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ABSTRACT

The hypothesis that *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) is more windfirm than *Pinus radiata* D. Don was tested by examining the factors which affect tree stability and comparing available data for each species. A tree-winching study performed on Douglas-fir trees of different sizes growing on Orthic Pumice soils found that their maximum resistive bending moments were not significantly different from those of *P. radiata* ($p > 0.05$). A literature search was performed to determine the relative overturning bending moments of the two species. For each species, information was obtained on the drag coefficient, the crown frontal area, and the mass of the stem and crown. A mechanistic model for predicting the threshold hourly mean windspeed at which damage occurs was applied to a baseline stand of each species (mean top height 30 m, dbh 40 cm, and stocking 310 stems/ha). The Douglas-fir stand had a threshold windspeed of 24.3 m/s and the threshold windspeed for the *P. radiata* stand was 20.6 m/s. A recurrence function, fitted to extreme windspeed data from Rotorua airport, was applied to these critical windspeeds and showed that the risk of damage to *P. radiata* was 2.3 times greater than that to Douglas-fir. Over a period of 90 years, the analysis predicted that a *P. radiata* stand grown on a 28-year rotation was 3 times more likely to suffer catastrophic wind damage than a Douglas-fir stand grown on a 45-year rotation. The most critical factor behind these differences was the lower drag coefficient of Douglas-fir foliage.

Keywords: wind damage; risk; tree stability; uprooting; *Pinus radiata*; *Pseudotsuga menziesii*.

INTRODUCTION

Wind damage is a significant natural hazard to plantation forestry in New Zealand. Records of wind damage date back to the 1940s and since this time catastrophic wind damage has affected at least 50 000 ha of New Zealand's plantation forests (Somerville 1995). Forest managers have often accepted wind damage and not adopted management strategies to reduce the risk. Although there is a general appreciation of the importance of the quality of tree stocks, planting technique, and the consequences of delayed or severe thinning on the risk of wind damage, there is often little regard paid to factors such as the location of forests, soil and site type, age class structure, exposure from upwind clearfelling, and the creation of new edges. There does appear to be an awareness that certain tree species are less susceptible to wind damage than others. In particular, there is a commonly held belief by most forest managers in New Zealand that Douglas-fir is more windfirm than *Pinus radiata* (Ainsworth 1989; Brown & Jones 1989; Studholme 1995). This is based largely on observations made after storm events. For example, the 1982 storm in Kaingaroa Forest caused damage to 2820 ha of *P. radiata* stands (8% of total area in this species) but to only 111 ha of Douglas-fir stands (2% of total area in this species) (A.R.Somerville unpubl. data). After the 1988 storm in Kaingaroa Forest, Brown & Jones (1989) observed that there were Douglas-fir stands in the south and west of the forest which remained almost completely intact while the *P. radiata* stands adjacent to them were damaged. A number of theories have been put forward to explain these differences between Douglas-fir and *P. radiata*. Most of them relate to Douglas-fir having a "softer" crown which has a lower drag coefficient, stronger root anchorage due to root grafting, and a stronger stem which offers greater resistance to stem fracture (Brown & Jones 1989; Studholme 1995).

Mechanistic (or process-based) models offer the ideal means to test these theories. From a mechanistic standpoint, wind damage is assumed to occur when the overturning bending moment (sum of the applied wind load plus the offset mass of the stem and crown) acting on a tree exceeds the maximum resistive bending moment that can be provided by roots and stem of the tree (Quine *et al.* 1995). Therefore, in order for a Douglas-fir stand to be more windfirm than a *P. radiata* stand of the same structure (i.e., same height, diameter-at-breast-height (dbh), and density), either the overturning bending moments acting on the trees within the stand are less, or the maximum resistive bending moments are greater, or there is some combination of the two. In the study reported here, the factors which affect tree stability were identified and comparisons were made between available data for each species to determine whether Douglas-fir is more windfirm than *P. radiata*.

METHODS

The relative windfirmness of Douglas-fir and *P. radiata* was calculated using a mechanistic model (Gardiner & Quine 2000; Gardiner *et al.* 2000). For a particular stand of trees, the model predicts the minimum mean windspeed required to generate an overturning moment equal to the maximum resistive bending moment that the trees can provide. This latter term is calculated using empirical relationships fitted to data collected from tree winching studies. The overturning bending moment is determined from information on tree height, dbh, canopy frontal area, and stand density. Using this information, the drag on the forest canopy is derived using relationships developed by Raupach (1992, 1994). The height up the tree at which the wind acts is given by the zeroplane displacement (Thom 1971). Multiplying these two quantities together yields the applied bending moment due to the wind. The total overturning moment, which includes the additional moment due to the mass of the offset stem and crown, can be calculated from a knowledge of the amount that the tree bends because of the applied wind load.

In this study, the data required to calculate both the maximum resistive and overturning bending moments for *P. radiata* and Douglas-fir were obtained from available literature as well as from field studies. These were then used to calculate the critical windspeeds required for damage as well as the annual and cumulative probabilities that they will be exceeded.

Maximum Resistive Bending Moment

Information on the maximum resistive bending moments of 38 *P. radiata* trees growing on Orthic Pumice soils at Kinleith and Kaingaroa Forests was obtained from a previous study (Moore 2000). A tree winching study was performed in order to collect information on the maximum resistive bending moments of Douglas-fir trees.

Site and sample selection

During December 1996, 20 Douglas-fir trees were winched over in four different stands at Kaingaroa Forest, Bay of Plenty region, New Zealand (lat. 38°20'S, long. 176°10'E). The topography is generally flat; however, there are some areas of rolling hills at the northern end of the forest. Soils are classified as Orthic Pumice soils (Hewitt 1993) belonging to the Kaingaroa series, with those in the northern part of the forest from Tarawera ash (DSIR Soil Bureau 1954). Mean annual rainfall in the forest is approximately 1500 mm.

These Douglas-fir trees were from the 17-, 25-, and 35-year-old age classes. The ranges of dbh and total heights of both the Douglas-fir and *P. radiata* trees winched over are given in Table 1.

TABLE 1–Minimum, maximum, and mean values of tree height and dbh for each species.

Species	Dbh (cm)			Height (m)		
	Min.	Max.	Mean	Min.	Max.	Mean
Pinus radiata	17.7	65.9	35.9	12.3	34.5	23.1
Douglas-fir	16.2	52.6	34.7	10.9	31.3	23.1

Measurements and observations

The selected trees were pulled over using a winch, cable, and pulley system. The system was the same as that used by Moore (2000) and a more detailed description can be found in that report. A hand winch ("Tirfor block") was used for winching the smaller Douglas-fir trees and a Habegger Hittrack 16 motorised winch was used for the larger Douglas-fir trees.

Four basic root-plate dimensions were measured for trees which failed by uprooting. Three radius measurements were made on the upturned root plates — two parallel to the ground and one perpendicular to it. In each, the root plate radius was recorded as the distance from the centre of the tree stem to the edge of the central mass of roots and soil. Root plate width was calculated as twice the average of these three measurements. The root plate depth was also measured.

Analysis of data collected

The data were analysed using the SAS System (SAS Institute Inc. 1989). Height, dbh, and stem volume were used as predictors of the maximum resistive bending moment (M_R) for both species. Analyses of covariance were used to investigate possible differences in M_R

between species as well as the effect that taper (ratio of height to dbh) and root plate dimensions have on M_R.

Overturning Bending Moment

Applied bending moment

For a given windspeed, the bending moment applied to a tree depends on the amount of momentum absorbed from the atmosphere by that tree. This in turn depends on both the crown frontal area presented to the wind and the drag coefficient of the tree crown. Information on these two parameters was obtained from available literature and from field measurements.

The crown frontal areas of both species were estimated from gross crown dimensions (i.e., crown width and length) by assuming that the crowns were triangular in shape. Data were collected from trees sampled in the tree winching studies. Additional data were also available for Douglas-fir trees (K.O'Hara unpubl. data). Relationships between crown width and potential predictor variables such as dbh, stocking, tree height, and crown length (Jacobs 1938; Moeur 1981; Leech 1984; Paton 1988) were developed using the SAS System (SAS Institute Inc. 1989).

Green crown lengths of *P. radiata* trees were predicted using the Beekhuis (1965) and PPM88 models. The latter was developed using data from both thinned and un-thinned stands growing in the central North Island (A.Dunningham & M.Lawrence pers. comm.). Douglas-fir green crown lengths were predicted using a model developed by Fight *et al.* (1995).

The effectiveness of momentum transfer between the atmosphere and a rough surface such as a tree crown is specified by a drag coefficient (C_D) which can be determined from Equation [1] (Thom 1971):

$$C_D = \frac{2D}{\rho U^2 A} \qquad [1]$$

where D is the drag force (kg)
ρ is the density of air (1.226 kg/m^3)
U is the windspeed
A is the projected frontal area of the tree.

An estimate of the drag coefficient for Douglas-fir was obtained from Raymer (1962) and Mayhead (1973) who performed wind tunnel tests on a number of coniferous tree species. No data were available for *P. radiata*; however, of the species tested by these authors, *P. sylvestris* L. (Scots pine) was assumed to have the physiological properties most closely resembling those of *P. radiata* (J.Grace pers. comm.).

Bending moment due to the mass of the offset stem and crown

For a given angle of deflection, differences between the two species in the magnitude of this component of the overturning bending moment depend on their relative crown and stem masses. A literature review was conducted in order to determine the relative masses of the stems and crowns of the two species. For each species, the biomass equations were applied to a baseline stand with a mean top height 30 m, mean dbh 40 cm, and density 310 stems/ha.

The bending moment due to the mass of the offset stem and crown was calculated from Equation [2]:

$$M_{off} = m\, g\, \text{CoM} \sin\phi \qquad [2]$$

where m is the mass of the tree
g is the acceleration due to gravity (9.81 m/s^2)
CoM is the height to the centre of mass (calculated using the equations described by Papesch *et al.* 1997)
ϕ is the angle of stem deflection from vertical.

The oven-dry crown mass of the "mean tree" within the *P. radiata* baseline stand was estimated using equations developed by Dargavel (1970), Madgwick (1983, 1994), and Baker *et al.* (1984). A function was also fitted to data collected from 6- to 22-year-old trees growing in Kaingaroa Forest (H.Madgwick unpubl. data). The oven-dry crown mass of the Douglas-fir "mean tree" was estimated using the biomass estimation software package, BIOPAK (Means *et al.* 1994). Only equations developed for Douglas-fir from the coastal and western Cascades areas of the Pacific Northwest region of the United States were used as these trees have crown physical properties most similar to those grown in New Zealand (K.O'Hara pers. comm.). The oven-dry masses were converted to green masses by applying a conversion factor to account for the moisture loss during drying. A factor of 2.5 was used for *P. radiata*, and a factor of 2.3 was used for Douglas-fir because of its lower moisture content (P.Beets pers. comm.).

Stem volumes for the *P. radiata* and Douglas-fir "mean trees" were calculated using stem volume equations 115 and 136 respectively in the forestry calculation package FFCalc (S.Pavarno, unpubl. data). Stem mass was then estimated using appropriate conversion factors (Ellis 1984).

Risk of Damage

The effect of silviculture on the relative stability of Douglas-fir and *P. radiata* was investigated by calculating the critical windspeeds for damage at yearly intervals over the length of typical rotations of each species. Information on height, dbh, stem volume, and stand density was obtained from the stand management simulation package STANDPAK (Whiteside 1990) for the silvicultural regimes listed in Table 2.

TABLE 2–Typical silvicultural regimes used for Douglas-fir and *Pinus radiata* in the central North Island region.

Operation	*Pinus radiata*	Douglas-fir
Site index (m)	29	30
Initial density (stems/ha)	833	1667
First thin	MCH* 7 m to 700 stems/ha	MCH 14 m to 750 stems/ha
Second thin	MCH 14 m to 317 stems/ha	MCH 22 m to 325 stems/ha
First prune	MCH 6 m to 2.5 m	none
Second prune	MCH 8.5 m to 4.5 m	none
Third prune	MCH 11 m to 6.5 m	none
Rotation length (years)	28	45

* MCH = mean crop height.

The risk of damage to these stands was determined using a recurrence function fitted, using the Lieblein method (Cook 1985), to a time series of annual maximum hourly (10-minute average) windspeeds. The annual probability of the critical windspeed for damage, V, being exceeded, AEP, was calculated using Equation [3]:

$$AEP + 1 - e^{-e^{-\frac{V-15.655}{2.604}}} \quad [3]$$

The cumulative probability of the occurrence of catastrophic damage (i.e., the whole stand is severely damaged) was calculated using Equation [4]:

$$CPD_i = CPD_{i-1} + AEP_i \times (1 - CPD_{i-1}) \quad [4]$$

where CPD is the cumulative probability of damage and AEP is the annual probability of exceeding the critical windspeed for catastrophic damage. The probability of occurrence of catastrophic damage was determined by assuming that the intensity of damage (i.e., the proportion of the trees in the stand that are uprooted or broken) will be a function of the amount by which the critical windspeed for the onset of damage is exceeded. At a certain level above the critical windspeed, any further increase in windspeed will not lead to an increase in damage intensity as the proportion of trees damaged will already be 100%.

RESULTS

Maximum Resistive Bending Moment

All of the Douglas-fir winched over failed by uprooting. A similar result was found in the previous study on *P. radiata* in which 34 of the 36 trees failed by uprooting and the other two failed by stem and root collar fracture. The range of root plate sizes for the two species is shown in Table 3. The volume of the root plate was estimated from measurements of diameter and depth by assuming that its shape conformed to an ellipsoid. There was a weak relationship between root plate volume and stem volume ($r^2 = 0.387$) with no significant difference in root plate volume between species ($p = 0.367$). No evidence of root grafting was found for the Douglas-fir trees.

Significant relationships were observed between height, dbh, and stem volume and M_R (Fig. 1, Table 4) with stem volume accounting for the greatest proportion of the variation in M_R for both species (Table 4, Equation [7]). The intercept term in Equation [7] was not

TABLE 3–Root plate characteristics of the *P. radiata* and Douglas-fir trees winched over.

		Pinus radiata	Douglas-fir
Root plate depth (m)	Min.	0.2	0.6
	Max.	2.1	2.0
	Mean	1.0	1.2
Root plate diameter (m)	Min.	1.4	1.9
	Max.	3.5	4.3
	Mean	2.5	2.6
Root plate volume (m^3)	Min.	0.51	1.34
	Max.	9.89	11.80
	Mean	3.79	4.58

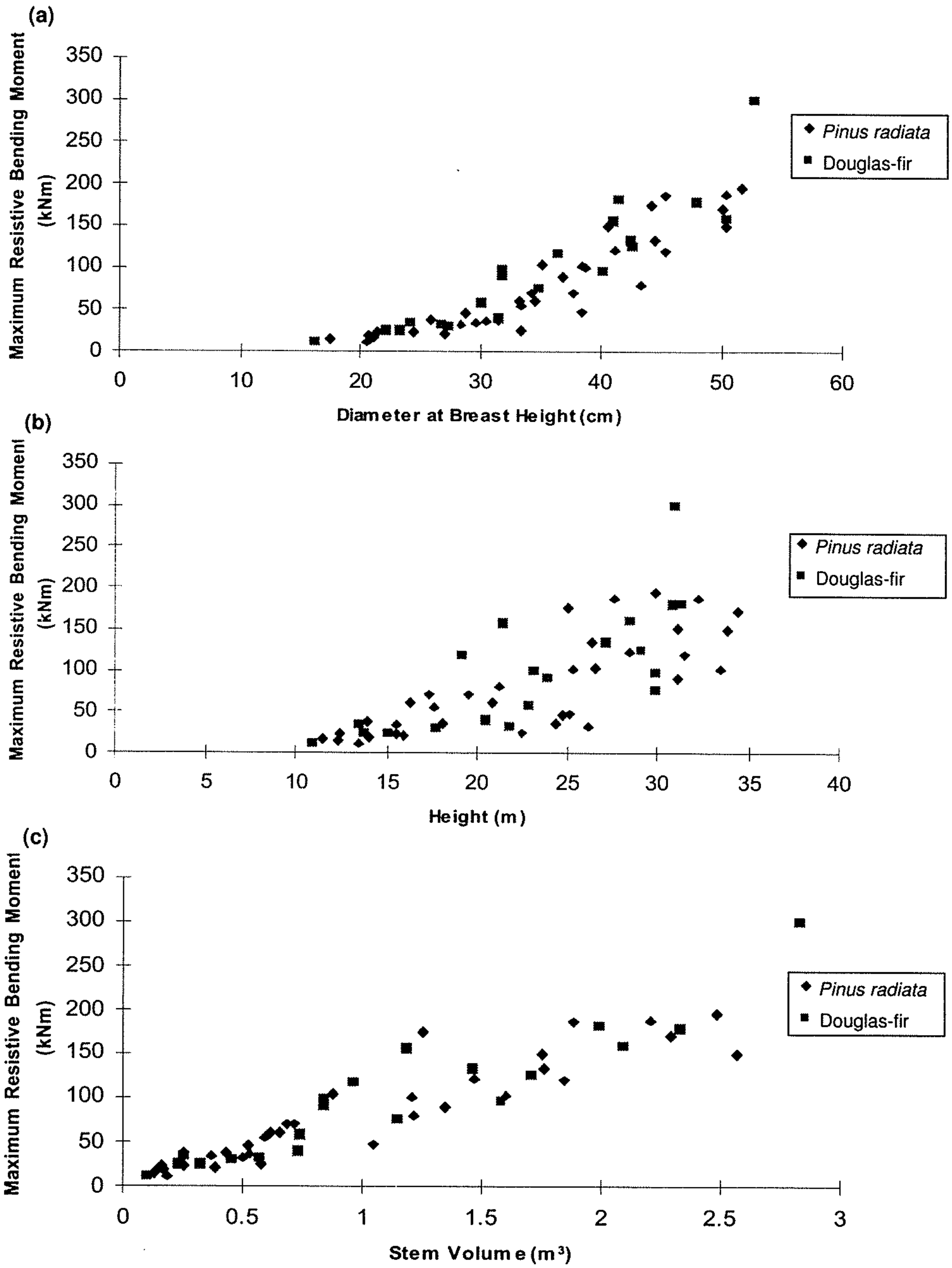

FIG. 1–Relationship between maximum resistive bending moment and (a) diameter at breast height, (b) tree height, and (c) stem volume.

significant and was therefore omitted. Neither root plate volume, nor diameter, nor depth had a significant effect on the maximum resistive bending moment once stem volume was accounted for ($p > 0.05$). After stem volume had been accounted for, no difference in M_R was

TABLE 4–Relationships between tree size variables (diameter; height; volume) and maximum resistive bending moment for *P. radiata* and Douglas-fir.

Model	Parameter estimates	p-value	Standard error	R^2
[5] $M_c = a_6$ dbh $+ b_6$	$a_6 =$ 5.618	0.0001	0.37	0.816
	$b_6 = -110.905$	0.0001	13.25	
[6] $M_c = a_7$ h $+ b_7$	$a_7 =$ 6.533	0.0005	0.74	0.602
	$b_7 = -66.453$	0.0001	17.49	
[7] $M_c = a_8$ vol	$a_8 =$ 81.779	0.0001	2.47	0.860

found between the two species ($p > 0.05$). The ratio of total tree height to diameter at breast height (h:dbh) ranged from 47:1 up to 86:1, with the former being more tapered. There were no significant relationships between stem taper and the maximum resistive bending moment for either species. However, for a given height and dbh, Douglas-fir trees have a greater stem volume and therefore are expected to have a greater value of M_R.

Overturning Bending Moment

Analysis of the data showed that a strong linear relationship existed between dbh and crown width of Douglas-fir ($r^2 = 0.80$); this relationship was weaker for *P. radiata* ($r^2 = 0.55$) (Fig. 2). There was some evidence that crown length influenced the crown width of *P. radiata* trees ($p = 0.10$). The effects of stand density and height were not significant for either species ($p > 0.05$). For a given dbh, the crowns of the measured Douglas-fir trees were significantly wider than those of *P. radiata* ($p < 0.01$). At the same stand density and mean top height, Douglas-fir trees have shorter green crowns than *P. radiata* trees (Fig. 3). Above a mean top height of 20 m, PPM88 predicts a longer green crown length for *P. radiata* than Beekhuis' model and hence a greater difference between the two species. In the critical

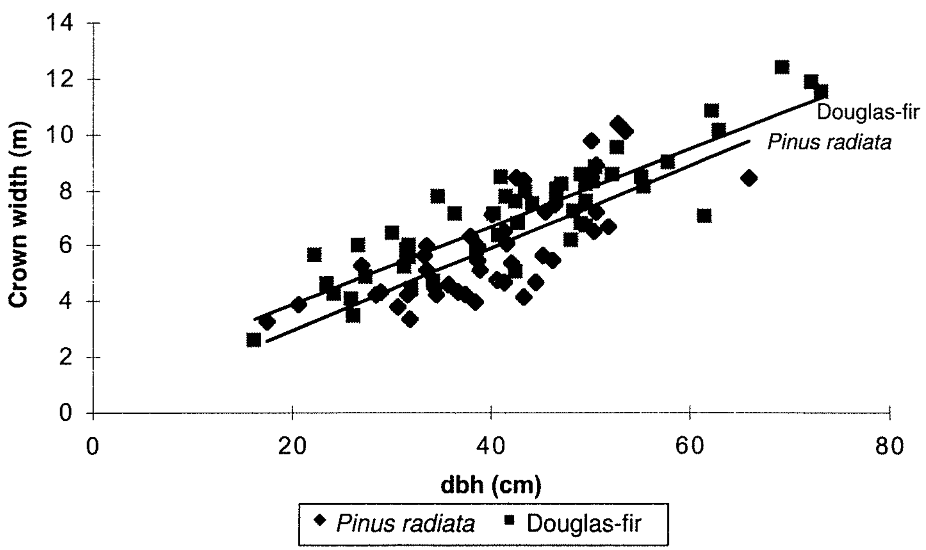

FIG. 2–Relationships between dbh and crown width for both Douglas-fir and *Pinus radiata*.

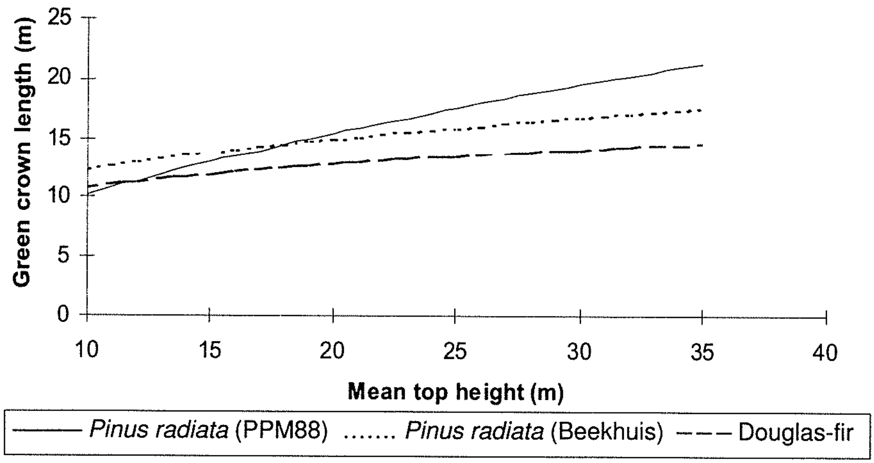

FIG. 3–Differences in predicted crown lengths between *Pinus radiata* and Douglas-fir stands with a stand density of 310 stems/ha.

windspeed calculations, PPM88 was used to predict green crown length when tree height was less than 20 m. Above this height, the Beekhuis model was used. Based on the information on crown width and length and the assumption about crown shape, the predicted crown frontal area of the Douglas-fir "mean tree" was on average 5 m^2 greater than that for the equivalent *P. radiata* "mean tree".

The relationships between windspeed and the mean value of drag coefficient for each species are shown in Fig. 4. Mayhead (1973) also determined windspeed-independent values for drag coefficient of 0.29 and 0.22 for *P. sylvestris* and Douglas-fir respectively. These indicate that for a given crown frontal area more momentum is absorbed by *P. sylvestris* (and hence *P. radiata*) crowns than by Douglas-fir crowns. The difference in drag coefficients between species increases with increasing windspeed (Fig. 4).

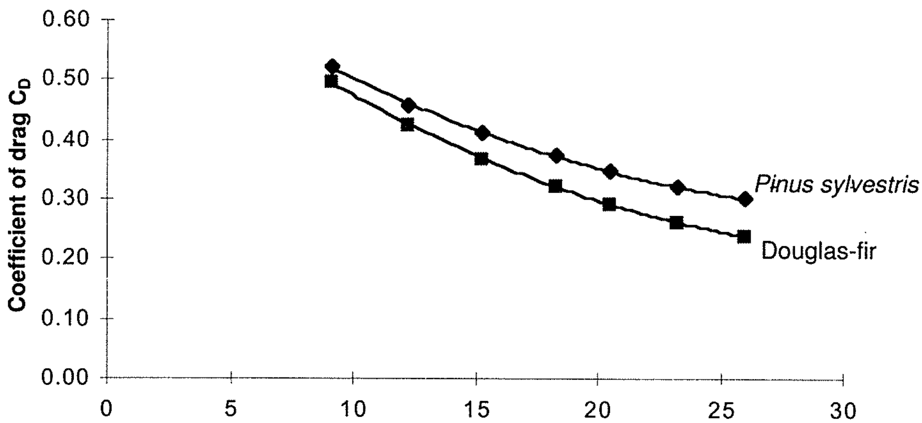

FIG. 4–The relationship between drag coefficient and windspeed for *Pinus sylvestris* and Douglas-fir (*from* Mayhead 1973).

Bending moment due to the mass of the offset stem and crown

The branch, foliage, and total oven-dry crown masses for the *P. radiata* and Douglas-fir "mean trees" predicted by the different equations are listed in Table 5. The mean oven-dry crown masses of both species were not significantly different ($p > 0.05$). Estimated green crown masses for the *P. radiata* and Douglas-fir "mean trees" were 257 kg and 225 kg respectively. The under-bark stem volumes for the *P. radiata* and Douglas-fir "mean trees" were calculated as 1.278 m^3 and 1.419 m^3, respectively. Using conversion factors of 987 kg/m^3 and 900 kg/m^3 Ellis (1984), the stem weights of the *P. radiata* and Douglas-fir "mean trees" were estimated as 1261 kg and 1277 kg respectively.

TABLE 5–Estimates of the oven-dry weight of live *P. radiata* and Douglas-fir crowns.

Equation source		Component of crown mass (kg)		
		Branches	Foliage	Total
Pinus radiata				
Kaingaroa Forest data		68	26	94
Dargavel (1970)		89	36	125
Madgwick (1983)		60	28	88
Baker *et al.* (1984)		65	33	98
Baker *et al.* (1984)		77	37	114
In Madgwick (1994)		67	29	96
Mean		71	30	101
Douglas-fir				
BIOPAK Equation No.				
Branches	Foliage			
2	1	66	31	97
445	446	39	40	79
823	825	65	52	117
Mean		57	41	98

The heights to the centre of mass of the "mean trees" were calculated as 10.68 m and 10.58 m for *P. radiata* and Douglas-fir, respectively. The difference in the bending moment due to the mass of the offset stem and crown between the two species was less than 2% for all angles of deflection. A tree winching study performed on *P. radiata* at Eyrewell Forest by Papesch *et al.* (1997) found that, at the point of failure, the bending moment due to the mass of the offset stem and crown contributed 9% to the total overturning bending moment. Provided that both species fail at similar angles of deflection, any difference in the bending moment due to the mass of the offset stem and crown between the two species will have only a minor effect on their relative windfirmness.

Risk of Damage

The predicted threshold windspeeds required to cause damage to the Douglas-fir and *P. radiata* baseline stands were 24.3 m/s and 20.6 m/s respectively, indicating that Douglas-fir is the more windfirm species. The lower drag coefficient of Douglas-fir accounted for 53% of this difference, and the greater stem volume of the Douglas-fir "mean tree" accounted for the other 47%. Differences in crown frontal area did not contribute to the difference in critical windspeed.

Over the length of typical rotations, model results indicate that at the same age a Douglas-fir stand is more windfirm than a *P. radiata* stand (Fig. 5). The predicted critical windspeed for damage decreases substantially after each of the two thinning operations carried out for both the Douglas-fir and *P. radiata* stands. Although *P. radiata* is taller than Douglas-fir for a given age, a comparison of critical windspeeds based on mean top height revealed that Douglas-fir stands were more windfirm than *P. radiata* stands of the same height. No data were available for Douglas-fir less than 15 years of age and *P. radiata* less than 4 years of age, as these were the lower age limits of the growth models used.

The probability that the critical windspeeds for the onset of damage would be exceeded, based on data from Rotorua Airport, was 0.115 and 0.050 for the *P. radiata* and Douglas-fir baseline stands, respectively. The *P. radiata* baseline stand was therefore 2.3 times more likely to suffer some form of wind damage than the Douglas-fir stand. Over the period of a rotation, both species exhibit the general trend whereby the risk of damage increases with increasing age (Fig. 6). For both species, the risk of damage occurring increases markedly after thinning.

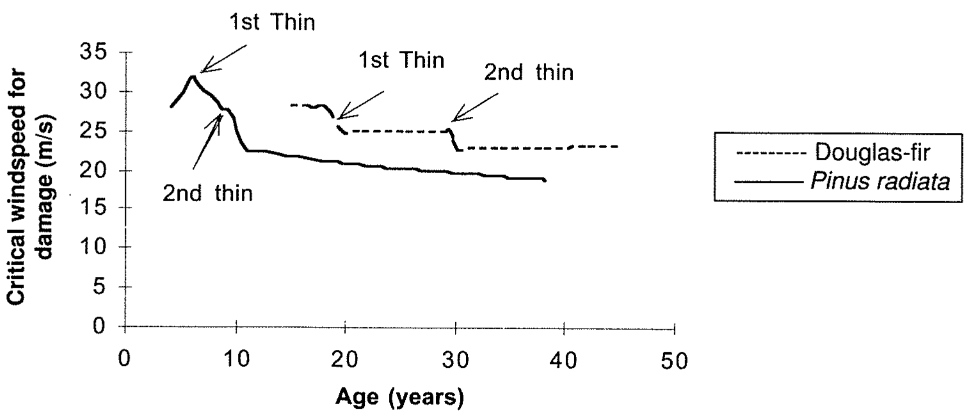

FIG. 5–Critical windspeed for damage for *Pinus radiata* and Douglas-fir.

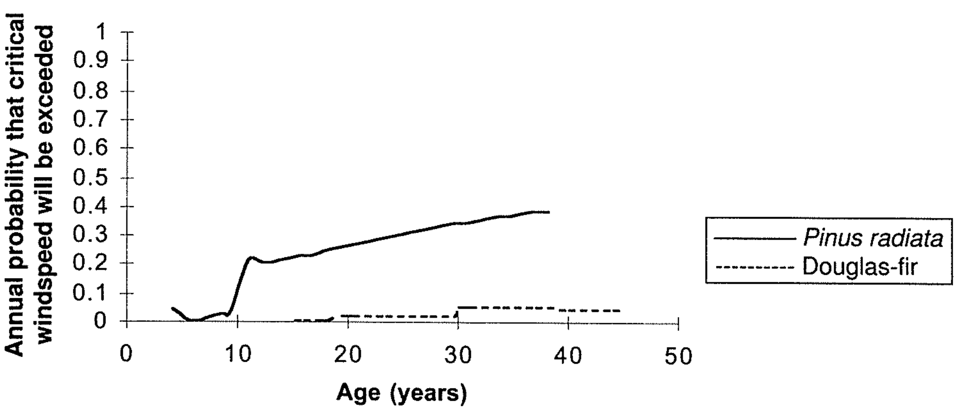

FIG. 6–Annual risk of damage for *Pinus radiata* and Douglas-fir.

Between the ages of 20 and 30 Douglas-fir stands are, on an annual basis, 10 to 14 times less likely to suffer wind damage than *P. radiata* stands; between 15 and 19 years of age the annual risk of damage to *P. radiata* stands is approximately 30 times that of Douglas-fir stands.

Over a 90-year time period (i.e., 2 rotations of Douglas-fir and 3.2 rotations of *P. radiata*) the cumulative risk of damage was 0.92 and 0.30 for *P. radiata* and Douglas-fir, respectively (Fig. 7). These calculations were performed assuming that the amount by which the critical windspeed must be exceeded to cause complete catastrophic damage is 5 m/s. This level was chosen as the resulting windspeeds were similar to those recorded at Taupo airport during the 1982 and 1988 storms (New 1989). Increasing the amount by which the critical windspeed has to be exceeded to cause catastrophic damage also increased the difference between the two species in the relative cumulative risk of catastrophic damage.

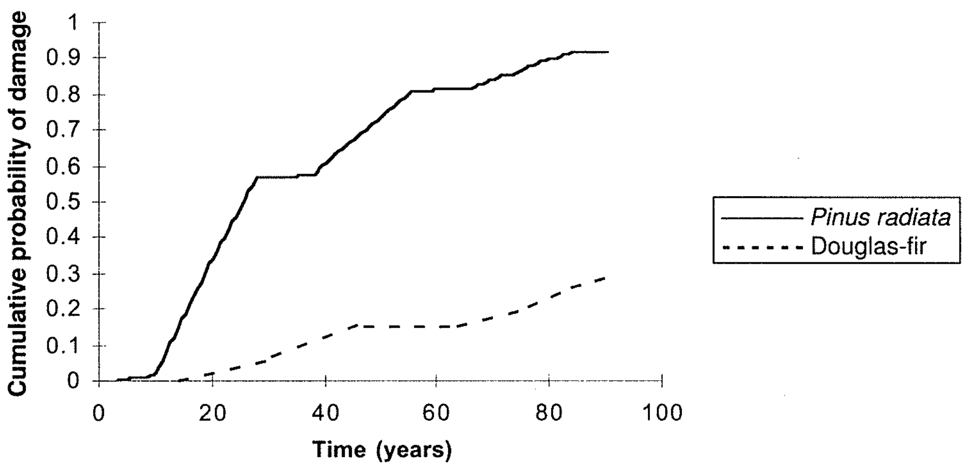

FIG. 7—Cumulative risk of damage for Douglas-fir and *Pinus radiata*.

DISCUSSION

Differences in the relative stability of *P. radiata* and Douglas-fir are due to a combination of differences in tree physical properties and silvicultural regimes. The most critical factor identified is the drag coefficient. This has generally been one of the factors suggested by forest managers as contributing to the difference between the species (Brown & Jones 1989; Studholme 1995). While the available literature indicates that Douglas-fir crowns have both a lower drag coefficient than *P. sylvestris* and a greater ability to streamline (i.e., align themselves in the along-wind direction) under windy conditions, no information is available for *P. radiata*. Further work is required to validate the assumption that the drag coefficient of *P. radiata* is greater than or equal to that of *P. sylvestris*.

Another possible factor identified by forest managers is root anchorage strength. From a study on shallowly rooted *Picea sitchensis* Bong. (Carr.), Coutts (1986) found that the greatest component of total root anchorage was provided by the resistance of the roots placed under tension on the windward side of the tree. However, Crook & Ennos (1996) found that for *Larix decidua* Mill. × *L. japonica* Carr. growing on a free-draining soil, approximately 75% of the anchorage strength was provided by the windward sinkers and tap root. Data collected by O'Loughlin & Watson (1979) and Phillips & Watson (1994) showed that at Ashley Forest in Canterbury the mean tensile strength of individual small-diameter (<15 mm) Douglas-fir roots was approximately 1.5 times greater than those of *Pinus radiata*. The lack of a significant difference between the maximum resistive bending moments of the two species suggests that in soils where vertical root penetration is not impeded, use of tensile strength measurements of small-diameter roots to predict root anchorage strength may not be appropriate.

The applied load on a tree will change if either the drag coefficient or the crown frontal area change (Hedden *et al.* 1995). The data from Mayhead (1973) are supported by the theory of Savill (1983) that under windy conditions the foliage of Douglas-fir streamlines to reduce the drag coefficient. However, further research is required to investigate to what extent streamlining occurs in *P. radiata*. Because drag coefficient decreases with increasing branch flexibility and crown permeability (Cannell & Coutts 1988), branch bending tests performed on the two species could provide a good initial estimate of their relative streamlining abilities. Trees are also able to reduce their crown frontal area exposed to the wind by shedding foliage or lateral branches (Putz *et al.* 1983). There is anecdotal evidence to suggest that Douglas-fir branches are more brittle than those of *P. radiata* trees and therefore break off in the wind more easily. Further work is required to investigate this crown adjustment mechanism as a model developed for *P. taeda* L. (loblolly pine) by Hedden *et al.* (1995) found that, compared with stem bending and branch streamlining, branch shedding offered the greatest protection against wind damage.

The model for determining the critical windspeeds at which a stand will fail is being continually developed. Improvements to the model, which will include better representation of crown frontal area, drag coefficient, and the incorporation of crown adjustment factors, should result in more accurate prediction of the critical windspeed for damage. However, at present it does show a substantial increase in the risk of damage for both species after thinning operations, which qualitatively agrees with many observations made after storms. In general, thinning not only increases the mean windspeed within a stand but it also increases turbulent component (i.e., greater maximum windspeeds occur for a given mean windspeed). Furthermore, thinning a stand reduces the mutual support of neighbouring trees, which can be one of the most important mechanisms available to trees for dissipating energy from the wind (Milne 1991). Expansion of the crowns of residual trees has also been associated with damage after thinning, particularly when thinning is combined with the application of fertiliser (Valinger & Lundqvist 1992).

The assessment of the cumulative probability of damage also has some limitations. While considering only catastrophic damage greatly simplifies the analysis, the relationship between damage intensity and the amount by which the critical windspeed is exceeded is largely unknown. If the amount by which critical speed must be exceeded in order to cause catastrophic damage is increased, the relative difference in the cumulative risk of damage between the two species will also increase. Because the cumulative probability of damage approaches 1 asymptotically, a lower annual probability of catastrophic damage will result in this limit being reached over a longer time period. Further research is required to quantify the relationship between damage intensity and the amount by which the critical windspeed is exceeded.

CONCLUSIONS

Data currently available suggest that the probability of wind damage occurring in a Douglas-fir stand is less than for a *P. radiata* stand with the same mean crop height, mean diameter, and stocking, growing in the central North Island. The difference in drag coefficients between the two species is the factor which has the greatest effect on their relative windfirmness. However, this conclusion is based on data collected in Great Britain, and further work is required to determine the drag coefficients for *P. radiata* and Douglas-fir trees grown in New Zealand. The greater stem volume of Douglas-fir trees of a given height and dbh appears to be an important factor. Different silvicultural regimes applied to the two species also affect their relative stability. Similar trends would be expected in other parts of the country, provided the silvicultural regimes employed were similar to those in this analysis.

Over an analysis period of 90 years and for current typical regimes, a *P. radiata* stand grown on a 28-year rotation is 3.1 times more likely to suffer catastrophic wind damage than a Douglas-fir stand grown on a 45-year rotation. However, these results are very dependent on the relationship between the intensity of wind damage and the amount by which the critical windspeed is exceeded. This relationship needs to be investigated much more rigorously. Canopy streamlining, branch shedding, and the relationship between stand structure and crown frontal area also need to be further investigated.

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