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Effects of thinning on wind damage in *Pinus thunbergii* plantation

–Based on theoretical derivation of risk-ratios for assessing wind damage

ZHU Jiao-jun[1,2], LI Feng-qin[1], Gonda Yutaka[2], Takeshi Matsuzaki[2], Masashi Yamamoto[2]
[1] *Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, 110016, P. R. China*
[2] *Faculty of Agriculture, Niigata University, Niiigata, 950-2181, Japan*

Abstract: Based on paper of "Theoretical derivation of risk-ratios for assessing wind damage in coastal forest", wind damage in the pine coastal forest, which was thinned at four levels in December of 1997, was investigated for four successive growing seasons. Besides wind damage, the wind profiles outside and inside the coastal forest stand and the distributions of optical stratification porosity (OSP) were also observed. Based on these data, risk-ratios of wind damage for both individual trees and stands were estimated according to the methods developed in "Theoretical derivation of risk-ratios for assessing wind damage in a coastal forest". 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, 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. This was due to the immediate effects of thinning on increasing the canopy roughness and wind load, and on decreasing the sheltering effects from surrounding trees. However, 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-min wind speed outside the coastal forest attained 30.2 $m\cdot s^{-1}$. The results obtained in this study indicate that thinning is the most effective silvicultural strategy available for managing coastal forest despite the increased probability of wind damage soon after thinning.

Keywords: Thinning; Wind damage; Pine forest; Risk-ratio
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Introduction

Thinning may result in high probability of wind damage, but thinning can also improve the stability by long-term effects on growth and development of trees against extreme wind (Cremer *et al.* 1982; Matsuzaki 1994). In order to assess risk-ratios of individual tree and stand in a pine coastal forest after thinning with various intensities, four thinning levels were set. Based on the discussions in paper of "Theoretical derivation of risk-ratios for assessing wind damage in a coastal forest", which presented the review on relationships between wind damage and stand density or thinning for the timber-production forests, and developed a method of wind damage-risk estimation for evaluating the effects of thinning on wind damage for individual trees and stands on the basis of published information (Zhu *et al.* 2003). This paper presents the application of the methods of estimating risk-ratios for individual trees and stands according to the investigation of wind damage for four growing seasons after thinning.

Materials and methods

Site description

The study site was located at the middle of the shoreline along the Japan Sea, Aoyama coastal area, Niigata Prefecture Japan, at N 37°52′41.3", E 138°56′ 16.8". Mean annual temperature is 13.2°C, maximum monthly temperature is 26.2°C (August), minimum monthly temperature is 2.1°C (January). The maximum and minimum temperatures are 39.1°C and -13.0°C. The mean annual precipitation and the maximum rain intensity are 1 778.3 $mm\cdot a^{-1}$ and 54 $mm\cdot h^{-1}$ respectively. The daily mean wind speed is greater than 10 $m\cdot s^{-1}$ 53 $days\cdot a^{-1}$, and greater than 15 $m\cdot s^{-1}$ 4 $days\cdot a^{-1}$. The maximum wind speed is 30.7 $m\cdot s^{-1}$. The first frost is November 24, and the last frost is April 8. The sunshine time is 1 687 $hrs\cdot a^{-1}$ (the means are calculated during 1961-1995, the observation station located at N 37°55′, E 139°03′) (National Astronomical Observatory, 1997). The soil is deep sand. Plantations of Japanese black pine (*Pinus thunbergii* Parl.) are the most important coastal forest type along Japan Sea.

Studied forest

The coastal *P. thunbergii* forest used in this study was located on a slope of about 4°, and it ranges in width between 100 m and 200 m. The micro-topography in the experimental area is almost the same in a wide range. The

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Biography: ZHU Jiao-jun (1965-), male, Ph. Doctor, PhD advisor, Professor of Institute of Applied Ecology, the Chinese Academy of Sciences, China Scholar researcher of Faculty of Agriculture, Niigata University, Japan. Email: jiaojunzhu@iae.ac.cn

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trees were planted about 40 years ago at a spacing of 1.5 m×1.5 m to give an initial density of approximately 4 500 stems·hm^{-2} and to discourage the development of an understorey. An average of 73% (68%-80%) were still alive by the beginning of this study.

Thinning treatment

The stand was thinned in four treatments with random sampling techniques in December of 1997. The thinning treatments were set as about 0.0% (unthinned, control), 20%, 30% and 50% thinned, which are referred to treatment 1, treatment 2, treatment 3, and treatment 4, respectively. Each treatment was 20 m×30 m, surrounded by a buffer zone of the same treatment so that the effective area reached 40 m×50 m. 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 diameters ($D_{1.3}$) were more than 4 cm before and after the thinning. The last caliper measurements were conducted in November of 2001. The mean stand characteristics before and after thinning are shown in Table 1.

Table 1. Mean characteristics of stand in a pine coastal forest with four thinning intensities

Treatment No.	DBH* /cm	Clear bole height (H_0) /m	Tree height (H) /m	Density /stem·hm^{-2}	Basal area /m^2·hm^{-2}	H_0/H	Thinning rate by stem /%	Thinning rate by basal area /%
Before thinning (December 1997)								
1	8.7	3.3	6.2	3600	23.15	0.53	0.0	0.0
2	9.2	3.9	7.5	3217	23.36	0.52	20.2	19.8
3	9.0	3.1	5.9	3167	21.42	0.53	31.6	32.5
4	10.1	4.2	7.3	3000	26.00	0.58	46.7	50.2
After thinning (February 1998)								
1	8.7	3.3	6.2	3600	23.15	0.53		
2	9.4	3.9	7.5	2517	18.75	0.52		
3	9.1	3.2	5.9	2100	14.46	0.54		
4	10.1	4.3	7.2	1483	12.94	0.60		
After thinning (January 2000)								
1	9.3	3.7	7.2	3600	26.13	0.51		
2	9.8	4.0	8.5	2517	21.27	0.47		
3	9.8	3.2	7.0	2100	16.91	0.46		
4	10.8	4.1	8.2	1483	15.48	0.50		
After thinning (November 2001)								
1	9.8	4.1	8.8	3600	28.84	0.47		
2	10.3	4.4	9.7	2517	22.66	0.45		
3	10.4	3.6	8.3	2100	19.53	0.43		
4	11.4	4.0	9.5	1483	17.82	0.42		

* DBH: diameter at breast height (1.3 m).

Collection of wind data

Wind speed and direction were continuously collected outside the coastal forest after the thinning. One propeller anemometer (Tokyo Ota No. 111-T, Kona Ltd. Japan) with a data logger (Kona DS-64K, Kona Sapporo, Japan) 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 Ldt. Japan). The interval for wind speed measurement inside stands was 0.5 min (Additional details can be found in Zhu *et al.* 2001a).

Measurement of optical stratification porosity (OSP)

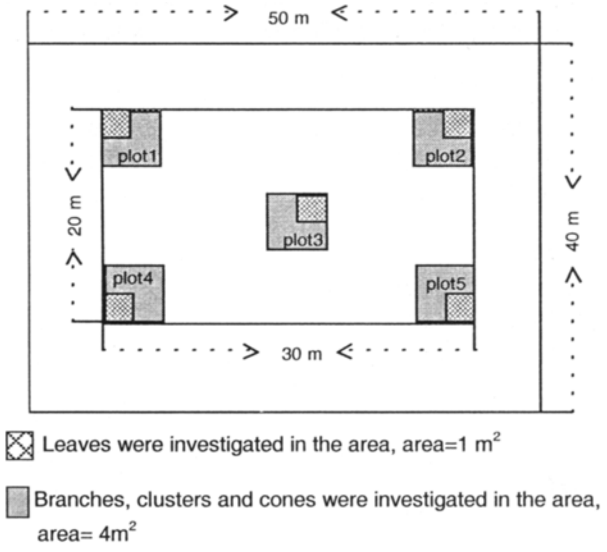
Optical stratification porosity (OSP) is a two-dimensional measure of porosity determined from the forest silhouette in vertical section. We measured the ratio of sky hemisphere not obscured by tree elements (including stems, branches, twigs and leaves) from a given height downward to the ground in each plot (see Zhu *et al.* 2000a and Zhu *et al.* 2003 for details).

Inventory of wind damage

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

The first investigation was conducted on September 16 of 1998 during typhoon No. 5 of 1998 in Japan. Wind measurement was not scheduled inside the coastal forest on this date because of scheduled equipment maintenance, and only limited wind data were recorded outside the coastal 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 forests of Aoyama coast, Niigata Japan. However, no stem breakage or uprooting occurred. Wind damage in the strong gale was investigated in 5 sub-plots in each treatment soon after the gale. Branches, clusters (twigs composing of some needles), cones and needles blown down by the extreme wind were collected and weighed (wet weight) in each plot of every treatment. Figure 1 shows the sample plot layout for measuring wind damage.

The second, third and fourth investigations of wind damage were carried out respectively after the strong winds of May 25 of 1999, February 9 of 2000 and April 15 of 2001. Only branches and clusters blown down by the strong winds were collected in each treatment (600 m^2) (Fig.1) because of less damage produced. Dry weight of the wind damage samples were obtained after 24 h. drying at 105°C.



⊠ Leaves were investigated in the area, area=1 m^2

▨ Branches, clusters and cones were investigated in the area, area= 4m^2

Fig. 1 Sample scheme for measuring wind damage (canopy damage). Branches, clusters and cones (4 m^2 in each plot) and needles (1 m^2 in each plot) were surveyed in 1~5 plots soon after the extreme wind on September 16 of 1998. Branches and clusters were collected in 20 m×30 m soon after the strong winds occurred on May 25 of 1999, February 09 of 2000 and April 15 of 2001, respectively.

Data analysis

Estimation of risk of wind damage (risk ratios) for individual trees was calculated using equation (1) (Zhu *et al.* 2000b, 2003). The risk-ratio of wind damage for stand was calculated in each thinned treatment using equation (2) (Galinski 1989; Zhu *et al.* 2003) with the observations of wind profiles (Zhu *et al.* 2001a) and distribution of optical stratification porosity (Zhu *et al.* 2000a, 2003).

$$R(s) = H / D_{1.3}^{3} \qquad (1)$$

$$R(t) = \int^{H} H_0 \; z\exp[-(2\alpha + v)(1 - z/H)]\mathrm{d}z/D_{1.3}^{3} \qquad (2)$$

where α and v were estimated from the observations of wind profile (Zhu *et al.* 2001a) and distribution of optical stratification porosity (Zhu *et al.* 2000a, 2003).

Multiple comparisons were conducted among the four treatments. Because of non-normal distribution in the observations of wind damage, the Kruskal-Wallis test (K-W test) was selected to test for differences. The K-W test requires the combination of all samples in each group into a larger sample, the sorting of result from the smallest (1) to the largest (*N*) and the assigning of average ranks to any observations in each group again (Ishimura 1994). The statistic produced in K-W test is K_w, which is calculated from the following equation.

$$K_w = [\frac{12}{N(N+1)} \frac{\sum R_j^2}{n_j}] - 3(N+1) \qquad (3)$$

where *j* is the number of groups, n_j is sample size in the *j*th group, *N* is the total number of the sample from all of the groups, R_j is the sum of ranks in the *j*th group.

When sample sizes are small in each group (<5) and the number of groups is less than 4, a tabled value for the K-W test should be compared to the statistic (K_w) to determine the significance level. Otherwise, a Chi-square with *j*-1 (the number of groups-1) degrees of freedom can be used to approximate the significance level for the test. If the calculated K_w exceeds the critical value for K_w (tabled value) at a certain significant level (usually 0.05), it means that there is evidence to reject the null hypothesis in favor of the alternative hypothesis (Ishimura 1994). Based on the W-K test, Bonferroni-type multiple comparison among the different treatments was conducted. When the number of groups is 2, K-W test becomes Mann-Whitney U-test.

Results

Estimation of risk of wind damage

The risk ratios of wind damage for individual trees were calculated using equation (2) combined with the data from the stem survey of individual trees in each treatment (Table 2). In the present analysis, both height and diameter at breast height (DBH) were calculated from the mean height (H) and mean diameter ($D_{1.3}$) of total stems, of the 200 largest stems per hectare (H_{L200}, D_{L200}) (Cremer *et al.* 1982) and of the stems whose DBH 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., treatment 1>treatment 2>treatment>3treatment 4 (Table 2). However, the ratios of $H_{L200}/(D_{L200})^3$ were different from both $H/(D_{1.3})^3$ and $H_{>mean}/(D_{>mean})^3$ after the thinning. 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 (November 2001) (Table 2).

The estimation of risk-ratio of wind damage for stand was calculated in each thinned treatment using the last surveyed data (November, 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: treatment 1 > treatment 3 > treatment 2 >treatment 4 (Table 3). This ranking differed from those calculated by the 200 largest stems per hectare (H_{L200}, D_{L200}) (Cremer *et al.* 1982) and of the stems whose DBH were greater than the total mean ($H_{>mean}$, $D_{>mean}$) (Zhu *et al.* 2000b, 2002), respectively. The ranks of risk-ratio calculated from the 200 largest stems per hectare and from the stems whose DBH were greater than the total mean showed the same order, i.e., treatment 1 > treatment 2 > treatment 3 >treatment 4 (Table 3).

Table 2. Indexes for evaluation of risk ratios of wind damage in the pine plantation of coastal forest with different thinning intensities

Treatment No.	DBH* /cm			Tree height (H) /m			Ratio of H/DBH^{3}		
	Total mean	The largest 200 stems·hm^{-2}	Stems whose DBH greater than the mean	Total mean	The largest 200 stems·hm^{-2}	Stems whose DBH greater than the mean	Total mean	The largest 200 stems·hm^{-2}	Stems whose DBH greater than the mean
Before thinning (December 1997)									
1	8.7	13.4	10.4	6.2	7.3	6.7	0.942	0.303	0.596
2	9.2	15.3	12.0	7.5	9.5	8.6	0.963	0.265	0.498
3	9.0	13.9	10.8	5.9	6.8	6.4	0.809	0.268	0.540
4	10.1	16.6	12.8	7.3	9.1	8.5	0.709	0.199	0.405
After thinning (February 1998)									
1	8.7	13.4	10.4	6.2	7.3	6.7	0.942	0.303	0.596
2	9.4	15.2	11.9	7.5	9.8	8.6	0.903	0.279	0.513
3	9.1	13.5	11	5.9	7.0	6.7	0.783	0.285	0.504
4	10.1	15.3	12.6	7.2	8.6	8.3	0.699	0.241	0.415
After thinning (January 2000)									
1	9.3	15.5	11.3	7.2	9.5	8.6	0.895	0.255	0.596
2	9.9	16.2	12.6	8.5	10.2	9.4	0.876	0.240	0.470
3	9.8	14.1	11.8	7.0	7.6	7.4	0.744	0.271	0.450
4	10.8	17.2	13.7	8.2	8.8	8.5	0.651	0.173	0.331
After thinning (November 2001)									
1	9.8	15.7	12.2	8.8	10.6	9.8	0.935	0.274	0.537
2	10.3	16.3	13.0	9.7	11.7	10.8	0.888	0.257	0.493
3	10.4	16.5	13.2	8.3	10.0	9.3	0.738	0.223	0.407
4	11.4	18.2	14.7	9.5	11.5	10.6	0.641	0.190	0.333

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

	Range for *R(t)* calculation		Parameters		Risk-ratio of wind damage*		
	Above bole** height /m	Canopy top** /m	α ***	ν ***	Total mean	The largest 200 stems·hm^{-2}	Stems whose DBH greater than the mean
Treatment 1	4.0	7.2	3.02	2.54	0.00467	0.00115	0.02150
Treatment 2	4.5	8.5	2.13	1.97	0.00238	0.00057	0.01520
Treatment 3	3.5	7.0	1.97	1.76	0.00427	0.00055	0.00752
Treatment 4	4.5	8.2	1.89	1.67	0.00169	0.00045	0.00456

*The value of risk-ratio of wind damage was calculated by substituting z from bole height to the canopy top at an interval of 1.0 m.

**Data measured in November 2001, the data of diameter (cm) and height (m) refer to Table 2.

***Data measured in October 2000.

Wind damage (canopy damage)

Canopy damage soon after the thinning (September 16 1998) was investigated. Though the extreme wind speed outside the coastal forest attained more than 30 m·s^{-1} (Fig. 2A), no stem breakage or uprooting occurred. The length and diameter of fallen branches ranged between 5 cm-103 cm and 0.3-1.5 cm, respectively. The number and length of branches fallen in treatment 1 (unthinned, control) were much less than in the thinned treatments. Needles blown down were least in treatment 4 (the most intensely thinned) (Table 4, A). The total weight (dry) of branch, cluster, needle and cone showed that wind damage in treatment 2 (20% thinned) was significantly higher ($p<0.05$) than that in other treatments. The unthinned treatment accumulated the least amount of canopy damage in the four treatments, i.e. canopy damage in unthinned treatment was lower than any other thinned treatments (Fig.3A). The weight of canopy damage in the thinned treatments, i.e., treatment 2 (20% thinned), treatment 3 (30% thinned) and treatment 4 (50% thinned), was respectively 239.4%, 164.0% and 114.4% of that in unthinned treatment (Table 4, A). In this extreme wind period, needles constituted the most of the canopy damage for all of the treatments (Table 4, B).

Canopy damage by the strong wind of May 1999 was relatively similar across treatments because of the relatively lower wind speeds (Fig. 2B, Fig.3B). However, during the subsequent strong winds (February 2000 and April 2001) (Fig. 2C, D), wind damage in treatment 1 (unthinned) was more than that in other treatments (thinned) (Fig. 3C, 3D), and the rank of wind damage corresponded to the rank of risk-ratios (Table 2, Table 3).

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

A	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Cone	24.72	45.92	36.84	28.76
Plot1	88.77	174.10	171.90	87.02
Plot2	108.82	534.23	186.51	143.26
Plot3	72.53	141.00	103.56	72.02
Plot4	87.17	105.28	150.36	113.07
Plot5	86.55	146.80	119.05	91.93
Total*	^{bc}468.57	^{a} 1121.51	^{b}768.22	^{bc}536.06
Percent by unthinned (treatment 4)	100	239.35	163.95	114.40

*Data in this line (total weight) 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.

B	Branch	Rate (%)	Cluster	Rate (%)	Needle	Rate (%)	Cone	Rate (%)	Total Rate (%)
Treatment 1	22.45	4.79	34 09	7.27	387 31	82.66	24.72	5.28	100.00
Treatment 2	524.11	46.73	45.00	4.01	506.48	45.16	45.92	4.09	100.00
Treatment 3	101.02	13.15	56.36	7.34	574.01	74.72	36.84	4.79	100.00
Treatment 4	208.38	38.87	26.82	5.00	272.11	50.76	28 76	5.37	100.00

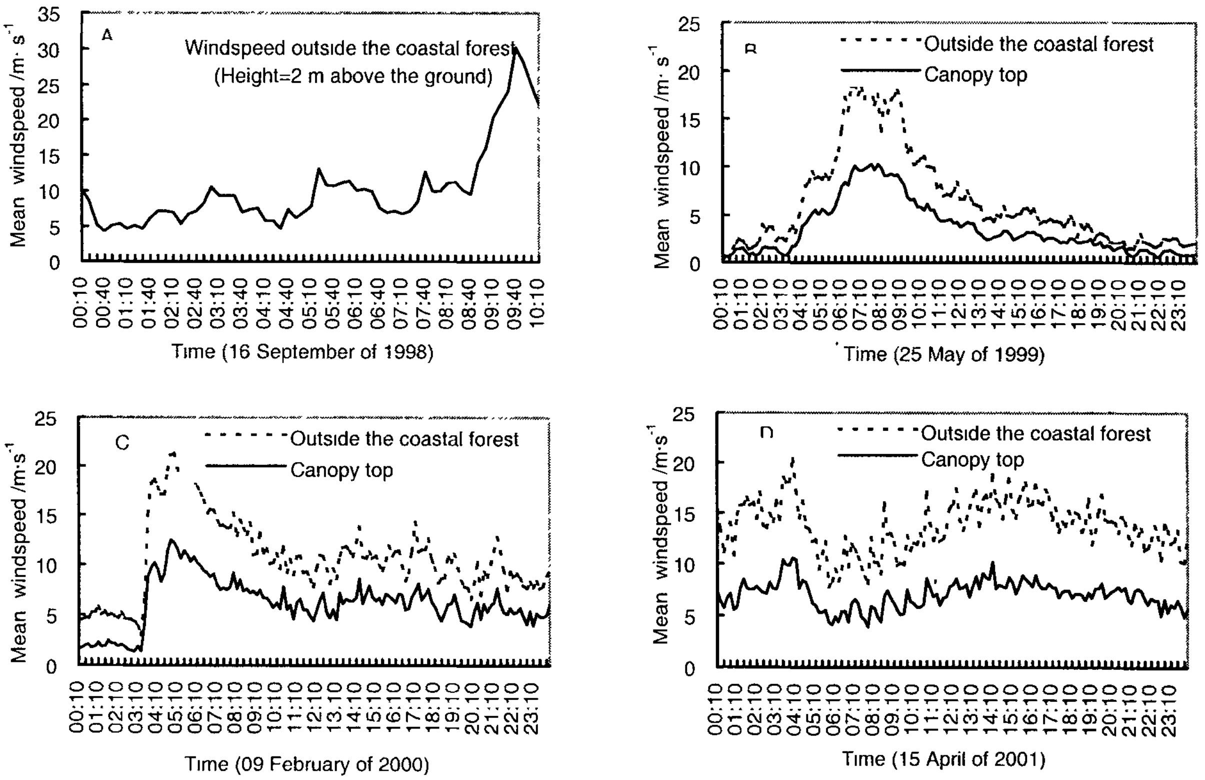


Fig. 2 Daily wind speed (10-min mean) during the extremes, which caused canopy damage. A, extreme wind on September 16 1998 (the anemometer being destroyed); B, on May 25 1999; C, on February 9 2000; D, on April 15 2001.

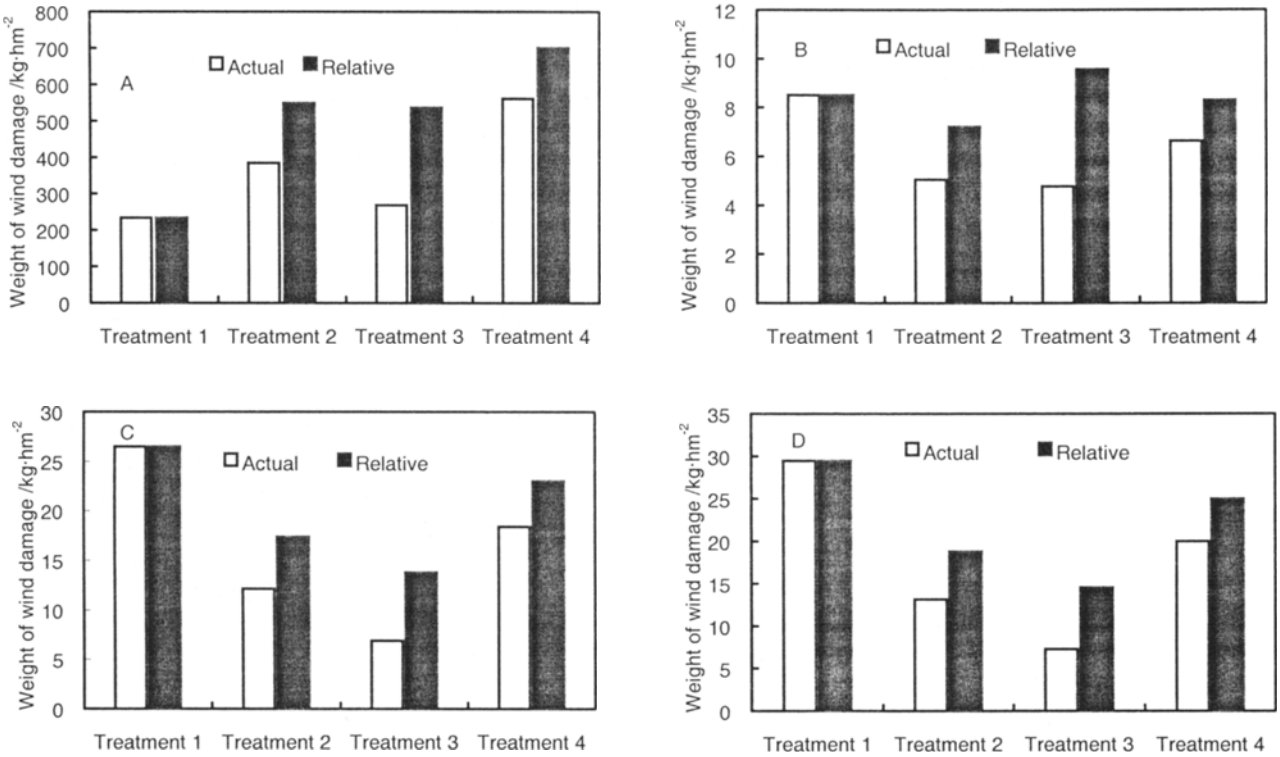


Fig. 3 Wind damage (canopy damage) during the extreme winds.

A, an extreme wind on September 16 1998; B, on May 25 1999; C, on February 09 2000; and D, on April 15 2001. Note: Relative values were calculated from the actual ones, i.e., Relative value=Actual value/（1-thinning ratio）.

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 February 9 of 2000 at a maximum wind speed of 21.3 $m{\cdot}s^{-1}$ (Fig. 2C, Fig. 3C) outside the coastal forest was about 2-3 times greater than that on May 25 of 1999 at a maximum wind speed of 19.7 $m{\cdot}s^{-1}$ (Fig. 2B, Fig. 3B). Because of the uncontrollable feature of meteorological factors, here, the discussion focuses on the stand conditions.

Although the risk-ratio of wind damage in unthinned treatment was higher than that in the thinned treatments (Table 2) soon after the thinning (September 16 1998), the canopy damage was least in the unthinned treatment (Table 4, Fig. 4A). 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 and Pettersson 1996; Gardiner *et al.* 1997), i.e., the more recent the thinning, the greater the risk of wind damage. However, our finding that canopy damage decreased with increasing thinning intensities was not consistent with previous studies showing greater damage when heavier thinning is used (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 m × 35 m).

The amount of canopy damage on February 9 of 2000 and April 15 of 2001 corresponded well to the rank of risk-ratio calculated for individual trees from H_{mean}/D_{mean}^{3}, and the risk-ratios calculated for the stand from $H_{>mean}/D_{>mean}^{3}$ and H_{L200}/D_{L200}^{3} (Table 2, Table 3, Fig. 3). The risk-ratio of wind damage for the stand, which is deduced from the theory of bending moments combined with the coefficients from wind profiles and distribution of optical stratification within the canopy, may be a good estimate of wind damage risk calculated from the largest 200 $stems{\cdot}hm^{-2}$ and the stems whose DBH greater than the total mean (Table 2, Fig. 3C, 3D). 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 $H/D_{1\,3}^{3}$. This appears to be useful where it is necessary to compare the risk of wind damage among stands with different silvicultural practices. However, further confirmation is needed because only minor damage was recorded in this study and not stem breakage or uprooting.

The vulnerability, which increased immediately after thinning will decline as the recovery of tree crowns (crowns grow in diameter) and stems and roots respond to the new wind environment. However there is currently little information on how quickly this occurs (Gardiner and Quine 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. Based on the calculation of risk-ratios for individual trees and stands, the lower ratios of $H/D_{1.3}^3$ (Table 2) and *R(t)* (Table 3) were found in thinned treatments after four growing seasons. This tendency may reflect the effect of thinning on reducing the risk of wind damage or improving the stability of the stand (Blackburn and Petty 1988; Mitchell 2000).

Conclusions and implications

The tendency of increased incidence of wind damage soon after a thinning has been confirmed in this experiment through the investigation of canopy damage caused by strong winds. The results show that in this and in other studies, any type of thinning reduces the wind stability of trees or a stand. The reduction of stability is relative to the increase in roughness of the canopy surface and the decrease in sheltering effects due to the surrounding unthinned forest.

In this study, the best indices of wind damage risk were calculated from the mean values of the largest 200 stems hm^{-2} and the stems whose DBH was greater than the total mean.

The implications of this study for managing coastal pine plantations are as follows:

- Thinning entails the risk of wind damage in the short term, but the stability of the stand will be improved in the long term if the thinning strategy is conducted early in the life of the stand. It can be concluded that early thinning at the period of canopy closure increases the resistance of the coastal *P. thunbergii* forest to wind damage. These results can be supported by many other studies recommending early thinning or wide spacing for stabilization of the timber production forests (Cremer *et al.* 1982; Peltola 1996; Gardiner *et al.* 1997). Conversely, later thinning has little or no effect on the stability of a stand but increases the risk of wind damage.
- From the view of wind damage, thinning should be conducted beyond the recurrence interval of the extreme wind (Quine 2000; Zhu *et al.* 2001b). The retained trees should be with low risk-ratio, i.e., the trees with high risk-ratio should be thinned.
- Thinning in a patch-pattern with patches surrounded by unthinned trees may reduce the risk of thinning-induced wind damage. Therefore, a partial or selective, patch thinning is recommended for the management of coastal pine plantations.
- Although the ratio of $H/D_{1.3}$ is fundamentally important, the ratio of $H/D_{1.3}^3$ (for individual trees), and the attenuation coefficient of the wind profile and the extinction coefficient of distribution of optical stratification porosity combined with $D_{1.3}^3$ (i.e., for stand level assessment) are suggested for evaluating the risk of wind damage, and the selection criteria for thinning of coastal forests should coincide with risk-ratios calculated in this way.
- The intensity of thinning for the pine plantation of coastal forest should be changed with age, state, stand structure, together with the meteorological factors and site conditions. About 1 500 stems·hm^{-2} was suitable for the current coastal pine forest from the view of wind stability.
- Finally, to retain perspective, it must be pointed out that the risk of wind damage in this coastal plantation is not very high compared with forests in Europe and elsewhere. In this coastal forest plantation, the wind and soil conditions, and stocking levels are rarely extreme, and *P. thunbergii* is a very flexible tree species; therefore, consideration of the wind risk is clearly needed, but a wide range of options of thinning intensities or stocking densities still remain available.

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References

Blackburn, P. and Petty, J.A. 1988. Theoretical calculations of the influence of spacing on stand stability [J]. Forestry, **61**: 235-244.

Cremer, K.W., Borough, C.J., Mckinnell, F.H. and Carter, P.R. 1982. Effects of stocking and thinning on wind damage in plantations [J]. New Zealand Journal of Forestry Science, **12**: 244-268.

Galinski, W. 1989. A windthrow-risk estimation for coniferous trees [J]. Forestry, 61: 139-146.

Gardiner, B.A., Stacy, G.R., Belcher, R. E. and Wood, C. J. 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability [J]. Forestry, **70**: 233-252.

Gardiner, B.A. and Quine, C.P. 2000. Management of forests to reduce the risk of abiotic damage, a review with particular reference to the effects of strong winds [J]. Forest Ecology and Management, **135**: 261-277.

Ishimura, S., 1994. Statistics processing [M]. Tokyo Book Ltd., Tokyo, Japan. 224 pp.

Matsuzaki, T. 1994. Impact of wind and snow on forest [C]. In: Proceedings of NAFRO seminar on sustainable forestry and its biological environment. Tokyo: Japan Society of Forest Planning Press, p145-148.

Mitchell, S.J. 2000. Stem growth responses in Douglas fir and Skita spruce following thinning: Implications for assessing wind firmness

[J]. Forest Ecology and Management, **135**: 105-114.

National Astronomical Observatory (NAO), 1997. Rika nenpyo (Chronological Scientific Tables). Maruzen Co. Ltd. Press. (in Japanese)

Peltola, H. 1996. Swaying of trees in response to wind and thinning in a stand of Scots pine [J]. Boundary-Layer Meteorology, **77**: 285-304.

Quine, C.P. 2000. Estimation of mean wind climate and probability of strong winds for wind risk assessment [J]. Forestry, **73**: 247-258.

Rollinson, T.J. 1989. Respacing Sitka spruce [J]. Forestry, **62**: 1-22.

Valinger, E. and Pettersson, N. 1996. Wind and snow damage in a thinned and fertilization experiment in *Picea abies* in southern Sweden [J]. Forestry, **69**: 25-33.

Zhu, J.J., Matsuzaki, T., Gonda Y., and Yamamoto M. 2000a. Estimation of optical stratification porosity (OSP) in a pine coastal forest with different thinning intensities using hemispherical photographic silhouettes [J]. Bulletin of Faculty of Agriculture, Niigata University, **53**: 55-70.

Zhu, J.J., Matsuzaki, T. and Sakioka, K. 2000b. Wind speeds within a single crown of Japanese black pine (*Pinus thunbergii* Parl.) [J]. Forest Ecology Management, **135**: 19-31.

Zhu, J.J., Matsuzaki, T. and Gonda, Y. 2001a. Wind profiles in a coastal forest of Japanese black pine (*Pinus thunbergii* Parl.) with different thinning intensities [J]. Journal of Forest Research, **6**. 287-296.

Zhu J.J., Matsuzaki, T. and Gonda Y. 2001b. Extreme wind over a pine coastal forest established for sand-control at Aoyama of Niigata in Japan [J]. Journal of Erosion Control, **54**: 12-20.

Zhu, J.J., Matsuzaki, T. and Gonda, Y. 2003. Optical stratification porosity as a measure of vertical canopy structure in a Japanese coastal forest [J]. Forest Ecology and management, 173: 89-104.

Zhu, J.J., Matsuzaki, T., Li Fengqin, Gonda, Y. *et al.* 2002. Theoretical derivation of risk-ratios for assessing wind damage in a coastal forest [J]. Journal of Forestry Research, **13**(4): 309-315.