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Original article

Wind-firmness in *Pinus pinaster* Aït. stands in Southwest France: influence of stand density, fertilisation and breeding in two experimental stands damaged during the 1999 storm

Véronique Cucchi and Didier Bert*

Laboratoire Croissance et Production, Unité de Recherches Forestières de Pierroton, Institut National de la Recherche Agronomique – Bordeaux, 69 Route d'Arcachon, 33612 Cestas Cedex, France

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Abstract – Maritime pine (*Pinus pinaster*) stands in the Aquitaine region are of great economic importance but subject to Atlantic storms. In the Bordeaux region, two experimental sites located near each other, aged 20 and 51 years, made it possible to study the effects of different types of silviculture on wind-firmness during the 1999 storm. Stand density has a major influence on tree growth. When density increases, height increases and circumference decreases appreciably. In the dense stands, windthrown trees were less abundant and there were more leaning pines. With respect to other silvicultural factors in stands planted at typical densities: (i) genetic breeding did not increase damage intensity at the 20-year-old experimental site and phosphorus fertilisation decreased the windthrow at the 51-year-old experimental site; (ii) compared to the undamaged trees, the circumference of windthrown trees was 3.6 cm smaller, the relative crown length was 10% shorter and the stem taper coefficient was higher. This research has shown that wind-firmness is better in stands where the height, circumference and crown length are homogeneous. A more closed canopy seems to improve wind resistance by increasing the damping effect of swaying as a result of the crowns being in contact with each other and provides a more favourable ratio between the aerial parts and the roots.

windthrow / silviculture / *Pinus pinaster* / stability / storm

Résumé – Résistance au vent de peuplements de pin maritime dans le sud-ouest de la France. Influence de la densité, de la fertilisation et de l'amélioration génétique sur deux dispositifs endommagés lors de la tempête du 27 décembre 1999. Les peuplements de *Pinus pinaster* en Aquitaine sont économiquement très importants mais exposés aux tempêtes océaniques. Dans la région de Bordeaux, deux dispositifs de 20 et 51 ans peu éloignés ont permis d'étudier l'influence de la sylviculture sur la résistance au vent lors de la tempête de 1999. La densité est le facteur sylvicole le plus influent sur les caractéristiques des peuplements. Quand la densité augmente, la circonférence moyenne diminue notablement et la hauteur moyenne a tendance à augmenter. Les chablis étaient moins abondants et les pins penchés plus nombreux dans les peuplements denses. Pour les densités pratiquées en forêt de production : (i) l'amélioration génétique n'a pas augmenté l'intensité des dégâts dans l'essai de 20 ans, et la fertilisation au phosphore a réduit le taux de chablis sur l'essai de 51 ans ; (ii) par rapport aux pins intacts, les chablis ont une circonférence inférieure de 3,6 cm, une longueur relative de houppier plus courte de 10 % et un coefficient d'élancement du tronc plus fort. Ces caractéristiques peuvent traduire la diminution des capacités d'amortissement du balancement des arbres lors des bourrasques. Ces recherches ont montré que la résistance au vent est meilleure dans les peuplements homogènes en hauteur, circonférence ou longueur de houppier. Un couvert plus fermé semble améliorer la résistance au vent en augmentant l'amortissement des oscillations des houppiers par contact entre houppiers, ainsi que le rapport entre les parties aériennes et les racines.

chablis / sylviculture / *Pinus pinaster* / stabilité / vent

1. INTRODUCTION

Intensive Maritime pine (*Pinus pinaster* Aït.) cultivation in the Aquitaine region is vital to the French wood-based sector. The Landes region produces 16% of the wood in France even though it only covers 7% of French forestland. The most violent storm known since this cultivated forest was established occurred in the southwest of France on the 27th December 1999. Winds of over 170 km h^{-1} devastated the north of the range and caused estimated losses of 26.1 million m^3 of wood, i.e. 19% of standing volume and 3.5 years of harvest (IFN, communication from the updated 4th Gironde and Landes inventory). This recent and considerable damage followed earlier and less severe damage of 1–2 December 1976 (2 million m^3 of windthrow), 7 February 1996 (1.5 million m^3 of windthrow) [16, 25].

Yet little research on vulnerability to wind has so far been conducted on species of commercial importance in France. Previous studies have focused mainly on broad-leaved trees or on conifers other than Maritime pine. Studies on *Abies alba*

* Correspondence and reprints
Tel.: (33) 05 57 12 28 44; fax: (33) 05 56 68 02 23; e-mail: bert@pierroton.inra.fr

Table I. Main features of the experiments. DBH and C130 are diameter and circumference at breast height, respectively. The complete height inventory for the 20-year-old stand was not available and the mean height is indicative.

	Experiment			
Age	**20 years old**		**51 years old**	
Name	U plot of Pierroton		Saint-Alban trial	
Number of plots	16		48	
Plot area (ha)	0.12		0.23	
Trees ha^{-1}	600, 1950		185, 310, 426, 624	
Treatments	Number of blocs	2	Number of blocs	6
	Genetic types	Natural, improved	Fertilization	Control, P fertilized
	Spacing	2 × 2 m, 4 × 4 m	Thinning intensity at 21 yr-old	Light, heavy
			Thinning intensity at 25 yr-old	Light, heavy
Replicates per treatment	4		6	
Mean height (m)	≈ 16		23.8	
Mean DBH (m)	0.22		0.37	
Mean C130 (m)	0.70		1.17	

(Mill.), *Picea abies* (L.) Karst, *Pseudotsuga menziesii* (Mirb.) Franco and *Larix decidua* (Mill.) in France [15, 43] have shown that vulnerability depends partly on the species and mainly on the site conditions and silvicultural context. Therefore, more knowledge of wind-firmness in Maritime pine forests in the Aquitaine region is necessary, particularly considering that the range was affected by three storms in 23 years.

Wind-firmness in forests should be dealt with at various scales. At the regional scale, stand stability depends on abiotic factors such as climatic conditions, site topography and type of substrate [7, 32, 46]. At the local scale, wind-firmness cannot be dissociated from the stand and the individual tree properties. The overturning moment of a tree has two main components: the lateral force applied by the wind loading on the crown, and the displaced weight of the stem and the crown when the tree bends [19, 41]. There are also two main resistive forces: the root anchorage and the damping due to the contact between crowns and stem strength [41]. These four components are subject to modification under the influence of silvicultural practices. The management and spatial structure of the stand determine dimensional features and tree morphology [1, 10, 11, 40, 45, 48], wind permeability [21, 26, 41, 51] and mechanical properties of the wood influenced by exposition to wind [20, 53, 54]. Wind-firmness of individual trees also depends on external or internal defects due to insects or fungi [47]. Silvicultural factors and situations vary greatly in commercial stands and it is difficult to distinguish between the ways in which they interact with wind. It was therefore very interesting to study two experimental sites damaged by the 1999 storm in which several silvicultural conditions varied according to well known experimental protocols.

The two stands of Maritime pine were not far from each other and complementary to each other in terms of silvicultural history and age. The silvicultural treatments applied differed by their initial density, thinning regimes, fertilisation and genetic improvement. These treatments partly represented the older as well as the more current practices used in forestry in the Landes region. Their stand densities span the normal density, which makes it possible to generalise the results to more varied conditions. These experimental sites also had the advantage of including replications and of having a spatial structure which made it possible to quantify and distinguish between the effects of the silvicultural factors on wind-firmness. Our approach was based on making observations at the stand scale and individual tree scale. We drew links between the various kinds of damage, on the one hand, and the silvicultural treatments and dendrometric features, on the other, with a view to answering the following questions:

• How do the various treatments affect the dendrometric features of the stands?

• How is the damage distributed with respect to the silvicultural treatments?

• Which dendrometric variables at the stand scale can best explain the level of damage?

• Are there dendrometric differences between the undamaged pines and the pines damaged by the storm?

2. MATERIALS AND METHODS

2.1. The storm of December 1999: climatic data (Météo-France http://www.meteo.fr)

The two storms that swept through France on the 26th and 27th December 1999 moved from west to east at a speed of 100 km h^{-1}. The first storm mainly hit the north of France, with peaks of 200 km h^{-1}. At Cap-Ferret, 50 km to the west of the study sites, gusts of 173 km h^{-1} at a height of 30 m were measured and 160 km h^{-1} at a height of 20 m. The second storm occurred farther to the south, and the maximal wind speeds at Cap-Ferret once again reached 173 km h^{-1} at a height of 30 m, and 144 km h^{-1} at 10 m at the weather station at Bordeaux-Mérignac airport. Considering the strength of these winds, such an event tends to occur in this temperate European climate less than once a century.

2.2. Study sites: presentation and background

The two INRA experimental trials were located in the south-west of France, 25 km from Bordeaux, at 44.42° north latitude, 0.46° west longitude and at an altitude of 60 m (*figure 1*). The sites were 4 km apart and established with a view to estimating Maritime pine growth using various silvicultural methods (*table I*) [29]. The relief is flat and

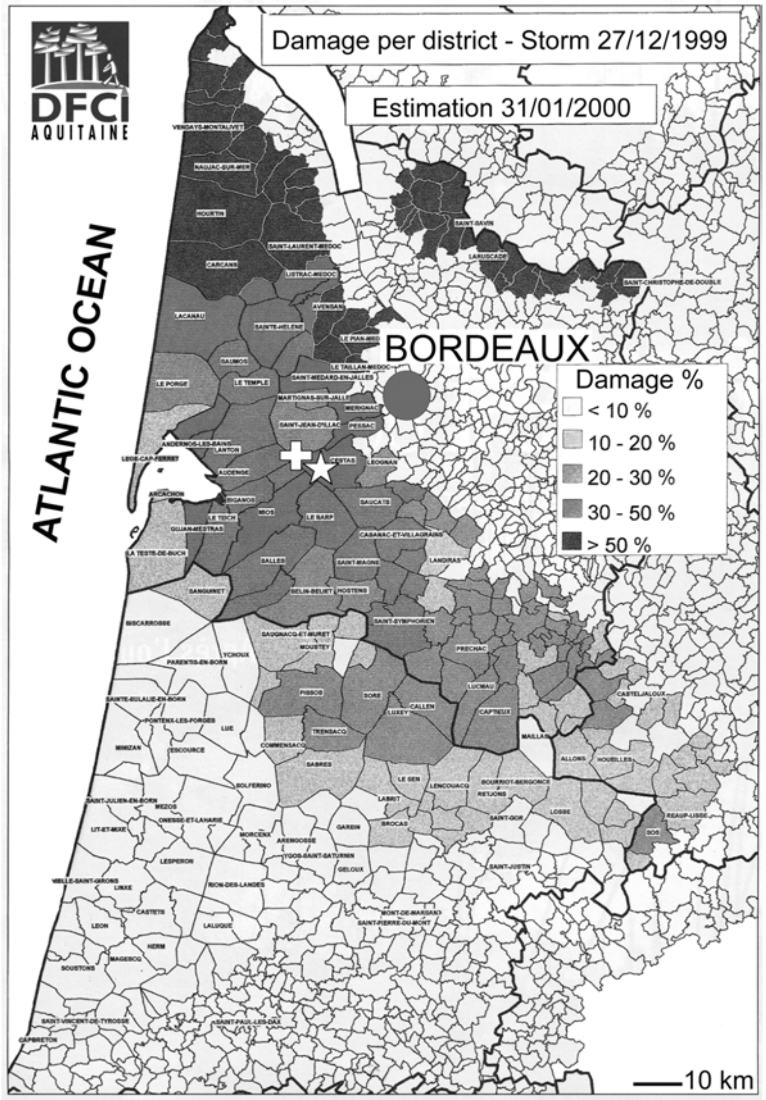

Figure 1. Map of the range in the Landes region indicating the district boundaries, the mean level of forest damage per district and the location of the two study sites: the cross indicates the 20-year-old experimental site and the asterisk gives the location of the 51-year-old experimental site. In the north of the range, certain agricultural districts are not very woody and are shown in white although they lie adjacent to highly damaged districts. Copyright for topographic base and damage belongs to the AR DFCI Aquitaine.

the soil is a hydromorphous humus podzol with a hardened iron pan horizon at a depth of about 60 cm [28, 55].

The location of the sites in a geographical area that had been moderately affected by the storm made it possible to study the effects of the wind. The damage was bad enough to be observed without the stands having been completely destroyed. A meteorological tower between the two sites recorded wind direction and speed from the 1st July 1998 to the 10th October 2000 (Bioclimatology Unit of INRA-Bordeaux). At a height of 40 m above ground, the prevailing winds were mainly from the west and north-west. During the storm of 27th December 1999, the most violent winds occurred between 17 and 24 h Universal Time particularly from the western and north-western directions (235 to 305°).

2.2.1. The 20-year-old stand = "U Plot of Pierroton"

This site covers 4.84 ha divided into 16 plots of 0.12 ha, separated by buffer zones. The plots were distributed according to two densities (2×2 or 4×4 metres spacing) and two genetic types (natural pine or improved pine). These four silvicultural scenarios were distributed in two scattered blocks determined on the basis of the colour of the surface soil (*figure 2A*). Therefore, each block contained two replications. The pines were sown in a nursery in August 1979 and the bareroot seedlings were replanted in December in moist mesophilic moorland fertilised with phosphorous. The stand was 20 years old at the time of the storm. The improved stands correspond to the first improved generation G1 obtained by selecting forest "+trees" and by conducting a progeny test on height and deviation from the vertical at the age of ten in the Saint-Sardos orchard, in south-west France. At other sites, Danjon [13] showed that this first generation generated a genetic gain of 25% in volume and stem straightness. The 2×2 m and 4×4 m spacings and natural mortality resulted in densities of 1952 stems ha^{-1} ($\sigma = 82$) and 605 stems ha^{-1} ($\sigma = 10$), respectively. As a basis of comparison, the density of 20-year-old Maritime pine stands which have undergone typical commercial sylvicultural practices is about 550 to 700 stems ha^{-1}.

2.2.2. The 51-year-old stand = "Saint-Alban site"

This site covers 25 ha of mesophilic moorland divided into 48 plots of 0.23 ha, separated by buffer zones. Plots are distributed according to four densities and two types of phosphorus fertilisation (fertilised or control), representing eight treatments in six scattered

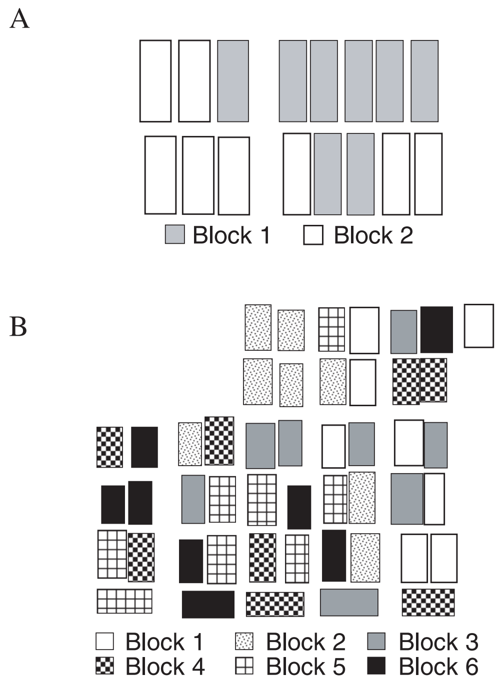

Figure 2. (A) Map of the 20-year-old experimental site with plot boundaries and two different colours for the two blocks. (B) Map of the 51-year-old experimental site with plot boundaries and six different patterns for the six blocks.

blocks (*figure 2B*). The pines were sown in bands and were 51 years old at the time of the storm. *Figure 3* shows the thinning scenarios applied over time, from the first intervention in 1961 until 1999. Each of the four thinning scenarios will be designated in this article by two letters corresponding to the intensity of each of the two differential thinning regimes: "H" for heavy, "L" for light. The four treatments are therefore designated HH, HL, LH and LL. These treatments correspond to four different mean densities in 1999: 624 stems ha^{-1} for LL, 426 for HL, 310 for LH and 185 for HH. Typical densities in production stands of this age are about 350 stems ha^{-1}. Initially, the experimental area was made up of tilled soil plots and controls, and pines in some plots were pruned up to 8 m high and 16 years of age as of 1964. Pruning was never sufficient to result in a measurable effect on growth. Since 1964, natural pruning has raised the base of the crowns above 14 m high and, consequently, artificial pruning has not been considered in the present study on the storm effects. Soil was tilled each year using a rotavator between rows until eight years of age, and then using a covercrop when the canopy had closed so as to avoid damaging the roots. Since the effect of soil tilling on growth had become imperceptible, phosphate fertilisation was applied at the age of 25 years on plots that had previously been "tilled". Fertilisation was applied once at a dose of 120 kg of P_2O_5 per hectare in the form of slag. The control plots for soil tilling were considered to be fertilisation controls.

2.3. Damage inventory and dendrometric measurements

2.3.1. Damage definitions and inventory

A joint protocol for Maritime pine has been set up by the French forest institutes, INRA, AFOCEL, CPFA and ONF, in order to compare the results of different inventories. The damage suffered by the stands was differentiated into five categories:

- **undamaged** trees with no hint of wind damage. Some of them were leaning before the storm but have not been included in the "leaning trees";
- slightly **leaning** pines (visually estimated angle from the vertical ≤ 20°) with a slightly upraised soil-root plate. They constitute the stand together with the undamaged trees after the harvest of damaged trees;
- **heavily leaning** trees (angle > 20°). They are removed from the stand at the time of the sanitary thinning following a storm;
- **windthrown trees** are those that were completely uprooted;
- **breakage**, where stems failed at the trunk level.

Each pine was included in the inventory and we noted its damage state and if it was dead or alive at the time of the storm. In total, we recorded 3276 pines in the 20-year-old experimental site and 4360 in the 51-year-old experimental site.

2.3.2. Dendrometric measurements

For the 20-year-old experimental site, the circumference at 1.30 m height (C130) was measured for all the trees. Measurement of tree height was not possible as stand density was very high, and it was difficult to manoeuvre among the fallen trees.

For the 51-year-old experimental site:

- C130 was measured for all the individuals;
- in each plot, the C130 distribution was split into six quantiles, i.e. 0.25, 0.5, 0.7, 0.8 and 0.9. The median undamaged pine of each quantile was chosen to measure the total height "H_t", and the height of the first living branch using an ultrasound hypsometer (Vertex);
- of the six previously sampled individuals, three were used to estimate the surface area of the crown projection on the soil using a kronenspiegel [36]. The surface areas were calculated via vector processing because the method of Pardé and Bouchon [36] overestimates the surface area to an even greater extent when the crown is eccentric, whereas vector processing underestimates it slightly but to the same extent in all pines. The method used for calculating the surface area of the crown using eight radii separated by 45° angles is summed up in the following equation:

$$\text{Surface} = \sum_{i=1}^{8} \frac{\left|(x_{A_i} \cdot y_{A_{i+1}}) - (x_{A_{i+1}} \cdot y_{A_i})\right|}{2}$$

- A_i is the point located at the intersection of a crown radius with the circumference. A_{i+1} is at the intersection of the next radius with the circumference. The co-ordinates for A_i are x_{Ai} and y_{Ai} in the referential axis whose origin is the point at which the northern face of the trunk meets the soil. The *y* axis is the radius pointing in a northern direction and the *x* axis the radius pointing towards the east. The asymmetry of the crown of standing pines was defined as the distance between the centroid of its horizontal projection and the centre of the stem at the base of the crown. The co-ordinates of the centroid are the mean of the co-ordinates of the eight points at the end of the eight radii;
- total height of windthrown trees and the height of the first living branch were measured using a decametre;
- the soil-root plates of uprooted pines were clearly delimited and made it possible to accurately measure the eight radii. The soil-root plate surface area was estimated using the method generally employed for estimating the crown surface areas (*figure 4*) [36]. The measurements were only made on the soil-root plates of uprooted trees and do not concern the "effective" root plate before the damage. However, this protocol does make it possible to make some comparisons between trees and plots. The asymmetry of the root plates of uprooted pines was calculated in terms of the distance between the centroid of the soil-root plate and the centre of the trunk (*figure 4*). Soil-root plate depth has been found to be constant, around 60 cm. Thus, the surface of the plate was used instead of the volume.

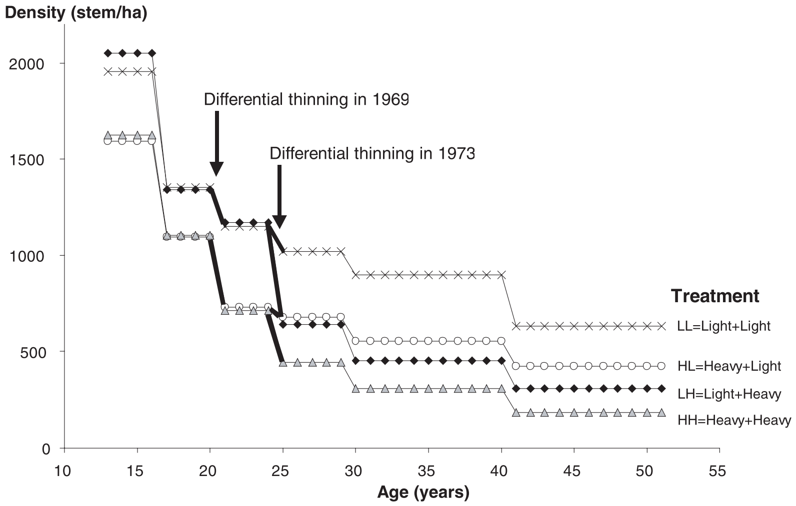

Figure 3. Evolution of mean density according to age per thinning regime from 1961 to 1999.

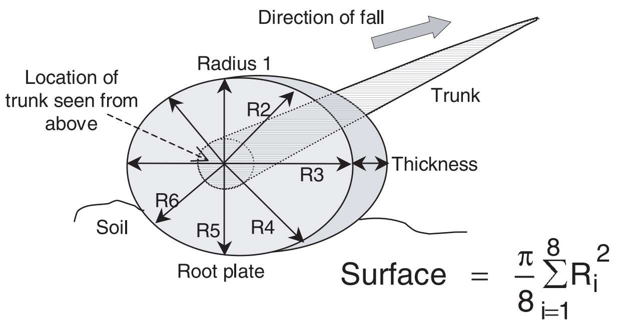

Figure 4. Method for estimating the surface area of the soil-root plates. To calculate the centroid and dissymmetry of the plate, the eight extremities of the radii were localised in an orthogonal referential axis with radii R7 and R3 as the abscissa axis and radii R1 and R5 as the ordinate axis.

2.4. Use of different dendrometric variables

The variables obtained from the sampling operations led us to consider the plot to be a sampling unit: each plot therefore has one value per dendrometric variable. This value is calculated differently depending on the type of variable:

• The mean pine circumference was calculated according to $C_g = \sqrt{C_{moy}^2 + ó^2}$, where C_{moy} is the arithmetic mean of C130 of all the pines in the stand and σ is its standard deviation [36];

• The dominant pine circumference C_o is the arithmetic mean of the 100 biggest trees per ha;

• The arithmetic mean per plot was calculated for the variables relating to windthrow, e.g. mean surface area of the soil-root plate, mean direction of tree fall;

• For the non-exhaustive variables, a classical method in dendrometry was used [36]. The relation between the tree height and the circumference was adjusted with the Monod model for each treatment using its 36 couples "H_t, C130":

$$H_t = \frac{a \times C130}{b + C130}.$$

When the circumference C_g of a given plot is put into the model, it gives the estimate of the height "H_g" of the mean pine circumference for the plot. Likewise, the dominant height "H_o" is obtained on the basis of the dominant circumference C_o. The base height of the crown has also been adjusted according to C130 with this method. Using the same scatter diagrams, we completed the description of each plot with a standard deviation value to express the variability within the plot. For the dominant height, for example, σ_{Ho} was estimated by applying the model to the "$C_o + \sigma_{Co}$" value, which gave the "$H_o + \sigma_{Ho}$" value, from which we then subtracted H_o. For the variables calculated arithmetically, the variability corresponds to the real standard deviation of the values.

In total, 59 dendrometric variables characterised each plot in the 51-year-old stand. For the 20-year-old stand, only those variables calculated on the basis of C130 are available, as well as their variability.

At the tree scale, it was more complicated to compare the height of the undamaged and the windthrown trees due to the fact that the two groups of trees were not constituted equally, i.e. all the windthrown trees had been measured, whereas the undamaged pines, of which there were far more, were sampled into circumference categories. Therefore, one Monod model or one allometric model per treatment and per variable was adjusted with the sampled undamaged pines on the one hand and windthrown pines on the other. The mean circumference of undamaged pines and windthrown pines per plot was then calculated and incorporated into the model in order to obtain the mean height per plot and per type of pine. The same approach was applied to the height of the living crown.

2.5. Statistical methods

2.5.1. Logistic regression

Logistic regression enabled us to test the effect of silvicultural scenarios on the percentage of damage. This type of regression predicts an event associated with a likelihood depending on one or several independent qualitative or quantitative variables and thus works with binary data or proportions [24]. The method has the advantage of being robust, even when working with small numbers of individuals, and does not require that the individuals be independent of each other as in the case of χ^2, since trees in a same plot are not independent individuals.

Table II. Stand density, mean circumference C_g, and dominant circumference C_o in the 20-year-old trial, and their standard deviation per treatment. For a given variable, the values associated with the same letter are not significantly different at the 5% threshold.

20-year-old stand	**Treatment**							
Variable	4 × 4 Natural		4 × 4 Improved		2 × 2 Natural		2 × 2 Improved	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Density (tree ha^{-1})	601	5	609	13	1963	110	1941	61
C_g (m)	0.78	0.04	0.85	0.08	0.57	0.03	0.61	0.02
Differences in block 1	b		a		c		c	
Differences in block 2	a		a		b		ab	
C_o (m)	0.96	0.06	1.04	0.09	0.85	0.06	0.86	0.02
Differences in block 1	a		a		b		b	
Differences in block 2	a		a		a		a	

In order to test a treatment effect, it was necessary to remove possible random effects. Different levels of damage in two treatments may be due to the treatments themselves or to a “plot” effect. The logistic regression makes it possible to identify the few plots that generate such an effect. Generally, the plots in a treatment presented a rather regular distribution of levels of damage, but it could possibly happen that one plot showed a very different level of damage than the others. The field measurements did not make it possible to explain such a pattern. These few plots have thus been eliminated from the regression analysis so as to test only the treatment effect on the level of damage. Regression analyses were carried out using the GENMOD procedure (generalised linear model) of SAS software (SAS Institute, Inc., Cary, NC, USA).

2.5.2. Other methods

The dendrometric differences between treatments were tested by analysis of variance using the Bonferroni t-test and the multiple rank test of Ryan-Einot-Gabriel-Welsch, which performs better in the case of equal numbers of individuals (GLM and REGWQ procedures of SAS). The comparisons between undamaged and windthrown pines were tested by analysis of covariance (REG and GLM procedures of SAS).

3. RESULTS

3.1. Effect of treatments on the dendrometric features of the stands

3.1.1. The 20-year-old stand

A “block” effect on stem size existed given that the pines had a larger mean circumference in block 1 than in block 2. Block 1 was therefore located in a more fertile zone of the site. However, regardless of the block, the decrease in **density** led to a significant increase in the mean stem circumference (*table II*). The **breeding** effect was weak and only the improved stands in the 4 × 4 arrangement in block 1 exhibited a significant gain of +12.7% in mean circumference compared to the natural stands (*table II*). The difference between natural pines and improved pines can therefore only be observed at low densities in the more fertile zone. Moreover, the treatments showed no effect on **variability** of stem size, with respect to either the mean or dominant height.

3.1.2. The 51-year-old experimental site

When the trial first began in 1957, the blocks were set up according to the mean height for each plot: block 1 with mean height of 2.19 m, block 2 at 2.13 m, block 3 at 2.03 m, block 4 at 1.89 m, block 5 at 1.76 m and block 6 at 1.63 m. The pines of blocks 5 and 6 were significantly smaller in terms of height and circumference at 8 years, 13 years and 30 years of age, but they were no longer significantly smaller at 35 years of age.

The effect of **soil tilling** was positive from 13 to 21 years of age with respect to circumference and only at 21 years of age with respect to height. This effect disappeared at 25 years of age and no pruning effect was observed. The “soil tilling” treatment was therefore replaced with phosphate fertilisation, and pruning operations were abandoned.

The **fertilisation** effect was positive with respect to circumference at 30 and 35 years of age. The mean pines in the fertilised plots were 6.5% larger in terms of circumference at both ages.

The effect of **thinning** operations on the circumference became visible at 25 years of age, i.e., four years after the first differential thinning operations. The mean pines in the heavily thinned plots were bigger than those in the lightly thinned plots. Conversely, height was not affected, and stem taper was therefore modified. At 35 years of age, the pines in areas of very low density were far more stocky than pines in areas of very high density. The mean *H/D* ratio was 72.7 ($\sigma = 2.1$) for the LL plots and 59.7 ($\sigma = 2.4$) for the HH plots.

At 51 years of age, density strongly changed the dendrometric features of the stands (*table III*). This effect was significant for all the variables except for those expressing aerial or root asymmetry. When density increased, the mean circumference decreased and the height increased appreciably. From the LL plot to the HH plot, the mean circumference increased by about 30% and the mean height decreased by about 2 to 3%, i.e., 0.50 to 0.80 m. Consequently, the mean stem slenderness increased with density from 54 for the very sparse plots to 75 for the very dense plots. The crown volume decreased when density increased. From a density of 200 to a density of 700 stems ha^{-1}, the relative crown length decreased by 10% and the horizontal surface area was reduced by 65%. The surface area of the windthrown soil-root plates at 700 stems ha^{-1}

Table III. Mean and standard deviation of the main dendrometric features of the 51-year-old stand per treatment. H: heavy thinning; L: light thinning; F: fertilised stands; C: control stands. For a given variable, the values associated with the same letter are not significantly different at the 5% threshold.

51-years-old stand	**Treatment**															
Variable	HHC		HHF		LHC		LHF		HLC		HLF		LLC		LLF	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Density (tree ha^{-1})	199	42	171	20	334	64	286	22	422	33	429	48	654	50	616	60
C_g (m)	1.27	0.04	1.39	0.03	1.17	0.03	1.25	0.04	1.12	0.03	1.17	0.02	0.99	0.04	1.05	0.03
	b		a		c		b		c		c		d		d	
C_o (m)	1.37	0.03	1.48	0.04	1.33	0.03	1.42	0.04	1.36	0.05	1.38	0.02	1.26	0.05	1.32	0.04
	ab		a		ab		ab		bc		ab		c		bc	
H_g (m)	22.87	0.28	23.86	0.14	23.33	0.21	24.65	0.18	23.12	0.12	24.43	0.10	23.67	0.20	24.38	0.14
	e		b		cd		a		de		a		bc		a	
H_o (m)	23.54	0.16	24.39	0.19	24.28	0.15	25.28	0.15	24.09	0.18	25.24	0.08	24.72	0.16	25.34	0.10
	d		c		c		a		c		a		b		a	
Variability of H_o (m)	0.56	0.11	0.53	0.12	0.41	0.02	0.31	0.06	0.30	0.05	0.26	0.05	0.25	0.04	0.28	0.07
	b		b		d		c		a		a		a		a	
H/D (mean pine)	56.7	1.2	54.1	0.7	62.4	1.1	61.8	1.6	65.1	1.2	65.8	1.0	75.4	2.6	73.4	1. 9
	a		a		c		c		b		b		d		d	
Horizontal crown surface area	29.2	1.7	35.6	0.6	18.6	1.8	24.0	1.6	15.5	0.8	16.5	0.6	9.5	1.2	12.6	0.9
for mean pine (m^2)	b		a		d		c		e		de		g		f	
Surface area of soil-root plate	4.1	1.5	4.6	1.7	3.3	1.3	3.6	1.4	2.7	1.2	2.8	1.0	2.3	0.9	2.7	1.2
for windthrow (m^2)	ab		a		cd		bc		de		dce		e		de	
Relative crown length on trunk	35.9	0.7	38.5	0.1	32.2	0.6	33.5	0.4	30.8	0.2	30.1	0.3	26.1	0.5	26.8	0.5
for mean pine (%)	b		a		e		d		c		c		f		f	
Dominant relative crown length (m)	8.82	0.16	9.47	0.10	8.51	0.17	8.83	0.14	7.86	0.15	8.13	0.09	7.16	0.17	7.75	0.16
	b		a		c		b		de		d		f		e	

represented only 58% of the surface area at 200 stems ha^{-1}. *Figure 5* shows that the surface area of the crown decreased about 10 times more rapidly than that of the root plate.

The **fertilisation** effect can be observed mainly in the aerial parts (*table III*). The circumference, height, crown surface area (*figure 5*) and crown length of pines in the fertilised plots were all greater than those in the control plots. This effect was clearer at low densities because the gain from the HHC plot to the HHF plot was 9% for the mean circumference, 4% for height, 3% for crown length and 22% for horizontal crown surface area. Conversely, no such fertilisation effect appeared in the surface area of the root plate or in the stem taper of the trunk.

3.2. The 1999 storm: mapping of the damage in the experimental sites

The aerial views and maps illustrate the structure of the experimental sites and the density of the plots. The maps also make it possible to control the geographical distribution of the damage (*figures 6, 7, 8* and *9*). No edge effect was visually observed, nor could a zone with the most damage be distinguished. No edge effect was expected since the plots are not very large and close to the non-wooded surfaces. Figure 6 shows that a small corner of a field was close to the south-western border of the stand but the gusts mainly blew over a large forest stand. The zone effect would thus be expressed by the local aggregation of damage caused by greater wind activity in the area. It was necessary to verify that there was no zone effect so as to prevent it from interfering with the treatment effect to be studied. The visual control of maps, both from an "overall" approach and from a "treatment by treatment" approach, did not show any potential agglomerates. Moreover, the plots with high damage levels were adjacent to those with low damage level.

The distribution of the angles of fall of the pines showed that they fell between 25 to 165°, with a majority in the easterly direction between 55 to 130°. This is consistent with the climatic data as most of the gusts came from 235 to 305° (Bioclimatology Unit of INRA-Bordeaux). Furthermore, our tree pulling tests for a current mechanical study about anchorage of *Pinus pinaster* have shown that the angle of fall of a tree can differ by more than 45° from the direction of pull due to its anchorage in the soil. Therefore, both meteorological and tree measurements indicate that the direction of the gusts was relatively homogeneous during the storm.

3.3. The stand scale: effects of silvicultural treatments on the damage proportions

The proportions of undamaged trees confirmed the indications given on the maps (*table IV*, *figure 10*). The 51-year-old stand was less affected by the storm than the 20-year-old one.

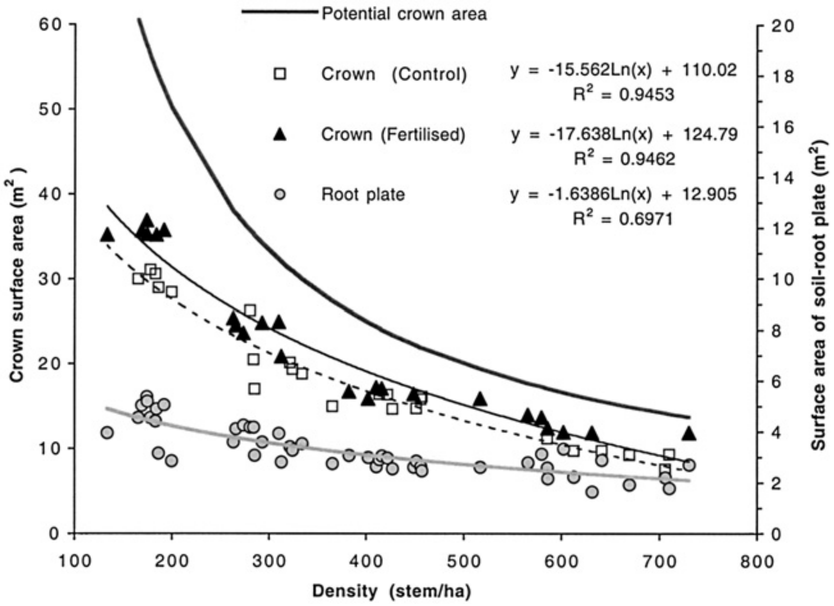

Figure 5. Evolution of means per plot of crown projection area on the soil and the soil-root plate as a function of density. Note the difference in scale between the two vertical axes. The potential crown area is the ratio: 10000 m^2/density, i.e. the mean available area for one single tree in the canopy. The thin solid line and the dotted line fit the scatters for the fertilised and control stands, respectively.

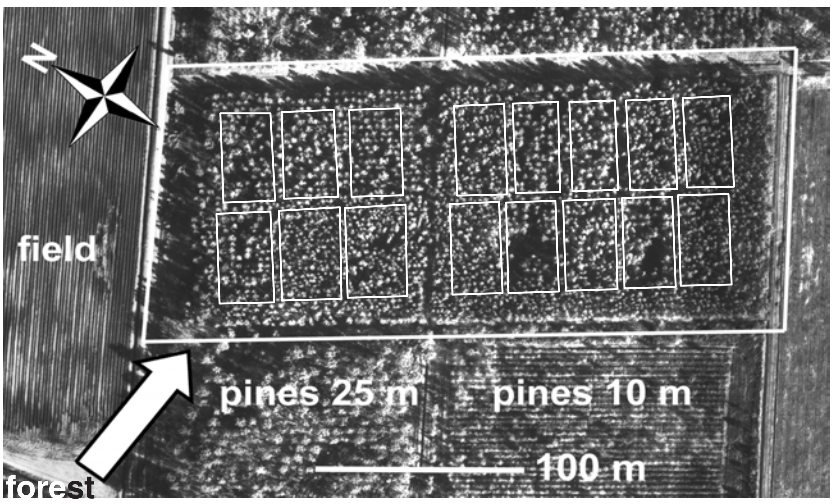

Figure 6. Aerial view of the 20-year-old stand on the 16th January 2000. The white perimeters indicate the boundaries of the experimental plots and stand. The white arrow represents the prevailing wind direction during the storm. The field was a small corner included in the westerly direction in a wide forest stand whose border is shown at the bottom left corner of the picture. The heights of the neighbouring stands in 1999 are indicated, and the studied stand was 16 m high.

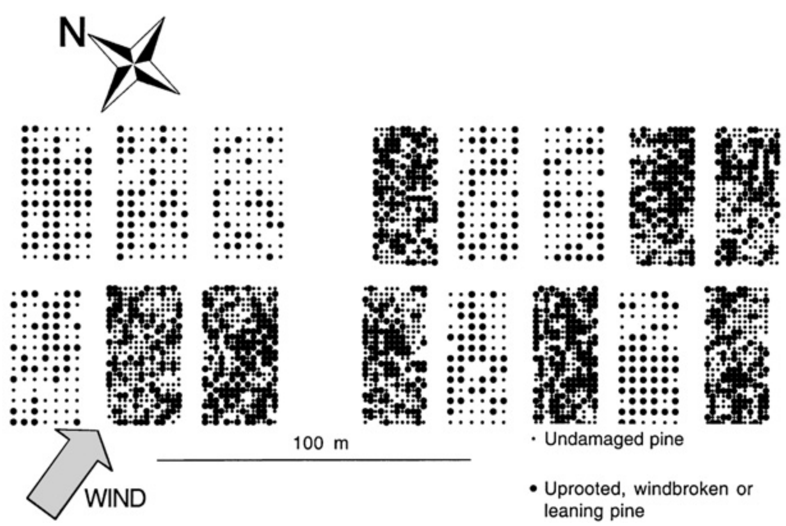

Figure 7. Map of damage to the 20-year-old stand. Each point represents a pine and the position of the pines within each plot is exact.

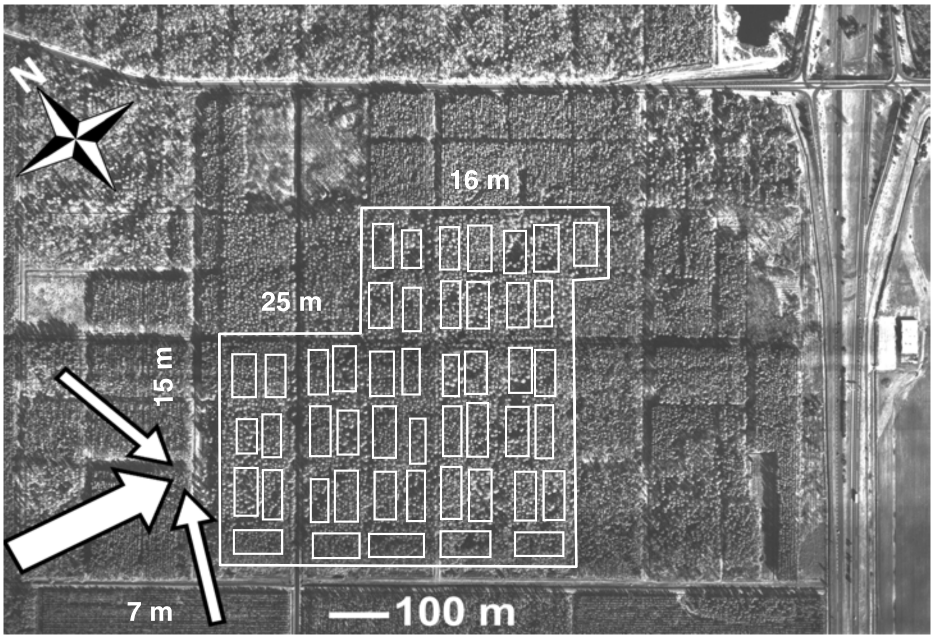

Figure 8. Aerial view of the 51-year-old Saint-Alban site on the 16th January 2000. The white perimeters indicate the boundaries of the plots and stand. The thick white arrow represents the prevailing wind direction. The small arrows show the extreme directions of the wind deduced from the direction in which the pines fell over a 25 to 165° range. The heights of the stands on the windward side of the 25 m-high studied stand are indicated.

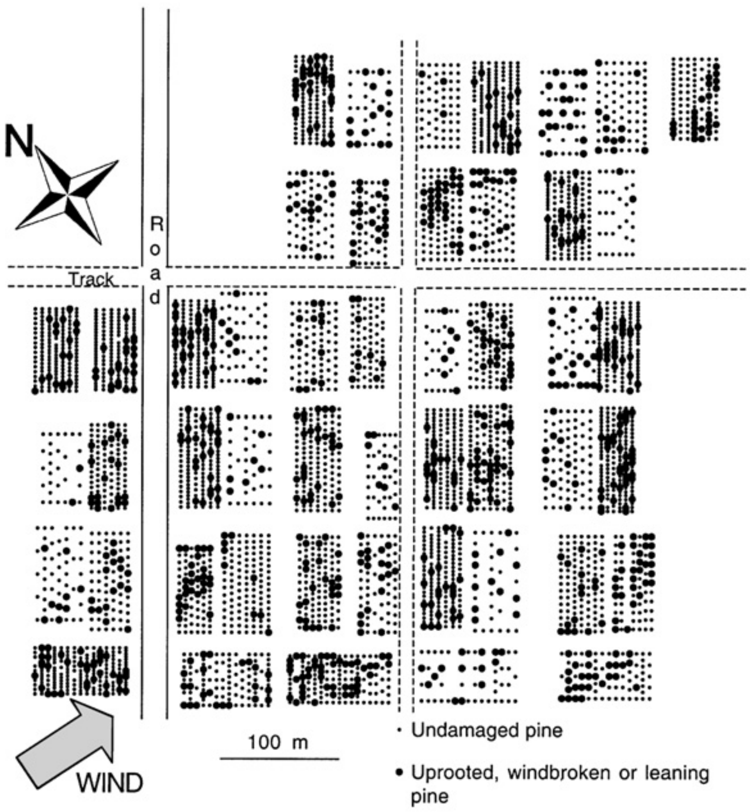

Figure 9. Map of damage to the 51-year-old stand. Each point represents a pine and the position and size of the plots are exact. The pines are shown to be distributed evenly within the plots because their exact co-ordinates were unknown.

Between 70 and 80% of the older stand remained undamaged as opposed to only 40 to 50% of the younger one. However, the damage in the young stand was minor since 50–80% of this damage concerned pines that were leaning but still rooted. In contrast, the damage observed in the 51-year-old stand was major because 65% of the pines affected corresponded to windthrow. In these plots, breakage and heavily leaning pines represented a small proportion of the stand.

Table IV. Percentage of pines per stand, treatment and damage category. The "Range of density" is the minimal and maximal stand density for the category, in stems ha^{-1}. "Unknown" individuals in the 20-year-old trial corresponded to windthrown trees or heavily leaning trees that were discarded before our inventory was compiled. They have been considered as windthrow in *figure 10*.

Stand age		State						
20 yrs	Treatment code & range of density	Population	Undamaged	Leaning	Heavily leaning	Windthrow	Breakage	Unknown
	2 × 2 = 1818–2060	Natural	55.4	36.3	6.1	0.7	1.6	0.0
		Improved	39.7	39.7	14.1	3.5	3.1	0.0
	4 × 4 = 590–618	Natural	49.2	24.0	1.8	8.3	9.8	6.8
		Improved	56.8	21.3	1.5	6.7	5.5	8.2
51 yrs	Treatment code & range of density	Fertilisation	Undamaged	Leaning	Heavily leaning	Windthrow	Breakage	Unknown
	LL = 565–730	Yes	79.8	6.1	1.8	10.5	1.7	.
		No	83.0	8.0	2.2	5.6	1.3	.
	HL = 365–516	Yes	79.4	5.1	2.0	11.1	2.4	.
		No	75.2	9.6	2.0	10.7	2.4	.
	LH = 263–456	Yes	81.6	3.6	1.5	10.7	2.7	.
		No	68.4	5.7	1.9	21.5	2.6	.
	HH = 133–280	Yes	76.3	3.9	0.5	16.4	2.9	.
		No	73.9	3.4	0.4	22.4	0.0	.

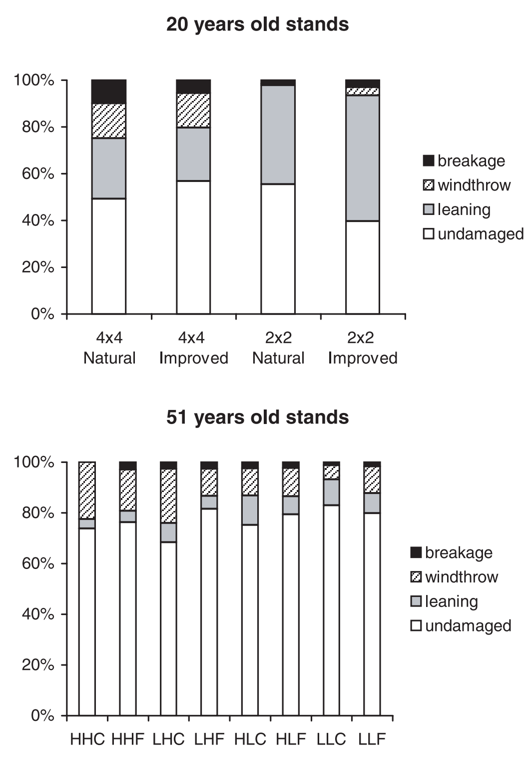

Figure 10. Percentage distribution of damage categories per site and per treatment. The heavily leaning trees are merged with the leaning trees. H: heavy thinning; L: light thinning; F: fertilised stands; C: control stands.

In *figure 11*, the damage in the plots was represented according to C_g, the circumference of the mean pine of the plot, because C_g integrates the effects of the management during the entire life of the stand, whereas the density is an instantaneous parameter. Moreover, C_g made it possible to take the effect of fertilisation on the mean tree size into account within each of the four density categories. C_g also has the advantage of being an efficient management guideline since foresters aim at harvesting the Maritime pine stands when the C_g reaches 1.30 m at breast height. The results are presented in *figure 11* for the two main categories of trees, i.e. the trees leaning at an angle ≤ 20° or > 20°, and the uprooted pines. The case of the broken trees is discussed in the text. The effect of the treatment on damage proportions was tested by covariance analysis for the 51-year-old stand since the C_g range was well sampled, and by logistic regression for the 20-year-old stand since only two groups of C_g were present in the stand. The logistic regression analysis revealed a few atypical plots that had to be removed from the data to make the comparisons valid.

3.3.1. The 20-year-old stand

• **Spacing effect.** The proportion of **leaning** pines was significantly higher in dense stands, with a C_g of around 0.6 m, whether the pines had been improved by selection or not ($P < 0.001$ within natural stands and $P < 0.001$ within improved stands) (*figure 11A*). Conversely, the proportion of **windthrown** trees was significantly lower in dense stands, regardless of the breeding ($P < 0.001$ within natural stands and $P < 0.001$ within improved stands) (*figure 11B*).

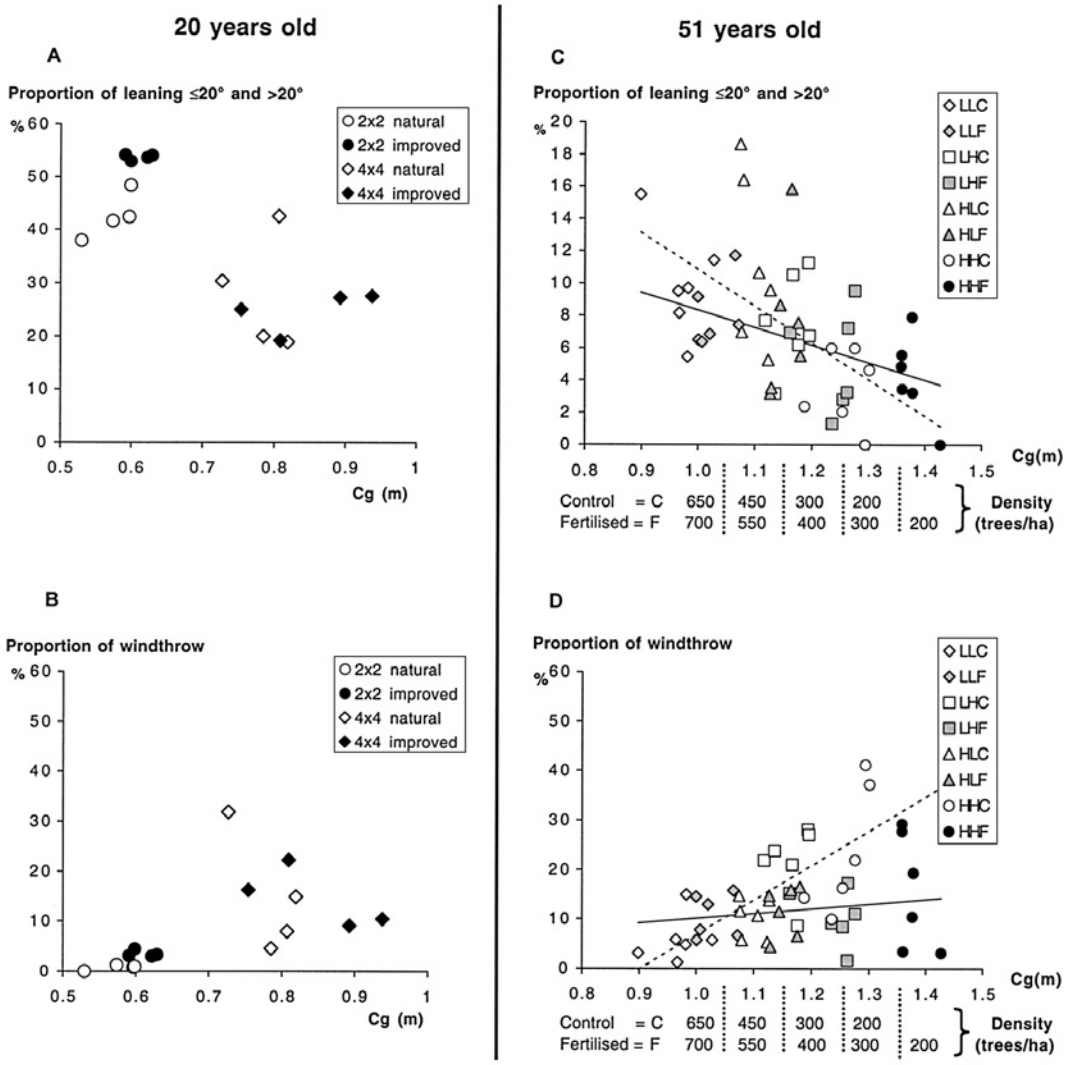

Figure 11. Percentage of pines according to the circumference of the mean pine of the plot per treatment for the leaning trees (angle ≤ 20° or > 20°), and for the windthrown trees. Note that the Y-scale for the 51-year-old leaning trees (C) is different from the other graphs. The dotted and solid lines are the regression lines for the control and fertilised plots, respectively. The white symbols are for the control plots and the black symbols are for the fertilised plots. For the 51-year-old stand, the stand densities corresponding to the C_g scale are given for control and fertilised treatments.

• **Breeding effect.** Breeding generated two different types of behaviour with respect to damage according to spacing: (i) in dense stands, the proportions of **leaning** and **windthrown** trees were significantly higher in the improved stands than in the natural ones ($P < 0.001$) and (ii) in sparse stands, with a C_g of around 0.85 m, the proportions were not significantly different (*figures 11A* and *B*).

For the proportion of **breakage**, the spacing effects are very similar to the results for windthrow, albeit the range of proportion reached only 18.9% instead of 31.8%, respectively. Due to the scattering of breakage percentage within dense stands or within sparse stands, it was not possible to show any significant difference according to breeding. However, it is possible to conclude that in areas of high density, trunks are not very thick and bend easily as the proportion of leaning trees was high, but hardly ever break. Conversely, in areas of low density, the trees are bigger and do not bend as much. They resist the wind better and eventually fail at the trunk or root level in a small proportion.

3.3.2. The 51-year-old stand

• **Spacing effect.** For the **leaning trees**, the Pearson correlation coefficients between the damage percentage and C_g are significantly negative both for control and fertilised plots: $r = -0.56$ ($P = 0.005$) and $r = -0.42$ ($P = 0.043$), respectively (*figure 11C*). Therefore, the dense stands with a C_g of around 1 m include 5 to 19% of leaning trees, whereas the sparse stands with a C_g greater than 1.30 m had less than 8% of them. Conversely, the correlation coefficient is

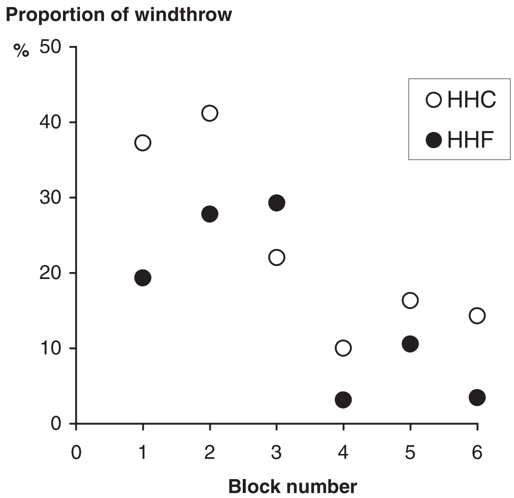

Figure 12. Proportion of windthrow in the six blocks of the 51-year-old stand for the lowest stand densities. HHF: fertilised; HHC: control.

significantly positive for the **windthrown trees** in control plots ($r = 0.73$; $P < 0.001$), and not significantly positive for the fertilised plots ($r = 0.18$; $P = 0.40$) (*figure 11D*). The percentage of windthrown trees is therefore higher in sparse control stands than in dense control stands.

• **Fertilisation effect.** For the **leaning trees**, the covariance analysis showed that the slopes of the regression lines were not significantly different between control and fertilised plots ($P = 0.18$). Conversely, the slopes for the **windthrow** were significantly different in the control plots and in the fertilised plots ($P = 0.002$). Therefore, phosphorous fertilisation seems to soften the relation between density of the stand and intensity of damage. Moreover, the percentage of windthrown trees is more variable in sparse stands where it may reach values as high as 41% in control stands and 29% in fertilised stands.

For **breakage**, the number of broken trees per plot was so small and variable that it was not possible to show any trend according to C_g or density.

3.3.3. Dendrometric explanation of the windthrow variability in the low density 51-year-old plots

The variability in windthrow proportions in the sparse plots (*figure 11D*) may be due to spatial phenomena related to wind exposure or proximity between different types of stands. Such variability may reflect a correlation between damage in the adjacent plots or a correlation between damage and density in neighbouring plots. Calculations of the Pearson correlation coefficient showed that this was not the case. Furthermore, the variability in damage could be related to the variability of the dendrometry of the HH plots. An analysis of variance carried out on the HH plots did not show any “block” effect on the different variables. Conversely, *figure 12* shows that the proportion of damage is related to the block number. For the fertilised and control plots, blocks 4 to 6 had less windthrow than blocks 1 to 3. The variability in damage is therefore not random. An analysis of variance carried out by placing the blocks in two groups, 1+2+3 and 4+5+6, revealed a significant effect of certain dendrometric variables. The variability in dominant height H_0 and the variability in dominant diameter D_0 were significantly higher for the group of blocks 1+2+3 than for the group of blocks 4+5+6. The standard deviations for H_0 were 0.61 m and 0.48 m, respectively (significant difference at the 0.025 threshold), and the standard deviations for D_0 were 0.035 m and 0.029 m (significant difference at the 0.04 threshold). Blocks 1, 2 and 3 were more **heterogeneous** in terms of dominant circumference and height than blocks 4, 5 and 6, and the importance of stand heterogeneity with respect to sensitivity to wind will be discussed later.

3.3.4. The variables that best explain damage intensity

It is possible to understand how silvicultural treatments determine stand vulnerability to wind by identifying the dendrometric variables that most influence the proportions of windthrow, breakage and leaning pines in the stand. For the 51-year-old stand, the best explanatory variables in a damage category were identified among the 59 potential variables by calculating the correlation coefficients and checking the linearity on the scatter diagrams. Explanatory variables differ according to the type of damage.

The proportion of **windthrow** showed the highest correlation with the variability in the dominant height, ETH_0, ($r = 0.612$; $P < 0.001$). There is more windthrow in plots with dominant pines having a wide range of heights. For this study, the standard deviation of the dominant height was deduced from the inventory of C130 and from the non-linear relation between height and C130. It is therefore worth noting that the initial variables, “dominant circumference” and its “standard deviation”, were not correlated with the windthrow intensity, where $r = 0.138$ ($P = 0.350$) and $r = 0.204$ ($P = 0.163$), respectively. Thus, converting C130 and its standard deviation into height provides information that is more closely related to vulnerability to windthrow. The variable ETH_0 is significantly and inversely correlated to stand density ($r = -0.725$; $P < 0.001$) and high values are therefore associated with sparse stands. This factor partly explains why there is more windthrow in areas of low density (*figure 11D*). Moreover, the second well-correlated variable was the variability of relative crown length of the dominant trees ($r = 0.566$; $P < 0.001$). The intensity of windthrow is higher in the stands where there is a wide range of crown lengths within the dominant trees. Both variables are an indication of the influence of the heterogeneity of the stand on the risk of windthrow.

The proportion of **leaning** pines was negatively correlated with the dominant crown length ($r = -0.533$; $P < 0.001$). The proportion of leaning trees increases if the length occupied by the crown on the trunk decreases. This result is the consequence of the fact that the pines with short crowns are mainly in high density stands where they have less chance of being uprooted and are therefore more likely to lean after the storm (*figures 11C* and *D*).

For **breakage**, no significant correlation was found and the dendrometric variables did not suffice because this type of damage is no doubt due to the mechanical properties of the wood in the stem instead. Moreover, breakage frequency was negligible in many of the plots.

3.4. The tree scale: differences between undamaged pines and damaged pines

In addition to the previous results which concerned wind-firmness at the stand scale, we also studied the dendrometric differences between undamaged pines and pines damaged by the storm. This comparison required the use of dendrometric variables that are common to both categories: circumference, total height, height of first living branch, absolute and relative crown lengths.

In the 20-year-old stand, there was no significant difference in circumference between the categories of damage in the 4×4 spacing. Conversely, the 2×2 spacing showed that the windthrown pines were significantly bigger than the other categories of trees. The mean circumference was 55.5 cm for the undamaged natural pines and 73.2 cm for the windthrown trees. For the improved pines, the values were 60.1 cm and 74.0 cm, respectively.

In the 51-year-old stand, no significant differences in circumference were observed between the different pine categories within a treatment since inter-tree variability in circumference was large. Hence, we used the mean circumference for each plot to compare pine categories. The graphs in *figure 13* compare the measurements of the mean undamaged pines and windthrown pines for each plot. The slope differences in the linear adjustments of the “undamaged” and “windthrow” scatter diagrams were tested by analysis of covariance.

In *figure 13A*, the slopes of the two scatter diagrams are significantly different ($P = 0.002$). The mean circumference of windthrow (120.0 cm) is significantly 3.6 cm smaller than the mean for undamaged pines (123.6 cm) at density under 500 stems ha^{-1} ($P = 0.004$). Beyond 500 stems ha^{-1}, this difference is no longer apparent. *Figure 13B* shows that the mean height of the windthrown trees is significantly 40 cm shorter than the mean height of the undamaged trees ($P < 0.001$, equal slopes). The first living branch of windthrow is significantly 57 cm higher than for undamaged trees ($P = 0.049$, equal slopes). The space between the two heights represents the length occupied by the crown on the trunk. *Figure 13B* also illustrates the increased height of the living branch as the density increases, whatever the category, whereas the total height varies little. However, the heights were not measured in exactly the same way for the windthrow and the undamaged pines. The former were measured on the ground using a decametre and the latter were measured upright using an ultrasound hypsometer. However, if the relative crown length on the trunk is considered (*figure 13C*), this bias is eliminated. The relative crown length was significantly shorter in the windthrown pines than in the undamaged pines ($P < 0.001$, equal slopes), i.e., the crowns of windthrown trees were 10% shorter than those of undamaged trees.

Lastly, the *H*/*D* ratio is often used to describe forest stand stability. Here, this ratio is used at the tree scale in order to illustrate the combination of the results found with C_g, on the one hand (*figure 13A*), and with the mean height, on the other hand (*figure 13B*). The slopes of the two scatter diagrams were significantly different (*figure 13D*; $P < 0.001$). For densities under 350 stems ha^{-1}, the *H*/*D* ratio of the mean windthrown tree was significantly greater than that of the mean undamaged pine ($P = 0.03$). But at densities above 350 stems ha^{-1}, the difference was reversed and also significant ($P = 0.04$).

To summarise, the trees most resistant to uprooting in plots within this 51-year-old stand had the following features:

- for low densities of about 200 stems ha^{-1}: the tallest trees with the largest C130, those with a long crown in relation to their height, and the least tapered trunks;
- for high densities of about 500-600 stems ha^{-1}: once again, the tallest trees with a long crown but smaller C130 and more tapered.

This typology gives an indication of the “individual” and “stand” effects that more or less predominate, depending on stand density.

4. DISCUSSION AND CONCLUSION

The storm caused moderate damage spread out over the study area (*figures 1* and *10*). This level of damage thereby makes it possible to compare the effects of different factors on wind-firmness. Most of the damage at the experimental sites was windthrown or leaning trees and breakage only occurred occasionally. As previous studies [3, 9, 31, 37, 41] have pointed out, windthrow occurs when the overturning moment caused by the wind exceeds various resistive forces in the root anchorage. The overturning force has two components: (i) the lateral force applied to the crown by the wind and (ii) the weight of the tree as it is bent by the wind. There are also two main resistive forces: (i) the damping of swaying of the aerial parts due to contact between crowns and (ii) the root anchorage due to the weight of the soil-root plate, the resistance to shearing of the soil, the tensile strength of roots on the windward side of the plate and the resistance to bending of the roots and soil in the hinge region on the lee side of the tree.

It is therefore possible for us to discuss our results for Maritime pine stands at the stand scale and at the tree scale, within this general framework.

4.1. Vulnerability to wind at the stand scale

4.1.1. Stand density and the damping stand effect

Thinning operations are a major element of silviculture and an important factor with respect to wind as they temporarily reduce stand stability [1, 11, 30, 51, 57]. Our experimental installations were unable to provide information on the effect of time since the last thinning operations because the 20-year-old stand had not yet been thinned and the 51-year-old stand had been thinned 16 years before the storm in all the plots at the same date (*figure 3*). However, these trials made it possible for us to study a variety of consequences of different degrees of thinning on tree density per hectare.

For the two trials, the denser stands resisted windthrow the most effectively and bending the least effectively (*figure 11*). Previous studies on cultivated stands indicate either an increased risk of damage as the density increases, e.g. in *Pinus*

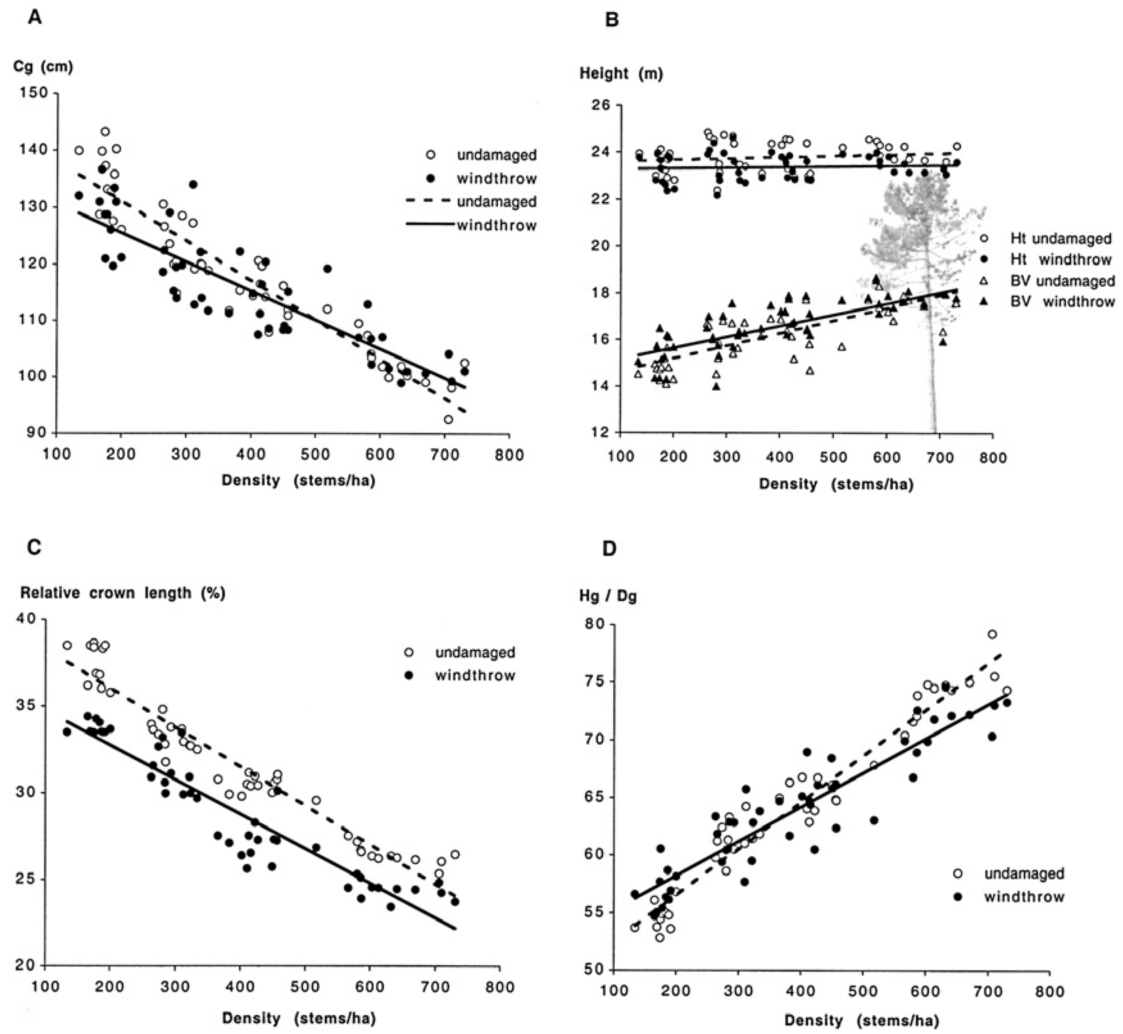

Figure 13. (A) Circumference of mean undamaged pine and windthrown pine per plot as a function of plot density in the 51-year-old trial. The straight lines indicate the linear trend of each scatter diagram, with the dotted lines corresponding to the undamaged pines. (B) Total height (H_t) and height of the lowest living branch (BV) for mean undamaged pine and windthrown pine per plot as a function of plot density. (C) Relative crown length of mean undamaged pine and windthrown pine per plot as a function of plot density. (D) Height/diameter ratio of mean undamaged pine and windthrown pine per plot as a function of plot density.

radiata [11], *Pinus sylvestris* [56] and *Picea abies* [1], attributed to the increase of *H*/*D* ratio, or a reduced risk as in *Picea sitchensis* on a peaty gley soil [9]. However, Gardiner et al. [21] argue that theses studies did not consider that the wind loading on trees at wider spacing is higher and leads the trees to overturn rather than to break. Maritime pine soil-root plates at our study sites clearly have a "pancake" type shape as root growth is restricted to a depth of about 60 cm by the hardened iron pan horizon or by the presence of the water table [28, 55]. These constraints mean that the root system cannot be very deep and that it develops due to a large number of short secondary taproots. As the depth cannot increase, the surface of the soil-root plate has to be considered. The surface area of the soil-root plate decreases ten times less rapidly than that of the crown according to stand density (*figure 5*). Therefore, in such shallow soils, the ratio between the two is more unbalanced at low densities. The above-mentioned particularities thus favour damage from windthrow. Furthermore, the comparison between the "potential crown area" and the crown surface area showed that stands with a density greater than 400/ha have closed canopies (*figure 5*). Finally, the greater resistance of dense plots can be explained by a **three-fold** stand effect. Firstly, the wind loading would be lower in the dense stands because of the increased difficulty of air circulation [21]. Secondly, the contact between crowns would make it possible to spread the kinetic energy transmitted to the tree by the wind more evenly in the canopy [31, 51, 57], and the energy transmitted to the trunk and roots would be reduced and therefore easier to withstand. As Milne aptly demonstrated [31], the damping of swaying is mainly due to three components in a

5/4/1 ratio: the interference of branches with those of neighbouring trees, the aerodynamic drag on foliage and stem stiffness. The most widely spaced trees are the least dependent on their neighbours for resistance to moderate wind but are vulnerable to extreme winds, and the vulnerability of thinned stands declines as soon as the crowns recover [21]. Therefore, the damping in the crowns is a very important factor to be taken into account. Thirdly, our field observations showed that nearby trees have interlaced roots. Therefore, resistance of anchorage is higher than for isolated trees.

At equal densities of close to 600 stems ha^{-1}, the 51-year-old pines suffered far less from the storm than the 20-year-old ones: the total level of damage was 20% for the former as opposed to 50% for the latter. Despite the lack of meteorological data, the hypothesis that the gusts of wind were similar at the two sites is likely because the sites were only 4 km apart in a totally flat field and the storm lasted seven hours. Under this hypothesis, the results contradict the positive relation generally observed between level of damage and stand height, i.e. age, which can be explained by an increasing wind speed as height increases [42]. As was previously observed for the density effect, the crown size in the two stands could also explain this difference. In the 20-year-old pines at a density of 600 stems ha^{-1}, the crowns had little contact with each other. Conversely, the 51-year-old pines were within a closed canopy where the crowns were in close contact. This structural difference in the canopy could possibly have resulted in decreased wind loading and increased damping effect.

Within the sparse 51-year-old stands, damage was greater on the whole and highly variable between plots (*figure 11*). When the density decreases, the stand effect in canopies disappears and wind-firmness depends more on the features of the individual elements. On the basis of these results, forest management of Maritime pine on this type of soil should aim at increasing the density to provide better canopy closure and improved windthrow resistance.

4.1.2. Breeding effect on wind-firmness

In the 20-year-old stands, genetic improvement only increased the proportion of damage at very high densities that are improbable in production forests (*figure 11A* and *B*). This can be explained by two complementary hypotheses. First of all, at high densities, improved pines are taller [12] and probably have longer crowns than natural pines. This assumption is supported by results for the dense 51-year-old stands if we consider that breeding effects are similar to those of fertilisation in relation to tree size. The dominant fertilised trees had crowns that were about 0.6 m longer than those of dominant control trees. Therefore, trees that grow rapidly due to either fertilisation or breeding may have larger crown biomass and, therefore, higher wind loading. Secondly, breeding for stem size may cause a decrease of the root/stem biomass ratio and result in decreased stability [34]. Nevertheless, the improved population studied here was selected using both height and stem straightness as selection criteria. Breeding for stem straightness may have lessened the decrease of root/shoot ratio, especially in the 4 × 4 m stands where the trees are more vigorous but as stable as the natural trees.

4.1.3. Phosphate fertilisation effect on windthrow resistance

The fertilised plots showed less windthrow than control plots at low densities and no significant difference at high densities (*figure 11D*). The effect of phosphate fertilisation on growth is still visible 26 years later although it was only applied once at 25 years of age. The gain in terms of circumference and, above all, in terms of height is maintained over time but its relative importance decreases [23, 55]. The horizontal extension of the crowns has been found to be significantly 15% greater in fertilised plots although only three representative pines per plot were measured (*figure 5*, *table III*). Therefore, the lower proportion of windthrow in the sparse fertilised stands could be explained by the effects of the three main components of damping [31]. Firstly, the greater closure of the canopy would increase the interference of branches. Secondly, the aerodynamic drag on foliage would increase as the crown became larger. Finally, the damping in the stem would increase since the diameter is 7–9% greater on the average. Therefore, the sparse fertilised stands benefited from a better damping effect than the control stands.

In an attempt to improve management, our results indicate that phosphate fertilisation applied at 25 years of age decreases the windthrow proportion in the range of densities found in commercial stands, i.e., 200–350 trees ha^{-1} (*figure 11D*, C_g around 1.30 m). However, we recall that the fertilisation is applied at the plantation establishment in commercial practice in the Landes region.

4.1.4. Why are there three different types of damage?

Uprooting and trunk breakage phenomena were found within the same stands, with uprooting as the dominant type of damage. Proportions of windthrow, leaning and breakage were correlated with different variables to varying degrees. During a storm, the dendrometric features [52] and health status of stands and the abiotic variables (wind, soil and water) are combined to determine the proportion of each type of damage.

In this study, the level of **breakage** has been positively correlated with the mean circumference of the plot at 20 years of age and not significantly correlated with any variable in the 51-year-old plots. This is no doubt a sign that there are not enough efficient variables, particularly with respect to the physical properties of wood. Previous studies on breakage phenomena particularly focus on these properties [4, 37, 40] and factors that decrease stem strength such as knots [22] or decay [47]. The insect *Dioryctria sylvestrella* is no doubt responsible for some of the trunk breakage observed, but the features of these attacks only explain a minority of breakage. In fact, *D. sylvestrella* mostly attacks pine trees under 20 years of age, i.e. below 15 m from the soil, and this occurs horizontally at the whorl level or, more rarely, between whorls [27]. The breaks measured in the 51-year-old stand were distributed quite regularly between 0.5 and 23 m, and the oblique break was often spread over 0.5 to 2 m of the trunk.

The variability in dominant height makes it possible to understand variability in the level of **windthrow** in the 51-year-old stands. The most affected plots are more heterogeneous than the least affected plots, in agreement with the results of Smith et al. [49]. One could hypothesise that the increase in canopy roughness could cause more turbulence in the wind flow and subject the trees to more violent gusts [11]. Spatial distribution of the pines within the sparse plots could also explain the variability of damage. Heterogeneity involves many different situations with respect to neighbouring trees and modifies their wind-firmness [21].

The level of **leaning pines** has been mainly correlated with crown length in the dominant storey. When it increases, the level of leaning pines decreases. This relation may be the translation of the interaction between stand effect and tree effect on wind-firmness. In dense plots, the crowns are in close contact and the stand effect prevails because each tree damps out vibrations due to wind as it is pushed against its neighbours. As a consequence, many pines lean because they cannot be uprooted. At lower densities, the stand effect decreases and more trees can be uprooted since their neighbours are too far away to provide any support. These assumptions imply that the relationship between the percentage of leaning pines and crown length is only a correlation. The crown length would be a better indicator of the local competition than the density itself but it would not be a true wind resistance factor.

4.1.5. Further studies

The relations presented in this study were aimed at explaining the level of damage per plot as a function of the mean variables per plot. The variables based on soil-root plate proved not to be effective. A likely reason would be that it was only possible to measure the features of the soil-root plates for the windthrown trees and the possibility of bias was high. In fact, this bias would tend to underestimate differences between plots since the measurements only concerned windthrow, i.e. pines exhibiting suitable features for uprooting. In plots with high levels of windthrow, a large number of plates were measured and the mean is probably quite accurately representative of the plot. In the plots with low levels of windthrow, the few plates measured resembled those of the previous plots and it was not possible to measure a large number of non-uprooted plates. Therefore, the mean is less representative of the plots, differs little from the mean for high levels of damage and, finally, the correlation with damage level is low. It would therefore be appropriate to be able to characterise the root plates of the undamaged pines in order to check this hypothesis and demonstrate the relative importance of root and aerial systems [38, 50]. Studies based on modelling the architecture of undamaged pines [14] and windthrow were undertaken with this in mind [5, 18].

The relations showed that the level of damage was better explained by variability in dendrometric features within a stand rather than by the features themselves. In such monospecific and even-aged stands, variability in structure and architecture therefore seem to be essential to understanding wind behaviour and other studies have also been undertaken to understand and model how they evolve [2, 6, 8, 14]. In the stand studied, other variables were more pertinent than the stem taper factor *H/D*, despite the fact that it is often considered to be an essential indicator of stand stability [1, 3, 11, 35, 57]. It would therefore appear that this ratio is not very indicative for Maritime pine, which usually has a stem taper value below the threshold of 80, often recommended to obtain wind-resistant stands [44].

Lastly, the correlations for the 51-year-old stands showed that stand stability appears to be based on dominant pines rather than on mean pines. This observation has also been made in several studies conducted previously, showing a considerable increase in forest vulnerability when the dominant individuals are eliminated [11, 57].

4.2. Vulnerability at the individual scale

The results enabled us to see which pines in a given stand were the most vulnerable to wind loading. When comparing circumferences, no clear difference appeared between the different types of damage within each treatment at 20 years of age, with the exception of very dense stands where the uprooted pines appear to be bigger. At 51 years of age, and at a density of below 500 stems ha^{-1}, the pines with a large circumference (*figure 13A*) and the least tapered trunk (*figure 13D*) were more resistant to windthrow. This is consistent with the results found at the stand level, as the fertilised stands at low density, i.e., with bigger pines, showed less windthrow than the control stands (*figure 11D*). Under 500 stems ha^{-1}, undamaged trees were 3.6 cm larger in circumference than windthrown trees. If the trunk is considered as a homogeneous circular beam, its stiffness is related to the fourth power of the diameter [33]. Therefore, this 3% increase in C130 implies an increase in stem strength of 12.5%. Consequently, stems of undamaged trees are able to better damp the swaying due to wind loading [31].

At the densities found in production forests in the Landes region, windthrown trees have shorter crowns than the undamaged pines (*figures 13B* and *C*), in agreement with the results of Dunham and Cameron for *Picea sitchensis* [17]. A model has already been established for a 26-year-old *Pinus pinaster* stand close to our study sites [39]. This model estimates the crown length from diameter at breast height with the allometric relation. On the basis of this model, we logically found that the windthrown trees have a shorter crown length because they have a smaller diameter. The differences between the crown length of undamaged and windthrown pines that we have measured are actually greater than what was expected with the model, i.e., the crowns were 10% shorter versus 2% as predicted by the model. This is probably due to the selection by the storm of pines with a short crown for a given diameter whereas the model has been built with a sample with no bias with regard to the crown length.

Finally, compared to windthrown pines, the most wind resistant pines in a stand were bigger and taller, i.e., the least tapered, and had a longer crown at normal densities. These features make it possible for them to benefit from better damping of the swaying due to gusts since the crown is larger and the stem more rigid.

Our study focused on two field experiments, which are part of a group of studies that have been undertaken or extended by all forestry research bodies in France following the exceptional storms of December 1999. It made it possible to unveil clues that will help in understanding wind-firmness in Maritime pine, a subject that has been dealt with little in this species of considerable economic importance. This knowledge can only be achieved if abiotic features of forests in the Landes region and the silvicultural practices used there are taken into consideration. These features include soil conditions, stand density, thinning regime, establishment method and improvement level. A comparison between undamaged pines and damaged pines as well as the effect of density on stand wind-firmness has shown that it is necessary to take several scales into consideration, from the intra-tree level (architecture and biomechanics), to the stand level (structure and silviculture), as well as to the level of all the stands in the landscape.

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