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Original article

Influence of individual tree and stand attributes in stem straightness in *Pinus pinaster* Ait. stands

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Abstract – The potential relationships between stem straightness and site, and both individual and stand attributes were studied in *Pinus pinaster* Ait. stands. To this effect, 32 plots encompassing different densities and sites of varying quality were laid out in mature stands. In a young stand, a completely randomised design with 9 plots was set up in order to compare three regeneration densities. During the study numerous saplings were bent down by heavy snowfalls. Data analysis using multinomial logistic regression failed to show any relationship between stem straightness and the attributes under study in mature stands. In young stands, however, stem straightness appeared to be influenced by the height/diameter ratio as well as by the total height and the density of the stand at the time of the snowfalls. High density plots were severely affected by snow and consistently contained the least satisfactory instances in terms of stem straightness.

stem straightness / *Pinus pinaster* / regeneration density / height-diameter ratio / snowfall

Résumé – Influence des caractéristiques des arbres individuels et des peuplements sur la rectitude du tronc dans les peuplements de *Pinus pinaster* Ait. Le rapport entre la rectitude du tronc et les caractéristiques du site, des arbres individuels et des peuplements a été étudié dans des peuplements de *Pinus pinaster* Ait. On a mesuré 32 parcelles dans des peuplements matures couvrant des sites de différentes densités et qualités. On a établi tout à fait au hasard, dans un jeune peuplement, un modèle comprenant 9 parcelles dans le but de comparer trois densités de régénération. Pendant cette étude, des chutes de neige ont plié un nombre élevé d'arbres dans les jeunes parcelles. L'utilisation de la régression logistique polynomiale n'a pas permis d'établir de rapport dans les peuplements matures entre la rectitude du tronc et les caractéristiques étudiées. Dans les peuplements jeunes, la rectitude du tronc a été influencée par le rapport hauteur/diamètre ainsi que par la hauteur totale et la densité du peuplement après les chutes de neige. Les parcelles à densité élevée ont été davantage touchées par la neige et montraient des troncs moins droits.

rectitude du tronc / *Pinus pinaster* / densité de régénération / rapport hauteur-diamètre / chutes de neige

1. INTRODUCTION

In management and genetic improvement of forests it is important to consider such a major character as stem straightness. Whenever large numbers of sinuous trees occur in a stand, it is certain that the cost of harvesting and the revenues from timber will be adversely affected. Moreover, stem curvatures, usually associated with the presence of compression wood, will surely diminish timber quality [2, 6, 21].

Stem malformation may be due to genetic, ecological and silvicultural factors. The genetic control of stem straightness is very variable. Different levels of heritability have been mentioned in reports dealing with a variety of species [8, 9, 26, 46]. Roussell [36], Yoshizawa et al. [48] and Sierra de Grado [37] found that the susceptibility to deformation and the magnitude and rate of the reaction producing compression wood differ between species and even between families within species.

Timell [44] pointed to wind and snow as the most important environmental factors causing stem deformations. Snow usually generates crooked stems after bending down slender trees or through the pressure exerted by snow creep. On the other hand, the relationship between unidirectional wind and basal sweep has been reported in several studies on different species [11, 33, 43]. The effects of snow and wind on stem straightness are often heavier on steep slopes. Other ecological factors that can determine stem straightness include the frequencies of frosts, insect attacks, fungal diseases or herbivore damage as when browsing on the apical shoots of young trees. This kind of damages induces lateral branch dominance that causes curvatures in the bole [16, 24, 44]. Lateral incidence of light plays also an important role in stem form [38]. This factor particularly affects intermediate or suppressed trees and trees growing at the edge of a stand.

Reactions to environmental factors vary according to the silvicultural characteristics of the stand. Thus, snow and wind deformation and damage depend on stand and individual attributes, such as density and height/diameter ratio [32, 35]. High stand densities favour higher rates of straight stems [27],

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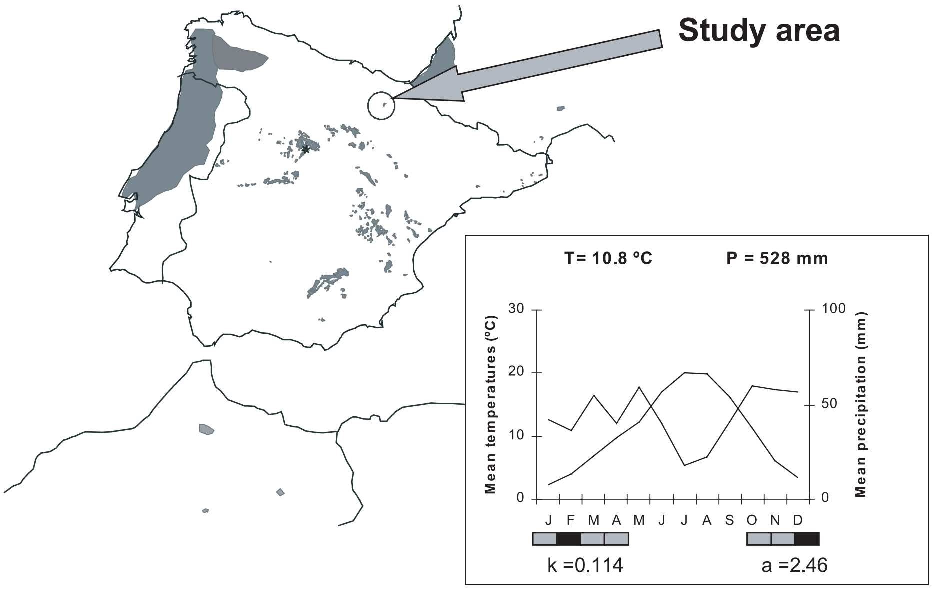

Figure 1. Walter-Lieth Climate Diagram and location map showing Oña area and its position in the Iberian Peninsula. The shadow area in the map indicates the distribution of maritime pine in the Iberian Peninsula. Climate Diagram Legend: T: annual average temperature; P: annual average rainfall; k: relative drought period/relative humid period ratio; a: period of relative drought in months.

although at the risk of increasing snow damages. Stand and tree characteristics could be modified by thinning, improving stem quality if an adequate selection is applied. Moreover, thinning is in relation to the formation of compression wood, associated with reorientation processes [5, 34, 44]. Root characteristics and deformations are also reported as influenced factors in stem straightness because of the relationships between root system and tree stability in first ages, particularly in plantations [12, 23].

Pinus pinaster is the most extensive conifer in Spain, covering over 700 000 ha in pure stands and 600 000 hectares in mixed stands, most of them in the Mediterranean area. The species has a widespread natural distribution and it is often used in reforestation. Twenty provenance regions of *P. pinaster* have been defined in Spain [4]. *Pinus pinaster* shows a general tendency for sinuosity in comparison with other Pinus species with a more straight characteristic stem. However, there is a wide variation between provenances, having some of them very straight stems typically, and very crooked others. This characteristic has been studied in provenance test trials and its stability out the original environment has been demonstrated [3, 39]. Sierra de Oña provenance is characterised by the low quality and sinuosity of their stems. This provenance usually presents polycyclic growth and some fire adaptations: great production of cones, serotinous cones and thick bark. After forest fires, high-density regeneration stands are common. Sierra de Oña provenance is isolated from other populations of this species.

Although there are information on silvicultural practices and population structure of maritime pine in the Mediterranean Spain [7, 18, 19, 28–31], references in the literature to stem straightness in young and mature stands are scarce [38, 39]. On the other hand, there are few studies that focus in the relation between stand and tree variables and stem straightness [5, 22, 27, 44].

In this paper we study the possible influence of silvicultural practices on the straightness of maritime pine trees from the Sierra de Oña provenance. Should this influence be confirmed, it would make possible an improvement in the quality of the stems by applying the appropriate silvicultural treatments. The aims of the present work are: (a) to find relationships between stem straightness and environmental, stand and individual attributes in different mature stands of this region; (b) to study the effect of density in young growth stands on the stem straightness.

2. MATERIALS AND METHODS

2.1. Study site

The study area is situated at 700–1000 m.a.s.l. in Sierra de Oña provenance (northern Spain) covering 15 000 ha. Its climate shows Mediterranean influences: an annual average rainfall is 528 mm; a drought period of 2.46 months in summer and an annual mean temperature of 10.8 ºC (Fig. 1). Soils are diverse: siliceous and limestone and frequently sandy with a pH ranging from 6.2 to 8.9. Silvicultural practice in this area is based on natural regeneration with a rotation of 100–125 years. Forest fires have a strong influence in stand dynamics in the area. Stands have adapted to fires and, consequently, high densities can be found in stands established after forest fires.

2.2. Sampling design and measurements

2.2.1. Mature stands

The sample includes 32 plots from a management-oriented inventory developed by using a 170 m squared grid. Plots were circular with radius equal to 11 m. In each plot exposure (sexasegimal degrees),

Table I. Main characteristics of the 32 plots used to analyses the silvicultural effect on stem straightness in older stands.

	SC	SI	Altitude (m)	Slope (%)	Exposure	N	BA	Dg	H_0
Mean	3.7	7.7	780	6.3	134.2	577	31.74	26.48	11.32
Minimum	3	6	544	0.5	2	316	8.60	18.61	7.35
Maximum	5	10	952	11.5	352	1421	67.23	36.83	15.50
Std. deviation	0.7	1.4				267.3	14.98	4.56	1.76

SC: stem straightness class according to Galera et al. (1997), SI: site index according to Gonzalo and Sánchez (1997), BA: basal area in squared meters per ha, N: number of trees per ha, Dg: mean quadratic diameter in cm, H_0: dominant height in m.

Table II. Main characteristics of the 160 trees used to analyses the silvicultural effect on stem straightness in older stands.

	SC	DBH	DB	HT	H/D	A	BAL/BA
Mean	3.68	23.09	28.57	9.67	34.43	50.5	0.76
Minimum	1.00	7.90	9.50	3.80	19.53	13.0	0.09
Maximum	6.00	45.50	52.30	20.50	55.04	90.0	0.99
Std. deviation	0.97	8.49	9.23	3.34	6.85	18.7	0.22

SC: stem straightness class according to Galera et al. (1997), DBH: diameter at breast height in cm, DB: diameter at base in cm, HT: total height in m, A: age, BAL: basal area in larger trees in squared meters per ha, BA: basal area in squared meters per ha.

slope (%) and altitude (m.a.s.l.) were recorded; climatic factors have not been considered because of their low variability in this area. In addition, the diameter at breast height (DBH) was measured in all trees over 10 cm; in two dominant trees randomly chosen the total height was also measured and in one tree per plot the total age was recorded. With the raw data several variables such as basal area (BA) in squared meters per hectare, number of trees per hectare (N), mean quadratic diameter (Dg) in cm and dominant height (H_0) in m were obtained. Gonzalo and Sánchez [20] site curves were used to estimate site index (SI). The 32 plots from the original data set were chosen to study the stem straightness to cover the range of (BA) and dominant height of maritime pine stands in Sierra de Oña. The main plot characteristics are represented in Table I. In order to select representative trees in each plot, the diameter distribution was divided in five parts and one tree per class was chosen randomly. In these trees, basal diameter (DB) in cm, total height (HT) in dm, age (A) and stem straightness class (SC) were recorded (Tabs. II and III). The competition position of each tree was represented by the ratio between the basal area in larger trees (BAL) as is described by Wykoff et al. [47] and the basal area. This

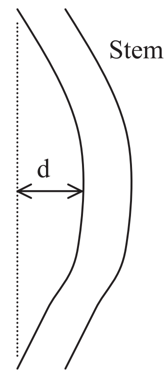

Figure 2. Scheme of the curvature deflection in a stem.

ratio is equal to 0 in a full dominant tree and closer to 1 as the trees became fully dominated. In order to describe stem form in mature stands Galera et al. [15] proposed one classification for stem sinuosity and another one for stem lean. In "Sierra de Oña" provenance stem sinuosity in mature trees is very sharp, being an own character more outstanding than stem lean. In this way, the stem straightness in mature stands was determined by the stem sinuosity classification [15]:

- SC1: Straight.
- SC2: Light sinuosity. Curvature deflection (see Fig. 2) lower than the breast diameter (DBH) in the top third of the stem.
- SC3: Light sinuosity. Curvature deflection lower than DBH in the middle or bottom part of the stem.
- SC4: Middle sinuosity. Curvature deflection lower than DBH in the middle and bottom part or in all stem.
- SC5: High sinuosity. Curvature deflection between DBH and 2 × DBH.
- SC6: Crooked. Curvature deflection larger than 2 × DBH.

Table III. Mean and standard deviation of individual trees characteristics in mature stands per stem straightness classes.

SC	DBH	DB	HT	H/D	A	BAL/BA
1	28.80 (1.84)	34.35 (2.90)	9.40 (0.14)	27.48 (2.73)	60.5 (26.2)	0.63 (0.04)
2	28.77 (4.43)	33.86 (5.32)	10.66 (1.74)	31.19 (2.00)	55.8 (11.9)	0.72 (0.16)
3	22.95 (9.66)	28.44 (10.50)	9.91 (3.98)	35.21 (7.00)	48.7 (20.1)	0.76 (0.23)
4	22.17 (8.07)	27.75 (8.99)	9.56 (3.36)	34.99 (7.10)	50.6 (18.4)	0.75 (0.23)
5	24.03 (6.77)	29.38 (7.32)	9.13 (1.91)	31.88 (6.10)	50.8 (18.1)	0.79 (0.19)
6	21.37 (8.40)	26.65 (8.10)	9.02 (1.91)	35.28 (7.71)	55.0 (18.9)	0.82 (0.17)

SC: stem straightness class according to Galera et al. (1997), DBH: diameter at breast height in cm, DB: diameter at base in cm, HT: total height in m, H/D: height-diameter ratio (adimensional), A: age, BAL: basal area in larger trees in squared meters per ha, BA: basal area in squared meters per ha.

Table IV. Main characteristics of individual trees in young growth stand.

	HT1	DB1	A1	H/D1	HT2	DB2	A2	H/D2
Mean	84.24	17.44	6.4	55.46	95.73	21.60	7.4	50.48
Minimum	29.00	4.00	5.0	18.91	34.00	7.00	6.0	16.98
Maximum	148.00	54.00	8.0	146.67	189.00	96.00	9.0	112.50
Std. deviation	22.46	8.48	0.7	20.52	27.46	11.07	0.7	18.45
CV%	26.66	48.62	11.2	36.94	28.68	51.25	9.8	36.44

HT: total height in cm, DB: basal diameter in mm, A: age in years, H/D: height/diameter ratio (adimensional), 1: inventory of November 1999, 2: inventory of November 2000.

Table V. Mean and standard deviation of individual trees characteristics in young growth stand per stem straightness classes (SSC).

SSC	HT1	DB1	A1	H/D1	HT2	DB2	A2	H/D2
1	85.55	17.49	6.4	56.93	87.81	20.52	7.3	50.39
	(22.99)	(8.76)	(0.7)	(21.69)	(24.56)	(12.22)	(0.7)	(19.00)
2	80.57	17.02	6.4	52.61	97.53	21.84	7.4	50.40
	(21.14)	(7.68)	(0.7)	(17.10)	(28.18)	(10.86)	(0.7)	(18.11)
3	84.33	18.18	6.5	52.28	96.85	21.80	7.40	50.89
	(21.17)	(8.46)	(0.8)	(19.11)	(26.12)	(10.70)	(0.7)	(19.40)

HT: total height in cm, DB: basal diameter in mm, A: age in years, H/D: height/diameter ratio (adimensional), 1: inventory of November 1999, 2: inventory of November 2000.

2.2.2. Young growth stand

Natural regeneration occurred in a young growth stand established after a forest fire in summer 1991. In 2000 trees of the stand were 5–9 years old showing the followed temporal establishment pattern after the fire: 3.5% of the trees the first year, 41.5% the second, 45% the third and 10% the fourth year. Stand characteristic vary between groups with densities of 9000–65000 stems per hectare, mean height of 0.65–1.05 m and mean basal diameter of 13–21 mm.

In this stand 9 circular plots were chosen to represent different stand density levels: low density (N < 15 000 trees/ha), middle density (15 000 < N < 40 000 trees/ha) and high density (N > 40 000 trees/ha). Plots have a radius of 2.5 m (19.6 m^2) in order to include at least 20 trees in the low density plots. The resultant data set was analysed according to a completely randomised design with 3 treatments. Total height in cm (HT), basal diameter in mm (DB), age (A) and stem straightness class (SSC) of all trees were recorded in each plot. Data description is presented in Tables IV and V. The straightness classification proposed by Galera et al. [15] can not be applied in young stands with heights lower than 1.3 m. According to Sierra de Grado et al. [39], stem straightness in young stands was assessed using the following subjective scale with three stem straightness classes (SSC):

SSC1: Straight. Curvature deflection lower than DB.

SSC2: Light sinuosity. Simple curvature and curvature deflection larger than DB or leaning angle smaller than 45º.

SSC3: High sinuosity. Multiple curvature and curvature deflection larger than DB or leaning angle greater than 45º.

Measurements were taken twice: after the growth period in November 1999 and in November 2000. In April 2000 the straightness class of all trees in each plot was recorded because of changes in stem form due to snowfalls, which only affected to young stands.

2.3. Statistical methods

2.3.1. Mature stands

Multinomial logistic regression [1] was used to explore the influence of environmental attributes (altitude, slope and exposure), stand attributes (N, BA, Dg, H_0 and SI), individual tree attributes (DBH, DB, HT, A and BAL/BA) and upon the stem straightness. Multinomial logistic regression has been used because the dependent variable is polytomic. Its expression has the following structure:

$$\ln\left(\frac{p_i}{p_6}\right) = Z_i$$

where i varies between 1 and 5; p_i and p_6 represent the probabilities of being included in the stem straightness classes (SC) 1, 2 , 3, 4, 5 and 6 respectively ($p_6 = 1 - p_1 - p_2 - p_3 - p_4 - p_5$); and Z_i are linear functions combining the explanation variables. The analysis has also been done grouping 1 and 2 classes and 5 and 6 classes in order to facilitate the detection of tendencies.

$$\ln\left(\frac{p_i}{p_4}\right) = Z_i$$

where i varies between 1 and 3; p_i and p_4 represent the probabilities of being included in the stem straightness classes (SC) 1–2, 3, 4 and 5–6 respectively ($p_4 = 1 - p_1 - p_2 - p_3$). Three different explanation functions were explored representing the environmental, stand and individual tree attributes. The following functions were explored:

Environmental attributes as explanatory variables,

$$Z_i = \beta_{0i} + \beta_{1i} \times Altitude + \beta_{2i} \times Slope + \beta_{3i} \times Exposure.$$

Stand attributes as explanatory variables,

$$Z_i = \beta_{0i} + \beta_{1i} \times N + \beta_{2i} \times BA + \beta_{3i} \times Dg + \beta_{4i} \times H_0 + \beta_{5i} \times SI.$$

Individual tree attributes as explanatory variables,

$$Z_i = \beta_{0i} + \beta_{1i} \times DBH + \beta_{2i} \times DB + \beta_{3i} \times HT + \beta_{4i} \times H/D + \beta_{5i} \times A + \beta_{6i} \times BAL/BA.$$

2.3.2. Young stand

In young growth stands the influence of height, basal diameter, age and height-diameter ratio (H/D) on stem straightness was also analysed

Table VI. Multinomial logistic regression in the first inventory of young growth stand (November 1999).

Source of variation	–2log likelihood	Chi-square	DF	P
Intersección	924 633	.	.	.
HT	924 936	0.303	2	0.860
DB	929 010	4.377	2	0.112
A	925 046	0.413	2	0.813
H/D	933 736	9.103	2	0.011
DENSITY	926 374	1.741	4	0.783

HT: total height in cm, DB: basal diameter in mm, A: age in years, H/D: height/diameter ratio (adimensional).

Table VII. Multinomial logistic regression in the second inventory of young growth stand (November 2000).

Source of variation	–2log likelihood	Chi-square	DF	P
Intersección	921 869	.	.	.
HT	932 194	10.325	2	0.006
DB	924 094	2.224	2	0.329
A	924 648	2.779	2	0.249
H/D	930 236	8.367	2	0.015
DENSITY	968 533	46.664	4	0.000

HT: total height in cm, DB: basal diameter in mm, A: age in years, H/D: height/diameter ratio (adimensional).

using multinomial logistic regressions. The expression of the model is:

$$\ln\left(\frac{p_i}{p_3}\right) = Z_i$$

where i varies between 1 and 3; p_i and p_3 represent the probabilities of being included in the stem straightness classes (SSC) 1, 2 and 3 respectively ($p_3 = 1 - p_1 - p_2$); In this case the factor density is included in the model and the explanation function is:

$$Z_i = \beta_{0i} + \beta_{1i} \times HT + \beta_{2i} \times DB + \beta_{3i} \times A + \beta_{4i} \times H/D + \beta_{5i} \times Density1 + \beta_{6i} \times Density2$$

where:

$$(Density1, Density2) = \begin{cases} (1,0) \text{ if } High \quad Density \\ (0,1) \text{ if } Midle \quad Density \\ (0,0) \text{ if } Low \quad Density. \end{cases}$$

In order to determine the goodness of logistic models and the significance of variables the –2log of likelihood and the Chi-square tests were used in mature and young stands. The parameter estimates were tested by the Wald's test. The Chi-square test has been used in young stand to study the independence of the stem straightness classes and stand density after the snowfall in the spring measurement. All statistical analyses have been done with SPSS Inc [42].

3. RESULTS

3.1. Environmental attributes

There was not evidence that stem straightness might be influenced by environmental attributes. The value of –2 log of likelihood was equal to 233 265 for the full model and equal to 255 870 just for intercept. No significative relationship was found between stem straightness classes and the different environmental attributes explored (altitude, slope and exposure). The significance of probability was always over 0.082.

3.2. Stand attributes

None of the studied stand attributes had a significative influence upon the stem straightness in maritime pine in Oña. The value of –2 log of likelihood is equal to 222 547 for the full model and equal to 255 870 just for intercept. No significative relationship was found between stem straightness classes and the different stand attributes explored (basal area, site index, age, quadratic mean diameter and dominant height). The significance of probability was always over 0.093.

3.3. Individual tree attributes

Similarly, none of the tree attributes had significative influence on stem straightness of the Pinus pinaster in the studied area. The value of –2 log of likelihood is equal to 391 730 for the full model and equal to 431 117 just for intercept. No significant relationship was found between stem straightness classes and the different individual tree attributes explored (basal diameter, diameter at breast height, total height and competition position). The significance of probability was always over 0.167.

After grouping data in four straightness classes results are similar for the three explanations functions, no finding any significant variable.

3.4. Young growth stand

Multinomial logistic regression showed that only the variable H/D ratio of the tree was significant in the first inventory (Tab. VI). However, Wald's χ^2 test showed that β_{41} and β_{42} are not significatively different from zero. It means that H/D variations did not produce significant changes in the ratios p_1/p_3 and p_2/p_3. In Table V can be seen that there are not a clear relationships between H/D and SSC in the first inventory.

In the second inventory (November 2000) there were statistical differences in stem straightness between stand densities. The covariables HT and H/D ratio were also significatives (Tab. VII). Wald's χ^2 test indicated that β_{11} and β_{41} are statistically different from zero, with a χ^2 of Wald value of 5.043 ($P = 0.025$) and 4.679 ($P = 0.031$) respectively. The odds ratio p_1/p_3 decreases 2.4% when height increases one unit ($\exp(\beta_1) = 0.976$) and increases 3.5% when H/D ratio of trees grows one unit ($\exp(\beta_4) = 1.035$). In Figure 3 the relationships between height, H/D ratio and diameter are presented, showing that the highest H/D ratios correspond with trees of low total heights and basal diameter.

The first measurement yielded no statistical differences between densities on the frequencies of straightness classes. The greatest percentage corresponded to the best straightness class (SSC1) with a mean value of 65.3%, followed by SSC2

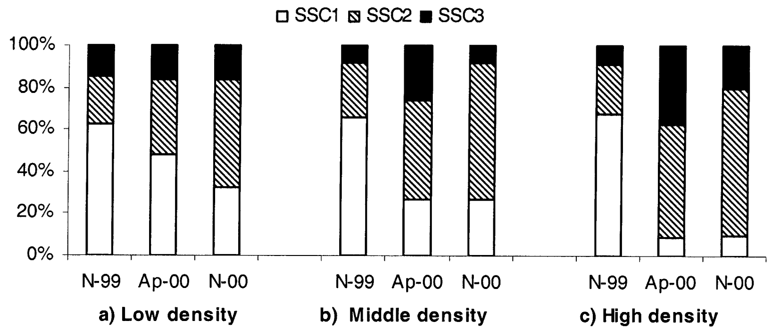

Figure 3. Evolution of percentages of trees, per stem straightness class, in different densities in young growth stands. (N-99, November 1999; Ap-00, April 2000; N-00, November 2000; SC, Stem straightness class).

(24.1%) and SSC3 (10.6%) (Fig. 3). The proportions vary in spring after the heavy winter snowfalls. At this point in time, there were statistical differences between densities, with a Chi square of 63.18607. The variation was light in the low density, with the same percentage of trees in SSC3. The percentage in the SSC1 decreased when the stand density increased, with a values of 48.2% in the low density, 26.6% in middle density and 9.1% in the highest. In the same way, the percentage of trees of the worst straightness class rose with the stand density.

Finally, after the growth period (November of 2000) the proportions varied again keeping up the statistical differences (Chi-square of 41.303). The low density showed a worse situation than in spring, with more trees in SSC2 and fewer in SSC1, but still maintaining the highest percentage of trees in SSC1. This density showed the same percentage in SSC3 in the three measurements (Fig. 3a). For the middle and high densities the situation was somewhat improved in the last inventory, since some trees passed from SSC3 to SSC2 while SSC1 remained unchanged (Figs. 3b and 3c).

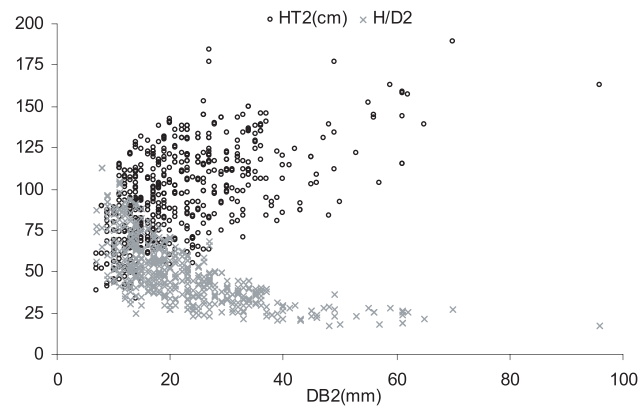

Figure 4. Height-diameter and H/D ratio-diameter relationships in young growth stand in November 2000. HT = total height in cm, DB = basal diameter in mm, H/D = height/diameter ratio (adimensional).

4. DISCUSSION

Pinus pinaster stands exhibit high rates of stem deformation that vary depending on the populations. Sierra de Oña provenance in Spain presents some of the worst instances of stem deformation with mean straightness values ranging between SC3 and SC5 (Tab. I). All environmental factors traditionally reported in the literature as causal agents of stem curvatures (wind, snow, and soil creeping) [33–45] could be related to the three site attributes analysed in the present study. However, a problem of spatial scale can obstruct the analysis of this result and no relationship between stem straightness and altitude, slope or exposure of the sites could be found. It may very well have been the case that the site variability in the study area was not broad enough for this type of relationship to become apparent. In the case of slopes the maximum value was only 11.5% (Tab. I) and that seems too low to illustrate the relationship between the steep slopes and basal stem crook corroborated by many authors [44].

In the mature maritime pine stands under study there is no statistically significant relationship between stem straightness and tree and stand attributes. This absence of relation can be due to the low variability of stands characteristics (Tab. I) as a consequence of the similar management in this area. Nevertheless, the treatments applied do not seem to have modified the stem straightness of trees and there are still a lot of trees with high SC. If the impact of silvicultural and environmental factors on stem development may be discounted, it seems that the main factor influencing in stem straightness should be sought in the genetic effect.

However, results from regeneration plots suggest that the first stages in stand development can subsequently condition stem form. The importance of the young stages in maritime pine has been reported by Sierra de Grado et al. [39], who found the worst straightness values in the bottom third of the stems, reflecting important deformations in youth. Crisan [10] obtained similar results comparing verticality above and under the height of 2.5 m in the same species.

Stem straightness in the studied young plots is influenced by H/D ratio, height and stand density. An increase in H/D ratio of a tree determines that the probability it will belong to the best straightness class is fairly strong. A positive relationship between H/D ratio and stem straightness in young trees has also been found in a provenances trial of *P. pinaster* in Spain [17]. On the other hand, the results of the last measurement after the snowfall show that taller trees are unlikely to belong to the best straightness class (SSC1). These results can be explained by the distribution of H/D ratio and total height by diameter, which indicates that the largest H/D correspond to the smallest trees (Fig. 4). The influence of H/D ratio and height on stem straightness ca be due to the higher flexibility of young trees which facilitates active straightening up [5, 13, 14]. Leaphart et al. [22]

reported a similar result in a mixed stand with six conifer species located on a steep slope exposed to heavy snowfalls, finding a larger percentage of stem deformities with increasing height classes (from 0.3 to 3.2 m). Carlsson (1948, in [44]) reported in *Picea abies* L. that the recovery of bent trees was faster in vigorous than in dominated trees, that usually have higher heights. However our young stand is still very young and the social differentiation has not clearly started. In this way it could be interesting to study the relationship between stem straightness and tree and stand attributes when the competition begins to be important.

Straightness of maritime pine seedlings and saplings was influenced by stand density only after the heavy snowfalls of the winter 1999–2000, when many trees were bent down by snow. The rate of bent trees was greater in the high-density plots (Fig. 4). In a study with saplings of *Pinus virginiana* Fenton (1959, in [44]) found also more damage in dense stand and in larger saplings (6–15 years old) than in smaller (3–6 years old). Trees bent down by snow began to recover the vertical position during the growth period, some trees being upgraded from SSC3 to SSC2 (Fig. 4). The reaction of trees is similar to that observed by Schmidt [41] in bent *Larix occidentalis* trees whose recovery starts in stem apex. As the leader grow vertically during the recovery of the leaned stem, permanent crooks and curvatures can be formed in stems. The response to the stimulus of inclination to recover the vertical position is different among species [48]. In experiments with *P. pinaster* with artificially bent stems very rapid reorientation of the apical portion of the stem have been found to reduce the leaning [14, 25]. On the other hand, a preliminary work of the straightening abilities in *P. pinaster* in different populations demonstrates that Sierra de Oña provenance reacts more slowly than a mountain provenance [40], which presents straighter stems in natural stands indicating an adaptation to snowfalls [3, 39].

According to these results high densities should be avoided in young stands in order to improve the stem form of trees in provenances with frequent crooked stems. Actually, in Sierra de Oña where the species shows signs of adaptation to regular fires (serotinous cones), high densities of seedlings are very frequent in *P. pinaster* stands after forest fires [43]. Although heavy snowfalls are no very usual in this provenance, cleanings or pre-commercial thinning are needed to reduce the risk of snow damages in high density stands and to eliminate as soon as possible trees with unacceptable stem forms.

In order to confirm this possible effect of the regeneration density and snowfalls in young ages on the straightness of trees in mature stands of maritime pine, it would be necessary to continue the experiment to monitor the development of the bending trees in the future.

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REFERENCES

[1] Agresti A., Categorical Data Analysis, Wiley Interscience, 1990.

[2] Aldohus J.R., Quality of softwood timber-market prices and revenue expectation, Q. J. For. 80 (1986) 233–240.

[3] Alía R., Gil L., Pardos J.A., Performance of 43 *Pinus pinaster* provenances on 5 locations in Central Spain, Silvae Genet. 44 (1995) 75–81.

[4] Alía R., Martín R., De Miguel J., Galera R.M., Agúndez D., Gordo J., Salvador L., Catalán G., Gil L.A., Regiones de procedencia, *Pinus pinaster* Ait., DGCONA, Madrid, 1996.

[5] Ancelin P., Modélisation du comportement biomécanique de l'arbre dans son environnement forestier. Application au pin maritime, Ph.D. thesis, Université de Bordeaux, Bordeaux, 2001.

[6] Bailleres H., Conséquences du bois juvénile et du bois de compression sur la stabilité dimensionnelle des contreplaques de pin maritime, in: Thibaut B. (Ed.), Proceedings of the Third Seminar "Architecture, Structure, Mécanique de l'arbre", LMGC, University of Montpellier II, Montpellier, 1991.

[7] Bravo F., Guerra B., Forest structure and diameter growth in Maritime pine in a Mediterranean area, in: von Gadow K., Saborowski J. (Eds.), IUFRO Conference on continuous cover forestry, Göttingen, 2001, pp. 101–110.

[8] Conche I., Déterminisme génétique de l'anisotropie et de certains caractères de forme chez le pin maritime, Mémoire de stage de fin d'études, INRA-FOREST, IUT de Tours, 1978.

[9] Cotterill P.P., Dean C.A., Van Wye G., Additive and dominance genetic effects in *Pinus pinaster*, *P. radiata* and *P. elliottii* and some implications for breeding strategy, Silvae Genet. 36 (1987) 221–232.

[10] Crisan P.A., Déterminisme génétique de la forme de pin maritime, Corrélations avec la vigueur et le rythme de croissance, Mémoire de stage de fin d'études, INRA-Cestas, 1977.

[11] Davies E.J.M., Unseless? The case against contorta, Scot. For. 34 (1980) 110–113.

[12] Danjon F., Bert D., Godin C., Trichet P., Structural root architecture of 5-year-old *Pinus pinaster* measured by 3D digitising and analysed with AMAPmod, Plant Soil 217 (1999) 49–62.

[13] Fourcaud T., Blaise F., Lac P., Castéra P., de Reffye P., Numerical modelling of shape regulation adn growth stresses in trees. II. Implementation in the AMAPpara software and simulation of tree growth, Trees 17 (2003) 31–39.

[14] Fournier M., Bailleres H., Chanson B., Tree biomechanics: growth, cumulative prestresses and reorientations, Biomimetics 2 (1994) 229–252.

[15] Galera R.M., Martín S., Alía R., Gordo J., Aguado A., Notivol E., Manual de selección de masas productoras de semillas, Evaluación de caracteres, Monografías INIA 97, Madrid, 1997.

[16] Gong Y.L., Swaine M.D., Miller H.G., Effects of Fencing and Ground Preparation on Natural Regeneration of Native Pinewood over 12 years in Glen Tanar, Aberdeenshire, Forestry 64 (1991) 157–168.

[17] González A., Evaluación de una parcela de ensayo de procedencias de *Pinus pinaster* Ait., T.M. La Pedraja de Portillo (Valladolid), Proyecto Fin de Carrera de Ingeniería de Montes, Universidad de Valladolid, Palencia, 1999.

[18] González-Martínez S.C., Gerber S., Cervera M.T., Martínez Zapater J.M., Gil L., Alía R., Detecting reliable parent-offspring matches in parentage analysis: a case study, in: Degen B. (Ed.), Modelling and experimental research on genetic processes in tropical and temperate forests, Belén, 2002, pp. 159–164.

[19] González-Martínez S.C., Salvador L., Agúndez D., Alía R., Gil L., Geographical variation of gene diversity of *Pinus pinaster* Ait. in the Iberian Peninsula, in: Müller-Starck G., Schubert R. (Eds.), Genetic response of forest systems to changing environmental conditions, Kluwer Academic Press, Dordrecht, 2001, pp. 161–171.

[20] Gonzalo J., Sánchez P., Análisis de calidad de estación en dos regiones de procedencias de *Pinus pinaster* Ait.: Oña (Burgos) y Sierra del Teleno (León), in: Puertas F., Rivas M. (Eds.), Proceedings of I Congreso Hispano-Luso (mesa IV), Pamplona, 1997, pp. 315–320.

[21] Laguardia A., The behaviour of *Pinus caribaea* var. *hondurensis* in Misiones, Suppl. For. 4 (1967) 53–58.

[22] Leaphart C.D., Hungerford R.D., Johnson H.E., Stem deformities in young trees caused by snowpack and its movement, U.S. For. Serv. Res. Notes INT 158, 1972, pp. 10.

[23] Lindstrom A., Rune G., Root deformation in plantations of container-grown Scots pine trees: effects on root growth, tree stability and stem straightness, Plant Soil 217 (1999) 29–37.

[24] Loup C., Le développement architectural du pin maritime, in: Thibaut B. (Ed.), Proceedings of the Second Seminar "Architecture, Structure, Mécanique de l'arbre", LMGC, University of Montpellier II, Montpellier, 1990.

[25] Loup C., Fournier M., Chanson B., Moulia B., Redressements, contraintes de croissance et bois de réaction dans le bois d'un jeune *Pinus pinaster* artificiellement incline, in: Thibaut B. (Ed.), Proceedings of the Third Seminar "Architecture, Structure, Mécanique de l'arbre", LMGC, University of Montpellier II, Montpellier, 1991.

[26] Magini E., The heritability of the stem form in *Pinus pinaster*, FAO-FTB 3/8, 1969.

[27] Malinuaskas A., The influence of the initial density and site conditions on Scots pines growth and wood quality, Baltic For. 5 (1999) 8–19.

[28] Montero G., Ortega C., Cañellas I., Bachiller A., Productividad aérea y dinámica de nutrientes en una población de *Pinus pinaster* Ait. sometida a distintos regímenes de claras, Investigación Agraria: Sistemas y Recursos Forestales FS 1 (1999) 175–206.

[29] Nanos N., Montero G., Spatial prediction of diameter distribution models, For. Ecol. Manage. 161 (2002) 147–158.

[30] Nanos N., Tadesse W., Montero G., Gil L., Alía R., Modelling resin productions for *Pinus pinaster* Ait. using two probability functions, Ann. For. Sci. 57 (2000) 369–377.

[31] Nanos N., Tadesse W., Montero G., Gil L., Alía R., Spatial stochastic modeling of resin yield from pine stands, Can. J. For. Res. 31 (2001) 1140–1147.

[32] Petty J.A., Worrell R., Stability of coniferous tree stems in relation to damage by snow, Forestry 54 (1981) 115–127.

[33] Polge H., Illy G., Observations sur l'anisotropie du pin maritime des Landes, Ann. Sci. For. 24 (1967) 205–231.

[34] Radi M., Catera P., Qualification de la forme de deux pins maritimes en liason avec la structure de leur bois, Ann. Sci. For. 49 (1992) 185–200.

[35] Rottmann M., Waldbauliche Konsequenzen aus Schneebruchkatastrophen, Schweiz Z. Forstwes. 136 (1985) 167–184.

[36] Roussel L., Le phototropisme juvénile des résineux, Rev. For. Fr. 11 (1966) 708–717.

[37] Sierra de Grado R., Mejora genética de *Pinus pinaster* Ait. de la procedencia Sierra de Gredos. Caracteres de crecimiento y forma, Ph.D. thesis, Universidad Politécnica de Madrid, Madrid, 1994.

[38] Sierra de Grado R., Moulina B., Fournier M., Alía R., Díez-Barra R., Genetic control of stem form in *Pinus pinaster* Ait. seedlings exposed to lateral light, Tress 11 (1997) 455–461.

[39] Sierra de Grado R., Díez-Barra R., Alía R., Evaluación de la rectitud del fuste en seis procedencias de *Pinus pinaster* Ait., Investig. Agrar., Sist. Recur. For. 8 (1999) 263–278.

[40] Sierra de Grado R., Martínez-Zurimendi P., Pando V., Straightening abilities in *Pinus pinaster* Ait.: variability between populations, in: Spatz H.C., Speck T. (Eds.), Proceedings of the third Plant Biomechanics Conference "Plant Biomechanics 2000", Thieme, Freiburg-Badenweiler, 2000, pp. 463–467.

[41] Schmidt W.C., Stand density in relation to biological functions in young Western larch forests, in: Bamsey C., Lake C. (Eds.), Stand density management: planting and implementation, Edmonton (Alberta), 1997, pp. 101–111.

[42] SSPS Inc., SPSS for Windows, Version 9.01 (1989–1999).

[43] Tapia R., Gil L., Pardos J.A., Los pinares (*Pinus pinaster* Ait.) de las estribaciones de la Sierra del Teleno (León), La influencia del incendio en su ordenación, Montes 52 (1998) 115–121.

[44] Timell T.E., Compression Wood in Gymnosperms, Springer-Verlag, Berlin, 1986.

[45] Valinger E., Lundquist L., Sunberg B., Mechanical bending stress applied during dormancy and growth stimulates stem diameter growth of Scots pine seedlings, Can. J. For. Res., 25 (1995) 886–890.

[46] Williams C.G., Lambeth C.C., Bole straightness measurement for advanced-generation loblolly pine genetic test, Silvae Genet. 38 (1989) 212–217.

[47] Wykoff W.R., Crookston N.L., Stage A.R., User's guide to the stand prognosis model, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah., General Technical Report INT 133, 1982, p. 122.

[48] Yoshizawa N., Okamoto Y., Idei T., Righting movement and xylem development in tilted young conifers trees, Wood Fiber Sci. 18 (1986) 579–589.