

Assessment of Effects of Thinning on Wind Damage in *Pinus thunbergii* Plantations

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Abstract A method for estimating risk ratios of wind damage for *Pinus thunbergii* trees and stands was developed based on stem bending theory and coefficients characterizing wind profiles (attenuation coefficients w_{tr} , w_{st} for single tree and stand respectively), distribution of branches (constant a_c) and optical stratification porosity (OSP) (extinction coefficient e_c). For individual trees, if a_{cs} equals w_{tr} in value, the parameter $H/D_{1.3}^3$ (H : tree height, $D_{1.3}$: diameter at breast height) can be used to compare and evaluate the risk-ratio of wind damage. The same method can be applied to stands using the coefficients of w_{st} , e_c and $H/D_{1.3}^3$. In order to test the effectiveness of the method, wind damage in a *P. thunbergii* plantation, which was thinned at four levels, was investigated for four successive growing seasons. Meanwhile, the wind profiles outside and inside the plantation, tree and stand features, and the distributions of OSP were observed. According to these data, risk-ratios of wind damage for both individual trees and stands were estimated using the developed method. The results showed that risk-ratios of wind damage, which were calculated from the mean height and diameter only, and from the combination of wind and stand structure profiles, both accurately predicted wind damage in the plantation. Relationships between different thinning ratios and incidence of wind damage showed that stand stability decreased soon after the thinning, but thinning strategies could improve the stability by long-term effects on growth and development of trees against extreme wind. Only canopy damage was recorded during the experimental period, no stem damage was found even though the maximum 10-minute wind speed outside the plantation attained 30.2ms^{-1} . The results indicate that thinning is the most effective silvicultural strategy available for managing coastal plantation despite the increased probability of wind damage soon after thinning.

Keywords: Pine (*Pinus thunbergii*) forest, Risk-ratio, Wind damage, Thinning

1 Introduction

The influence of wind on forest management and planning can be considered at two main stages in the life of the forest: during and after regeneration (Godwin 1968). Obviously, the influence of wind on the latter, i.e., established stands, has been paid great emphasis, resulting in many published studies (Hutte 1968, Stumbles 1968, Petty et al 1981, Cremer et al 1982, Petty et al 1985, Galinski 1989, Peltola et al 1993, Quine 1995, Gardiner et al 1997, Peltola et al 1999, Moore et al 2000). Almost all of the studies are concerned with timber-production forests, forest managers, however, need to understand effects of wind in forests used for non-timber purposes. Coastal forests, for example, alter the wind thereby providing protection as well as many other benefits such as recreation, nature conservation, timber, fungi, and berries. Therefore, it is desirable and necessary to make coastal forests resistant to severe damages, especially those resulting from strong wind. However, research in this regard has been poorly developed because it has been thought that there is no countermeasure against meteorological extremes that are beyond human control (Matsuzaki 1994). Thinning is one of the few countermeasures against wind damage that can be considered in the management of forests, however, thinning entails risk of wind damage in the short term, particularly, it could have an important and unanticipated impact on the occurrence of wind damage where the climate is windy and sites are poor (Quine 1995, Deans et al 1999, Gardiner et al 2000). The outcomes of thinning in coastal forests are difficult to determine

because the forests suffer from exposure to relentless winds blowing off the sea (Perry 1994, Zhu et al 2001). Although thinning may result in high probability of wind damage, it is necessary to have narrow initial spacing for the survival and growth of the trees in the ruthless coastal area. Therefore, it is important to understand the relationships between thinning and wind damage in detail, and recognize how to estimate the risk of wind damage for the coastal forest stand with various thinning intensities, and what damage will be caused by extreme winds.

Recently, we completed an experiment of the influence of thinning on the incidence of wind damage in a coastal pine (*Pinus thunbergii* Parl.) plantation. The objective of the study is to identify 1) what factors influence the stability of individual trees and stands, 2) how wind damage is related to thinning, 3) how degrees of risk may be quantified after thinning, and 4) how thinning strategy should be designed to reduce risks of wind damage.

2 Estimation of risk of wind damage

Foresters need a practical measure to assess the risk of wind damage for a particular tree or stand. Blackburn et al (1988b) and Galinski (1989) suggest a practical method for evaluating the risk of wind damage from the combination of stem bending theory and wind regime. The fundamentals of this method are accepted in this paper also, but some details are developed for estimating the risk of wind damage for a single tree and a stand of *P. thunbergii*.

2.1 Risk-ratio for individual tree

The diagnosis of wind risk for individual trees requires evaluation of how well trees are acclimated to wind load (Mitchell 2000). Firstly, it is assumed that a single tree of *P. thunbergii* can be modeled as an elastic beam with constant modulus of elasticity. Wind acting on the tree crown creates a drag force, which when acting along the stem produces increasing turning moments towards the base of the tree (Galinski 1989). These moments are resisted by the strength of stem and the root-soil system, and the drag force that causes the tree to be bent results from wind action (Galinski 1989, Mitchell 2000). If it is assumed that the main cause of the drag force is the presence of needled tree branches which can be approximately characterized by their length, then the momentum exchange between moving air (wind) and the tree branches causes the drag force which for a given tree is nearly proportional to the wind speed (Peltola 1996a, b). Therefore, the drag force in a single whorl of branches in a single tree can be represented by Eq. (1) (Galinski 1989).

$$F_i = k L_i V_{sz} \quad (1)$$

where k , constant, F_i , the drag force (N), L_i , the total length of needled branches in i th whorl from the base, V_{sz} is wind speed within a single crown corresponding to the height of the i th whorl (ms^{-1}).

The length of needled branches is summed over the whorl because the influence of the wind direction is not considered. Galinski (1989) suggests the principle of Eq. (1) for conifer trees is that the whorl is the smallest reasonable unit for which the drag force can be calculated without considering the behavior of each branch under wind action. The leeward branches are bent into a parallel position to the wind speed vector, and the windward branches are strongly deflected from the position by wind. Thus, it is reasonable to assume that the whole whorl resistance results from wind speed and the sum of needled branches in the whorl.

The bending moment in basal cross-section (M_i) resulting from action of the drag force F_i :

$$M_i = H_i F_i = k H_i L_i V_{sz} \quad (2)$$

The total bending moment (M_{ts}) equals the sum over all whorls along the whole tree height.

$$M_{ts} = \sum H_i F_i = k \sum H_i L_i V_{sz} \quad (3)$$

Wind speed within a single tree crown of *P. thunbergii* obeys the exponential form.

$$V_{sz} = V_{out} \exp[-w_{tr}(1-H_i/H)] \quad (4)$$

where V_{out} , wind speed (ms^{-1}) outside the canopy at a certain height, H_i , the height of interest within the crown (m), H , maximum height of the tree crown (m), and w_{tr} , attenuation coefficient, which determines the form of wind profile within the single tree crown (Zhu et al 2000).

The parameter of L_i is unique for each tree species, for *P. thunbergii*, the distribution of L_i increases exponentially with decreasing height (Zhu et al 2000), i.e.,

$$L_i = \exp [a_{cs}(1-H_i/H)] \quad (5)$$

where a_{cs} , a constant coefficient.

Replacing V_{sz} and L_i in Eq. (3) with Eqs. (4) and (5) results in:

$$M_{ts} = k V_{out} \sum H_i \exp[(a_{cs} - w_{tr})(1 - H_i/H)] \quad (6)$$

According to the proposition by Galinski (1989), if every transverse cross-section of the stem is circular, the strain in its outer wood ($S(t)$) is given by Eq. (7) (Galinski 1989, Blackburn et al 1988a).

$$S(t) = 4 M_{ts} / D_{1.3}^3 P_i \quad (7)$$

where P_i , Pythagoras constant, 3.1416.

Integrating Eqs. (6) and (7) results in:

$$S(t) = \{4k V_{out} \sum H_i \exp[(a_{cs} - w_{tr})(1 - H_i/H)]\} / D_{1.3}^3 P_i \quad (8)$$

For a given wind speed V_{out} , the difference in tree architecture causes a difference in risk of wind damage for particular trees. Thus, it is possible to define the risk of wind damage as the individual tree architecture contribution to the strain from Eq. (8).

As $4k V_{out} P_i$ is constant for a given wind speed outside the tree crown, the risk-ratio $R(tr)$ suggested by Galinski (1989) can be defined as,

$$R(tr) = \{ \sum H_i \exp[(a_{cs} - w_{tr})(1 - H_i/H)] \} / D_{1.3}^3 \quad (9)$$

Galinski (1989) suggests that the variation of individual ratio, $R(tr)$, is relatively low for most trees. This means that a unique value of $R(tr)$ exists for each tree and it is independent of the site. Therefore, Eq. (9) can be used to evaluate and compare the risk of wind damage for individual trees. For tree species of *P. thunbergii*, we found that if V_{out} in the model of wind speed within the single tree crown (Eq. 4) is replaced by V_H (wind speed at tree top), then the value of coefficient w_{tr} in Eq. (4) nearly equals constant a_{cs} in Eq. (5). In order to simplify the expression of Eq. (9), we assume that $w_{tr} = a_{cs}$ in value, which means that Eq. (9) becomes:

$$R(tr) = H / D_{1.3}^3 \quad (10)$$

The simple expression of risk estimation of $R(tr)$ (Eq. 10) allows a comparison of growth strategies among individual trees. The higher the $R(tr)$ is, the higher the probability that the considered tree will be destroyed during a strong wind.

2.2 Risk-ratio for stand

Applying the same approach used for a single tree, if the dynamic wind load is the presence of area of the canopy and stem, the momentum exchange between moving air (wind) and the tree elements in the stand, which causes the drag force, can be estimated from the wind speed profiles within the canopy (Peltola et al 1993), i.e.,

$$F_d(z) = k F_s(z) = k(0.5 C_d D_{air} A_z V_{tz}^2) \quad (11)$$

where $F_d(z)$, the drag force or dynamic wind load (N), $F_s(z)$, the static wind load (N), c_d , the drag coefficient (dimensionless), here assumed to be constant, d_{air} , the air density (kgm^{-3}), A_z , the projected area of the crown and stem (m^2) at height z , V_{tz} , wind speed (ms^{-1}) at height z within the canopy. As k , c_d and d_{air} are constant, let, $k(0.5 C_d D_{air}) = c_{st}$, then Eq. (11) becomes,

$$F_d(z) = c_{st} A_z V_{tz}^2 \quad (12)$$

A_z can be approximated as,

$$A_z = B_z dz \quad (13)$$

where B_z represents the leaf area index (dimensionless), can be represented by the distribution of optical stratification porosity (OSP) (Zhu et al 2003).

$$B_z = d\{\exp[-e_c(1-z/H)]\} / dz = (e_c/H) \exp[-e_c(1-z/H)] \quad (14)$$

where e_c , extinction coefficient of distribution of OSP (Zhu et al 2003).

Wind speed (V_{tz}) within the canopy obeys the exponential form given in Eq. (15) (Bergen 1971, Landsberg et al 1971, Amiro 1990, Wenzal et al 1997, Zhu et al 2001).

$$V_{tz} = V_H \exp[-w_{st}(1-z/H)] \quad (15)$$

where z , the interest height within the canopy (m), H , height of canopy top (m), V_H , wind speed (ms^{-1}) at height H , w_{st} , the attenuation coefficient.

Replacing A_z , V_{tz}^2 with Eqs. (14) and (15), Eq. (12) becomes:

$$F_d(z) = c_{st} (e_c/H) \exp[-e_c(1-z/H)] \{V_H \exp[-w_{st}(1-z/H)]\}^2 \quad (16)$$

The total bending moment for a stand, M_{tt} equals:

$$M_{tt} = \int_0^H z F_d(z) dz = (c_{st} V_H^2 e_c / H) \int_{H_0}^H z \exp[-(e_c + 2w_{st})(1-z/H)] dz \quad (17)$$

where H_0 , the bole height (m).

For a stand, the strain ($S(st)$) is given by the same form as that of the single tree (Eq.7).

$$S(st) = (c_{st} V_H^2 e_c / H) \int_{H_0}^H z \exp[-(e_c + 2w_{st})(1-z/H)] dz / D_{1.3}^3 P_i \quad (18)$$

As $c_{st} V_H^2 e_c / H P_i$ is constant for a given wind speed at the canopy top, the risk-ratio for a stand ($R(st)$) can also be expressed as,

$$R(st) = \int_{H_0}^H z \exp[-(e_c + 2w_{st})(1-z/H)] dz / D_{1.3}^3 \quad (19)$$

$D_{1.3}$ in Eq. (19) is the mean diameter of the stand calculated from various sample patterns. $R(st)$ can be used to measure and compare the risk of the growth strategy and the thinning measures adopted by the stand. The higher the $R(st)$ is, the higher the probability that the considered stand will be destroyed by the strong wind.

3 Materials and methods

3.1 Site description

The study site was located at the middle of the shoreline along the Japan Sea, Niigata Prefecture Japan, at N37°52'41.3", E138°56'16.8". Mean annual temperature is 13.2 degrees centigrade. The mean annual precipitation is 1778.3 mm yr⁻¹. The days of daily mean wind speed greater than 10 ms⁻¹ are 53 days yr⁻¹, and greater than 15 ms⁻¹ are 4 days yr⁻¹. The maximum wind speed is 30.7 ms⁻¹. (NAO, 1997). The soil is a deep sand. Plantations of Japanese black pine (*P. thunbergii*) are the most important forest type along Japan Sea.

3.2 Studied forest and thinning treatment

The *P. thunbergii* forest was located on a slope of about 4°, and it ranges in width between 100-200 m. The micro-topography in the experimental area is almost the same in a wide range. The trees were planted about 40 years ago at an initial density of 4500 stems ha⁻¹, no understorey. An average of 73% were still alive by the beginning of this study.

The stand was thinned in four treatments with random sampling techniques in Dec. of 1997. The thinning treatments were set as 0.0% (control), 20%, 30% and 50% thinned, which are referred to T1, T2, T3, and T4, respectively. The effective area of each treatment reached 40×50m². Caliper measurements of diameter at breast height ($D_{1.3}$), tree height (H) and clear bole height (H_0) were made on all trees whose $D_{1.3}$ were more than 4 cm before and after the thinning. The mean stand characteristics before and after thinning are shown in Tab. 1.

Table 1. Mean characteristics of stand in the pine plantation with four thinning intensities

Investigated date	Dec. 1997				Feb. 1998				Jan. 2000				Nov. 2001			
Treatment No.	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
$D_{1.3}$ (cm)	8.7	9.2	9	10.1	8.7	9.4	9.1	10.1	9.3	9.8	9.8	10.8	9.8	10.3	10.4	11.4
(H_0) (m)	3.3	3.9	3.1	4.2	3.3	3.9	3.2	4.3	3.7	4	3.2	4.1	4.1	4.4	3.6	4
(H)(m)	6.2	7.5	5.9	7.3	6.2	7.5	5.9	7.2	7.2	8.5	7	8.2	8.8	9.7	8.3	9.5
Basal area (m ² ha ⁻¹)	23.2	23.4	21.4	26	23.2	18.8	14.5	12.9	26.1	21.3	16.9	15.5	28.8	22.7	19.5	17.8
Density (stem ha ⁻¹)	T1=3600, T2=3217, T3=3167, T4=3000															
T_{rate} (%)	0				20.2				31.6				46.7			

$D_{1.3}$: Diameter at breast height, H_0 : Clear bole height, H: Tree height, T_{rate} : Thinning rate by stem

3.3 Collection of wind data

Wind speed and direction were continuously collected outside the forest after the thinning by a propeller anemometer (Ota 111-T, Kona Ltd., Japan), which was mounted at a height of 2 m above ground nearby the sea, the sampling interval was 10 min. Wind profiles inside the forest were measured using one set of 5-channel hot wire anemometers (Rion Tr-Am-11, Rion Ltd. Japan). The interval was 0.5 min (details in Zhu et al 2001).

3.4 Measurement of OSP

Optical stratification porosity (OSP) is a two-dimensional measure of porosity determined from the forest silhouette in vertical section. The ratio of sky hemisphere not obscured by tree elements (including stems, branches, twigs and leaves) from a given height downward to the ground in each plot was measured (see Zhu et al 2003 for details).

3.5 Inventory of wind damage

Wind damage was investigated in each treatment after gales, which caused wind damage. Four investigations were made in the experimental period.

The first investigation was conducted on Sept 16 of 1998 during typhoon No.5 of 1998 in Japan. Wind measurement was not scheduled inside the forest on this date because of equipment maintenance, only limited wind data were recorded outside the forest because the tower supporting the anemometer was broken by the extreme wind. The gale did considerable damage on the branches, cones and needles of the trees in the experimental forest, however,

no stem breakage or uprooting occurred. Wind damage in the strong gale was investigated in 5 sub-plots (4 m² in each plot) in each treatment soon after the gale. Branches, clusters, cones and needles blown down were collected and weighed in each sub-plot of every treatment.

The second, third and fourth investigations of wind damage were carried out respectively after the strong winds of May 25 of 1999, Feb. 9 of 2000 and Apr. 15 of 2001. Only branches and clusters blown down by the strong winds were collected in each treatment (600 m²) because of less damage produced. Dry weight of the wind damage samples were obtained after 24 hr. drying at 105 degrees centigrade.

3.6 Data analysis

Because of non-normal distribution in the observations of wind damage, the Kruskal- Wallis test (K-W test) was selected to test for differences (Ishimura et al 1994). Based on the W-K test, Bonferroni-type multiple comparison among the different treatments was conducted.

4 Results

4.1 Estimation of risk ratios

The risk ratios of wind damage for individual trees were calculated using Eq. (10) with the data from the tree survey (Tab. 2). Both tree height and diameter at breast height ($D_{1.3}$) were calculated from the mean height (H) and mean $D_{1.3}$ of total stems, of the 200 largest stems per hectare (H_{L200} , D_{L200}) (Cremer et al 1982) and of the stems whose $D_{1.3}$ were greater than the total mean ($H_{>mean}$, $D_{>mean}$) respectively. The ratios of $H/(D_{1.3})^3$ and $H_{>mean}/(D_{>mean})^3$ ranked in the same order after the thinning, i.e., $T1>T2>T3>T4$ (Table 2). However, the ratios of $H_{L200}/(D_{L200})^3$ were in the same order as $H/(D_{1.3})^3$ and $H_{>mean}/(D_{>mean})^3$ until the last growing season of the observed period (Nov. 2001) (Tab. 2).

Table 2. Risk ratios of wind damage in the pine plantation with different thinning intensities based on individual tree calculation

Period	Dec. 1997				Feb. 1998				Jan. 2000				Nov. 2001			
No.	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Total	0.94	0.96	0.81	0.71	0.94	0.90	0.78	0.70	0.90	0.88	0.74	0.65	0.94	0.89	0.74	0.64
L_{200}	0.30	0.27	0.27	0.20	0.30	0.28	0.29	0.24	0.26	0.24	0.27	0.17	0.27	0.26	0.22	0.19
> mean	0.60	0.50	0.54	0.41	0.60	0.51	0.50	0.42	0.60	0.47	0.45	0.33	0.54	0.49	0.41	0.33

Total: total mean of stems, L_{200} : The largest 200 stems ha⁻¹, > mean: Stems whose $D_{1.3}$ greater than mean.

The risk-ratio of wind damage for stand was calculated in each thinned treatment using the last surveyed data (Nov. 2001). Different results were found among the calculations from various mean values of height and diameter. After four growing seasons since thinning, the risk-ratio of wind damage calculated according to total mean values of diameter and height ranked as: $T1>T3>T2>T4$ (Tab. 3). But the ranks of risk ratio calculated from H_{L200} , D_{L200} and from $H_{>mean}$, $D_{>mean}$ showed the same order, i.e., $T1>T2>T3>T4$ (Tab. 3).

4.2 Wind damage (canopy damage)

The first investigation was conducted on Sept. 16 1998, considered as soon after the thinning. The wind speed outside the forest attained more than 30 ms⁻¹ (Fig. 1A), but no stem breakage or uprooting occurred. The length and diameter of fallen branches ranged between 5cm-103cm and 0.3cm- 1.5cm, respectively. The number and length of branches fallen in T1 (control) were much less than in the thinned treatments. Needles blown down were least in T4 (Fig. 2A). The total dry weight of branch, cluster, needle and cone showed that wind damage in T2 was significantly higher ($p<0.05$) than that in other treatments. The weight of canopy damage in the thinned treatments, i.e., T2, T3 and T4 was 239.4%, 164.0% and 114.4% of that in T1 (control), respectively (Tab. 4A). In this extreme wind period, needles constituted the most of the canopy damage for all of the treatments (Tab. 4B).

Canopy damage by the strong wind of May 1999 was similar across treatments because of the relatively lower wind speeds (Fig. 1B, 1B). However, during the subsequent strong winds (Feb. 2000 and Apr. 2001) (Fig. 1C, 1D), wind damage in T1 (control) was more than that in other thinned treatments (Fig. 2C, 2D), and the rank of wind damage corresponded to the

rank of risk-ratios (Tab. 2, Tab. 3).

Table 3. Estimation of risk-ratios of wind damage for the stand of each treatment*

Treatment No.	e_c^{**}	w_{st}^{**}	Total mean	The largest 200 stems ha^{-1}	Stems whose $D_{1.3}$ greater than mean
1	3.02	2.54	0.00467	0.00115	0.02150
2	2.13	1.97	0.00238	0.00057	0.01520
3	1.97	1.76	0.00427	0.00055	0.00752
4	1.89	1.67	0.00169	0.00045	0.00456

*The values of risk-ratio of wind damage was calculated by substituting z in Eq.(9) from bole height to the canopy top at an interval of 1.0 m. The data of diameter and height refer to Tab. 1 (Nov. 2001).

** e_c and w_{st} were obtained in Oct. and Dec. 2000, respectively.

Table 4. Weight (dry) including branch, cluster, needle and cone blown down in each treatment (A) and rates of different tree elements (B)

A					B									
	T1	T2	T3	T4	Br (%)	Clu (%)	Nee (%)	Co (%)	Total (%)					
Cone	24.72	45.92	36.84	28.76	T1	22.5	4.8	34.1	7.3	387	82.7	24.7	5.3	100
Plot1	88.77	174.1	171.9	87.02	T2	524	46.7	45	4	507	45.2	45.9	4.1	100
Plot2	108.8	534.23	186.51	143.26	T3	101	13.2	56.4	7.3	574	74.7	36.8	4.8	100
Plot3	72.53	141	103.56	72.02	T4	208	38.9	26.8	5	272	50.8	28.8	5.4	100
Plot4	87.17	105.28	150.36	113.07										
Plot5	86.55	146.8	119.05	91.93										
Total*	^{b c} 468.57	^a 1121.51	^b 768.22	^{b c} 536.06										
% by T4	100	239.35	163.95	114.4										

*Data in the total line not followed by the same letter are significantly different at level $p < 0.05$ based on the W-K test and Bonferroni-type multiple comparison. Br: branch, Clu: Cluster, Nee: Needle, Co: cone

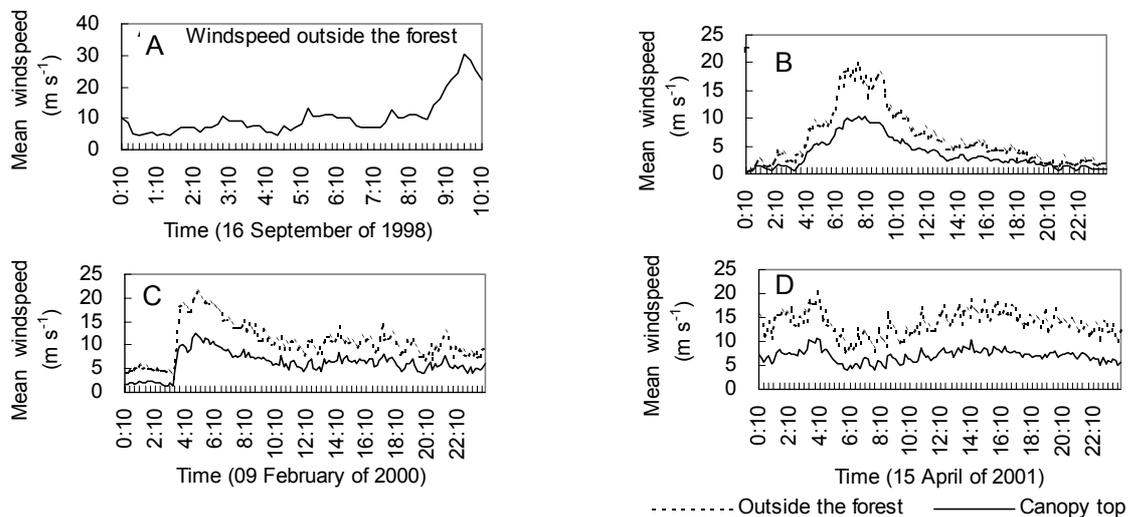


Fig. 1 Daily wind speed (10-min mean) during the extremes, which caused canopy damage. A, on Sept. 16 1998; B, on May 25 1999; C, on Feb. 09 2000; D, on Apr. 15 2001.

5 Discussion

Wind damage is influenced by many factors such as wind speed, precipitation, site and stand conditions etc. Particularly, difference of wind speed is very sensitive to wind damage. For example, the canopy damage observed on Feb. 9 of 2000 at a maximum wind speed of 21.3 ms^{-1} (Fig. 1C, 2C) outside the forest was about 2-3 times greater than that on May 25 of 1999 at a maximum wind speed of 19.7 ms^{-1} (Fig. 2B, 3B). Because of the uncontrollable feature of meteorological factor (wind), here, the discussion focuses on the stand conditions.

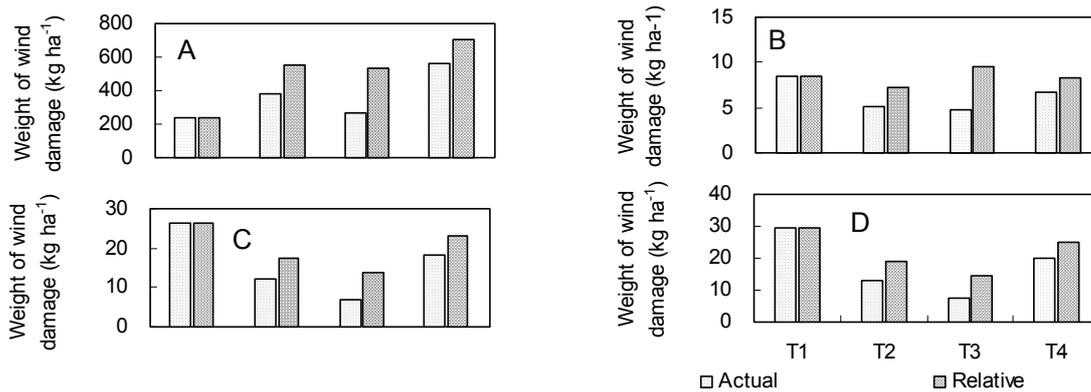


Fig. 2: Canopy damage during the extreme winds. A, on Sept. 16 1998; B, on May 25 1999; C, on Feb. 09 2000; and D, on Apr. 15 2001. Relative value=Actual value/(1-thinning ratio)

Although the risk-ratio of wind damage in unthinned treatment was higher than that in the thinned treatments soon after the thinning (Tab. 2), the canopy damage was least there (Tabs. 2,3, Fig. 2A). These results indicate that vulnerability of wind damage of trees increased immediately following thinning, which is consistent with most of the results obtained in studies of timber- production forests (Rollinson 1989, Valinger et al 1996, Gardiner et al 1997). However, our finding that canopy damage decreased with increasing thinning intensities, was not consistent with previous studies showing greater damage with heavier thinning (Cremer et al 1982). This inconsistency between studies may be due to the thinning pattern in this experiment, i.e., the sheltering effect of the normal forest surrounding the patches. Gardiner et al (1997) also found sheltering effects according to bending moment measurements within patch thinning plots ($60 \times 35 \text{ m}^2$).

The amount of canopy damage on Feb. 9 of 2000 and Apr. 15 of 2001 corresponded well to the rank of risk-ratio calculated for individual trees from $H_{\text{mean}}/D_{\text{mean}}^3$, and the risk-ratios calculated for the stand from $H_{>\text{mean}}/D_{>\text{mean}}^3$ and H_{L200}/D_{L200}^3 (Tabs. 2, 3, Fig. 2). The risk-ratio of wind damage for the stand, which is deduced from the theory of bending moments combined with the coefficients charactering wind profiles and distribution of OSP within the canopy, may be a good estimate of wind damage risk calculated from the largest 200 stems ha^{-1} and the stems whose $D_{1.3}$ greater than the total mean. As Cremer et al (1982) suggest that this is because the smaller trees are far less significant than the dominant trees in determining the stability of the stand, and selective removal of the smaller trees by thinning will at once reduce the ratio of $H/D_{1.3}^3$.

The vulnerability, which increased immediately after thinning, will decline as the recovery of tree crowns, stems and roots respond to the new wind environment. However there is currently little information on how quickly this occurs (Gardiner et al 2000) because many conditions such as tree species, age and state of the stand at the beginning of thinning influence the recovery. Generally, the earlier the thinning takes place in the life of a stand, the more quickly the stand recovers.

6 Conclusions

The method for estimating risk ratios of wind damage for *Pinus thunbergii* trees and stands was established and tested. In this study, the best indices of wind damage risk were calculated from the mean values of the largest 200 stems ha^{-1} and the stems whose $D_{1.3}$ was greater than the total mean. This appears to be useful where it is necessary to compare the risk of wind damage among stands with different silvicultural practices.

The implications of this study for managing the pine plantations can be summarized as: 1) Thinning entails the risk of wind damage in the short term, but the stability of the stand will be improved in the long term, especially for the early thinning. 2) Thinning in a patch-pattern with patches surrounded by unthinned trees can reduce the risk of thinning-induced wind damage. Therefore, a partial or selective, patch thinning is recommended for the management of the coastal pine plantations. 3) About 1500 stems ha^{-1} was suitable for the current pine plantations nearby the coastal area from the view of wind stability.

Acknowledgement

We would like to appreciate Mr. Sakioka K., Mr. Yamazaki H, Mr. Yoshita T., Mr. Hasegawa Y. and Mr. Zhu J.Y. for their help in data collection. This study was supported by a grant KZCX3-SW-418 of Chinese Academy of Sciences and Monbusho of Japan Government.

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