22.6	7.4	21.8	6.4	22.2	6.9
	CVdbh	0.36	0.11	0.36	0.10	0.36	0.11
	H_m (m)	8.8	2.7	9.4	2.6	9.1	2.6
	H_0 (m)	13.5	4.0	13.4	3.9	13.4	4.0
	PSLC ($m{\cdot}cm^{-1}$)	0.44	0.10	0.40	0.10	0.42	0.10
	SLCdom ($m{\cdot}cm^{-1}$)	0.61	0.20	0.61	0.20	0.61	0.20

PDAM: Percentage of trees presenting damages; *TCC:* Tree Canopy Cover; *N:* Stocking; *BA:* Basal area; NC_{BA}*:* Non-coniferous basal area; D_q*:* Quadratic mean diameter; *CVdbh*: Coefficient of variation of the diameter at breast height; H_m*:* Mean height; H_0: Dominant height; *PSLC*: Plot Average Slenderness Coefficient; *SLCdom:* Dominant strata Slenderness Coefficient.

2.2 Data Preparation

The data used in this study were obtained from plots of the 2nd and 3rd Spanish National Forest Inventory (NFI2 and NFI3) in Catalonia (ICONA 1993, DGCN 2005) and Aragon (ICONA 1996, DGCN 2009) regions. The NFI data consisted of a systematic sample of permanent plots distributed over a 1 km square grid surveyed in 1989–1994 (NFI2) and 2000–2005 (NFI3). The sampling method used circular plots with the radius depending on tree diameter at breast height (dbh, 1.3 m): a 5 m radius was used for trees with a dbh of 7.5–12.49 cm, 10 m for 12.5–22.49 cm; 15 m for 22.5–42.49 cm, and 25 m for trees with a dbh of 42.5 cm or higher. NFI data for each sample tree included species, dbh, height, and distance and azimuth from the plot centre. A further database NFI3 recorded information on tree health status, indicating whether the tree showed evidence of damage, and the origin and severity of the damage. Site variables such as elevation, slope, aspect, and soil pH were also recorded.

From the whole NFI dataset, only those plots dominated by Scots, black or mountain pine (in terms of % basal area) and measured during both, the NFI2 and the NF3, were susceptible to be analysed (n = 3952). From these plots a set of variables defining the structure and composition of the forest plots (prior to any WS-damage) were calculated from the NFI2 dataset. Information on trees showing WS-damage, regardless of severity, was obtained from the NFI3 dataset. This information was used to define the degree of WS-damage at stand level (*PDAM*, observed proportion of damaged trees) which was then used as response variable in our damage models. From the plots presenting *PDAM* > 0 (n = 460), we selected a number of stand-related variables that were used as potential predictors in the modelling process (Table 1).

We used two different variables to capture the effect of stand structure on the WS-damage of our plots. First, the coefficient of variation of the diameters at breast height (*CVdbh*) was considered as a sound and simple proxy to reflect the stand's vertical structure, or degree of unevenagedness (Montes et al. 2005, Aunos et al. 2007). In its formalization, we assumed the positive correspondence among tree age, tree height and tree diameter in uneven-aged stands (Schütz 1997). Second, the dominant strata slenderness coefficient (*SLCdom*) was defined as the relation between the height of the dominant trees and the quadratic mean diameter within a plot. This variable represents a modification of the plot aver-

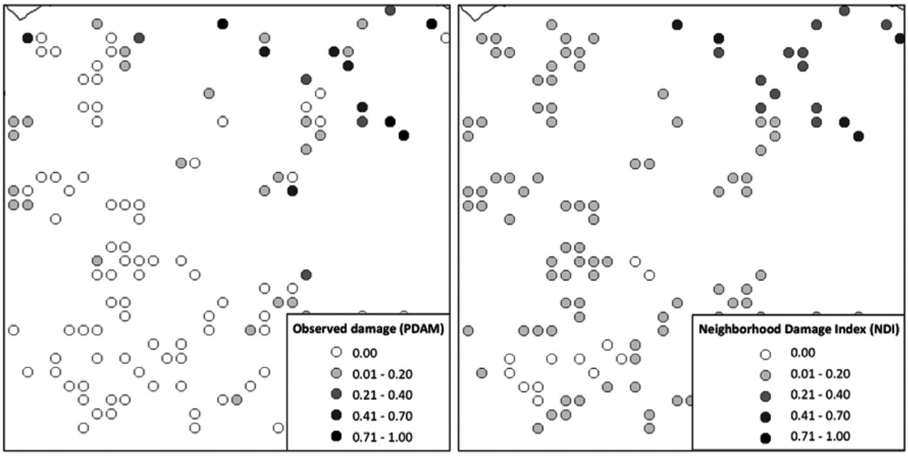

Fig. 3. Observed damage (*PDAM*) and Neighbourhood Damage Index (*NDI*) for plots in an extent of the study area

age slenderness coefficient (*PSLC*) or the ratio between the average tree height and the average tree diameter, commonly used to describe even-aged coniferous stands (Wang et al. 1998).

Finally, the physiographic position (ridge or hilltop) of the plot was approached by the dummy variable *TOP*. We considered *TOP* = 1 if the elevation of a specific plot is higher than the mean elevation of its neighbours within a 5000 meter radius.

2.3 Analysis of Spatial Variation in Stand Damage

We ran an exploratory analysis of the spatial distribution of WS-damage using all the plots dominated by the studied pine species, in order to identify departures from randomness. For this purpose, we estimated the Moran's Index, which measures spatial autocorrelation based on both plot location and the recorded plot damage values (*PDAM*) simultaneously. The Moran's *I* for our data was 0.13, indicating that the plots showed spatial clustering. To evaluate if this clustering trend of *PDAM* was associated to stand level characteristics (Table 1), we also estimated the Moran's *I* for our stand level variables. The analysis showed that these variables did not follow similar spatial autocorrelation pattern than the *PDAM* and, therefore, the clustering trend was considered to be caused by local variations in the storm regime, which differentially affects a given plot depending on its location but also affects the neighbouring plots within a defined distance.

In order to obtain variations in the local storm regime and include them in the modelling process, we analyzed the spatial variability of WS-damage using semivariograms to identify a between-plot threshold distance where data were no longer spatially autocorrelated (Diem 2003). The between-plot threshold distance in our study was found to be close to 5200 meters. With the aim to define a simple storm regime for each plot, the mean damage observed in plots located within a distance of 5200 meters of a given plot was calculated and considered to explain the specific storm regime for that plot. In practice, this value was converted into a new variable called Neighbourhood Damage Index (*NDI*) (Fig. 3). To test whether the *NDI* helped correct spatial correlation, we re-estimated the Moran Index by calculating *PDAM* minus *NDI* for each plot. This re-assessed Moran Index was 0.0, indicating random spatial distribution. This result was considered indicative of spatial independence of storm damage, meaning that after extracting the effect of local storm regime on the damage, the remaining portion of damage could be explained by plot site and stand characteristics alone.

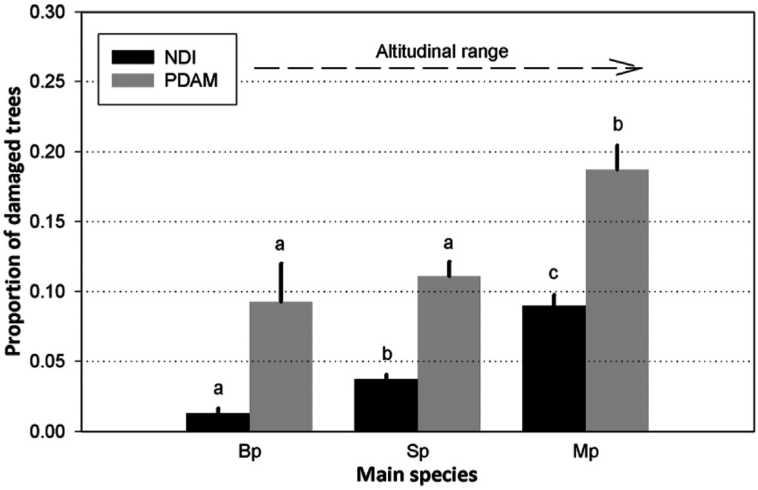

Fig. 4. Mean (bars) and standard error (lines) of *NDI* and *PDAM* for each main species (*Bp* black pine; *Mp* mountain pine; *Sp* Scots pine). Different letters indicate significant differences between species for each variable.

2.4 Stand-Level Damage Modelling

In order to examine the effects of site and stand characteristics on the degree of forest damage occurring during an 11-year period, stand-level models were developed for mountain pine and Scots pine stands. Stand-level models for black pine were not developed due to the limited number of observations. The models were fitted using a subset of 75% of the plots for each species (randomly selected), and were validated using the coefficients from the primary regression on the remaining 25% of the plots. These models used the *NDI* plus a number of stand-level variables (stand structure and location) as predictors (Table 1), and were estimated using the ordinary least squares (OLS) method to describe the linear relationship between the degree of WS-damage and these selected stand level predictors:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_n \quad (1)$$

where y was the $\log_{10}$ of the proportion of damaged trees (*PDAM*) for an arbitrary plot, $x_1, x_2, \ldots, x_n$ the independent variables, and $\beta_1, \beta_2, \ldots, \beta_n$ the parameters. The same explanatory variables were used in both species. However, from the large number of variables selected a priori as predictors, we only integrated into the models the variables presenting a significant effect and non-colinearity problems. A log transformation of the *PDAM* was applied in order to obtain a normally distributed variable.

3 Results

There were significant among-plot differences in Neighborhood Damage Index (*NDI*) depending on species dominance, with mountain pine plots presenting the highest *NDI* values followed by Scots and then black pine (Fig. 4). Stand *PDAM* followed the same pattern as *NDI*, although the differences among species were less marked, and only mountain pine presented significantly higher values (close to 20%).

The following models were selected to predict the degree of WS-damage occurring at stand level for mountain and Scots pine species (Eq. 2 and Eq. 3, respectively):

$$y = \beta_0 + \beta_1 NDI + \beta_2 \left(\frac{SLCdom}{BA} \right) + \beta_3 TOP + e \quad (2)$$

$$y = \beta_0 + \beta_1 NDI + \beta_2 \left(\frac{SLCdom}{BA} \right) + \beta_3 TOP + \beta_4 CVdbh + e \quad (3)$$

Table 2. Regression coefficients values, standard error, statistical significance and Variance Inflation Factor for the two stand damage models described in Eqs. 2 and 3.

Main species. Parameter and Variable		Coefficient	Std. Error	p-Value	VIF
Mountain pine (Eq. 2)					
β_0	*Intercept*	–1.363	0.124	<0.001	
β_1	*NDI*	2.166	0.315	<0.001	1.005
β_2	*SLCdom/BA*	2.314	0.619	<0.001	1.005
β_3	*TOP*	0.194	0.078	0.013	1.005
Scots pine (Eq. 3)					
β_0	*Intercept*	–1.363	0.124	<0.001	
β_1	*NDI*	4.359	1.202	<0.001	1.013
β_2	*SLCdom/BA*	4.359	1.202	<0.001	1.010
β_3	*TOP*	3.438	0.648	<0.001	1.015
β_4	*CVdbh*	0.225	0.059	0.021	1.022

where $y = log_{10}(PDAM)$, with *PDAM* at stand level, and the *NDI* represents a local degree of damage due to local storm regime also expressed as proportion of damaged trees, *SLCdom* is an estimation of the dominant strata slenderness coefficient estimated from the relation between dominant height and quadratic mean diameter ($m \cdot cm^{-1}$), *BA* is stand basal area ($m^2 \cdot ha^{-1}$), *TOP* is a dummy variable indicating if the plot was allocated in ridge or hilltop terrain, *CVdbh* is the coefficient of variation of the diameter at breast height (indicating the degree of uneven-agedness), and *e* is the standard deviation of the residual (standard error) (Table 2).

The coefficient of determination (R^2) was 0.316 for mountain pine and 0.262 for Scots pine models, with $\log_{10}(PDAM)$ standard errors ranging from 0.351 for mountain pine to 0.373 for the Scots pine model. In the adjustment of the models on the validation subset we obtained a R^2 of 0.357 for mountain pine and 0.308 for Scots pine.

For the two modelled species, the proportion of trees presenting WS-damage decreased with increasing stand basal area if the slenderness coefficient (*SLCdom*) was kept constant (Fig. 5). This tendency was found to be very pronounced until the basal area reached a threshold value of about 10–15 $m^2 \cdot ha^{-1}$, but completely disappeared in forests presenting basal area values above the 20–25 $m^2 \cdot ha^{-1}$ mark. On the other hand, the proportion of trees presenting WS-damage increased with increasing *SLCdom*, at constant basal area (Fig. 5). This effect was more pronounced in stands with lower basal areas, particularly in Scots pine stands.

Stand diameter irregularity only had a significant effect on *PDAM* in Scots pine stands, which presented higher degrees of even-agedness most liable to suffer higher degrees of WS-damage (Fig. 6). Other factors driving an increase in *PDAM* values in stands dominated by mountain or Scots pine were ridge or hilltop terrain position (the *TOP* variable) and high *NDI*.

4 Discussion and Conclusions

4.1 The Role of the Geographical Stand Site in Relation to WS-Damage

This study analyzed the factors driving wind and snow-induced damage on mountain conifer forests at stand level under a regional spatial framework based on the comparison of two measurements used in the Spanish National Forest Inventory (NFI). Although NFI data is known to have a high level of variability, NFI results can be usefully analyzed to describe trends at broad spatial and temporal scales (Bergstedt and Milberg 2001). In our models, we considered the combined effect

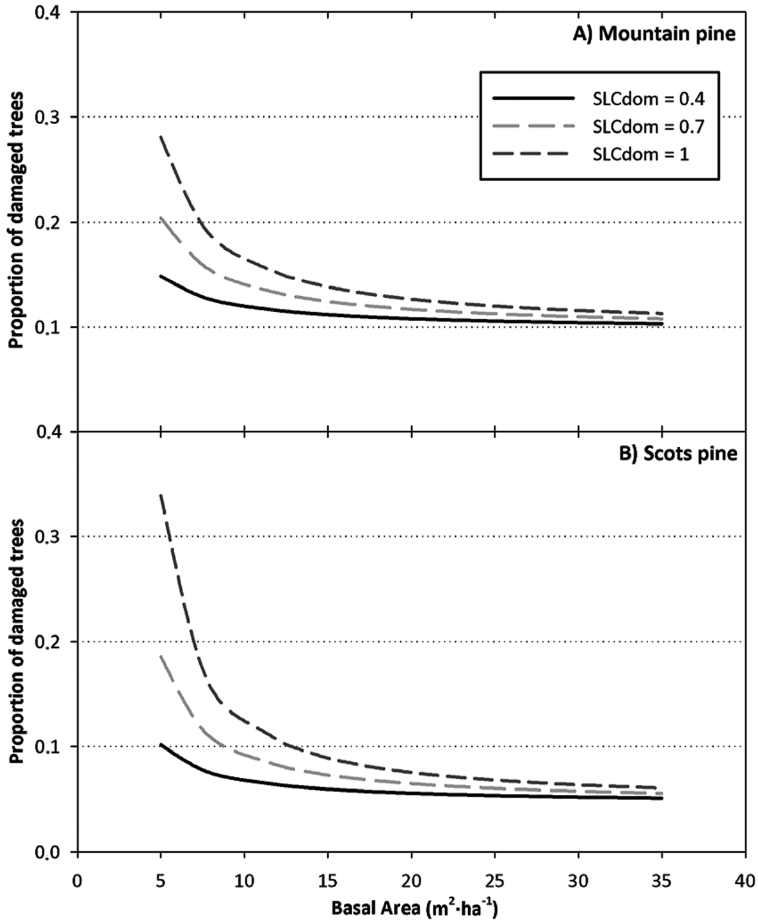

Fig. 5. Effect of stand basal area (*BA*) and slenderness coefficient of dominant trees (*SLCdom*) on the proportion of damaged trees for mountain pine (A) and Scots pine (B) stands. Variables *NDI*, *Top* and *CVdbh* (only in Scots pine) were fixed to their mean value for each species in the modelling dataset.

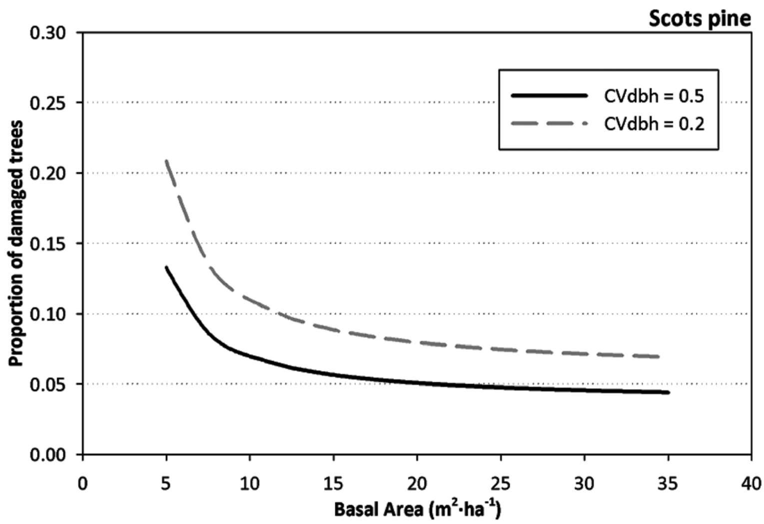

Fig. 6. Effect of the degree of uneven-agedness (stand diameter irregularity) on the proportion of trees damaged for Scots pine stands. Variables *NDI*, *Top* and *SLCdom* were fixed to their mean value in the modelling dataset.

of wind and snow because in our study area these both factors are jointly behind damages (Martín-Alcón and Coll 2008).

The Neighbourhood Damage Index (*NDI*), a variable integrating mean damage observed in the forest at a certain distance, appeared as an appropriate tool for assessing local wind and snow disturbance regimes in areas where analysis based on climatic information is compromised by complex topography (Quine 2000). *NDI* was found to be positively related to the altitudinal rank in which species develop. The strong site elevation-related variation in the effect of climatic factors on WS-damage has previously been observed in other regions (Fridman and Valinger 1998, Hanewinkel et al. 2008). In our study, climatic variables gained importance in relation to stand attributes to explain the degree of WS-damage as altitude increases (e.g. mountain pine, which occupies the sub-Alpine belt in the upper limit of the forested area), where the disturbance regime is characterized by particularly harsh climatic conditions (Blumen 1990, Bosch and Gutiérrez 1996, Bosch 1999). Another variable used to characterize the effect of location factors on the degree of WS-damage was a ridge or hilltop terrain site (the *TOP* variable). This variable indicated stand exposure to wind and snow events depending on topographical position, and has been found to significantly affect *PDAM* in mountain and Scots pine stands.

4.2 The Role of Stand Structure in Relation to WS-Damage

The slenderness coefficient has generally been considered as the factor most influencing single-tree resistance to WS-damage (Wang et al. 1998, Peltola et al. 1999). However, at stand level, the role played by the slenderness coefficient strongly interacts with stand basal area. Our results show that the proportion of WS-damaged trees in a stand decreases strongly at higher stand basal area for a given slenderness ratio of dominant trees (*SLCdom*). At lower stand density, trees are probably more exposed to wind and snow, and consequently more likely to suffer their effects (Valinger and Fridman 1997, Cucchi and Bert 2003). In contrast, dense stands may experience a decrease in wind loading associated with more difficult air circulation with crown contact, thus spreading the kinetic energy transmitted by the wind among the tree crowns (Gardiner et al. 1997). Our regression models performed in the two most affected pine forests show an important effect of stand basal area on *PDAM* in stands presenting basal area values below 15 $m^2 \cdot ha^{-1}$. Above these values, the relationship between both variables gets weaker, and practically disappears when stand basal area reaches 20–25 $m^2 \cdot ha^{-1}$. Above this threshold, trees composing the stand may benefit from a certain degree of mutual support that confers them a collective stability. Our results confirm the findings of Schütz et al. (2006) and Schelhaas et al. (2007) showing that slenderness by itself is not a good indicator of stand stability, because some indicator of the effect of mutual support within the stand is needed.

Our models did not show a significant effect of both mean and dominant stand height by themselves in *PDAM*. In contrast, the average slenderness coefficient of the stand (*PSLC*) significantly increases the proportion of WS-damaged trees in a stand, although this effect was weaker than the one observed for *SLCdom*. Our results agreed with previous studies that found individual tree height for a given diameter to have a significant effect on stand susceptibility to strong winds because large trees are highly exposed to wind forces (Cucchi and Bert 2003, Ancelin et al. 2004, Xi et al. 2008). In our study, the low values of WS-damage found in stands with a higher degree of uneven-agedness could be explained in part by the lower proportion of high trees they present compared to the even-aged ones, at least in adult stands. Tree-level models would in any case be needed to adequately elucidate the role of tree height in the susceptibility of these species to WS-damage.

Between-species comparisons of the effect of stand structure on degree of WS-damage revealed that vulnerable stands (high values of *SLCdom* and low values of basal area) of mountain pine (the species that is distributed at higher altitudes) are the least likely to suffer dramatic damages. This trend is probably explained by a greater structural adaptation to this kind of risk at single mountain pine level (Dhôthe 2005). Although there are not specific studies in our region regarding the role played by the tree architecture or structure of the studied species on their stability face to climate disturbances, mountain pine is known to develop a sound root system with thick secondary roots that confer its strong anchoring into the soil (Ruiz de la Torre 2006). Furthermore its adult trees present in general a higher root to shoot ratio than the other species (Montero et al. 2005).

Scots pine stands with a higher degree of uneven-agedness were less affected by WS-damage than more even-aged Scots pine stands, confirming the results reported in other studies conducted with different species (Mason 2002, Schütz et al. 2006, Schelhaas 2008). In even-aged stands, neighbors can in principle support each other generating a more aerodynamic structure if height difference among individuals is low (Quine et al. 1995). In contrast, the largest trees receive low mutual support by neighboring in the case of uneven-aged stands (Drouineau et al. 2000), and then become more exposed to hazardous winds. However, the minor mutual support that trees receive in uneven-aged stands is compensated with a major resistance at single-tree level because they present in general lower slenderness (Dhôthe 2005). In WS-damage prone areas, silvicultural practices play an essential role in maintaining a given stand structure resistant to the occurrence of these perturbations in both even-aged and uneven-aged structures. In these areas, partial cuttings in even-aged stands should be done in a way they do not excessively break mutual support among individuals whereas, in uneven-aged stands, caution should be taken when removing large sheltering trees because this increases the risk of damages in the trees located in the lower canopy.

In contrast to Scots pine stands, we found the structure of mountain pine stands to have a lower effect on the degree of WS-damage (Table 2), specially in the case of the stand vertical structure, which has no significant effect. This species distributes in the sub-Alpine belt, a particular prone area to the occurrence of these perturbations and is known to present a higher single-tree level adaptation to them (Ruiz de la Torre 2006). This probably reduces the relative effect of stand vertical structure which may play a secondary role.

4.3 Implications for Forest Management

This study highlights how the degree of WS-damage in mountain and Scots pine forests strongly depends on climatic and topographic factors. The relatively poor prediction power of the models is consequence of the highly stochastic nature of these disturbances, and the strong topographic and climatic variability at fine spatial scale (Blumen 1990, del Barrio et al. 1990). Given that risk assessment is especially important for these forests, there is a need for more detailed insight into wind and snow behaviour at fine spatiotemporal scales. Low-density pine stands presenting high slenderness coefficients are those most prone to WS-damage. Thinning operations should thus be directed towards trying to enhance single-tree stability factors (mainly slenderness, but also crown form) without undermining stand cohesion. In even-aged forests at high risk for WS-damage, early and frequent selective thinning, starting with by low heavy thinning in early ages and reducing the thinning intensity with age, seems the best forest management strategy for maximizing stand-level and single tree stability (Montero et al. 2001, Ni Dhubhain et al. 2001, Cameron 2002). In uneven-aged stands, which a priori are less vulnerable, stand resistance must be kept with adequate selection cuttings (Mason 2002). Further research is needed to provide more concise and empirical-based recommendations on using suitable silvicultural practices to minimize the risk of wind and snow-related forest damage.

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