EFFECTS OF STOCKING AND THINNING ON WIND DAMAGE IN PLANTATIONS

K. W. CREMER, C. J. BOROUGH
CSIRO Division of Forest Research, P.O. Box 4008, Canberra, A.C.T. 2600, Australia

F. H. McKINNELL
Forests Dept., 50 Hayman Road, Como, Western Australia 6152

and P. R. CARTER
Forestry Commission, Tumut, New South Wales 2720, Australia

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ABSTRACT

Examination of relations between stocking or thinning and the incidence of wind damage by uprooting or the bending and breakage of stems showed that stocking and thinning strategies can reduce the risk of damage in plantations of **Pinus radiata** D. Don. Except on sites where root growth was very restricted, plantations raised at lower stocking generally experienced markedly less wind damage. The risk was increased, however, immediately after a thinning, especially if the retained trees were tall and slender, and the thinning had been heavy and had removed dominants. These influences were explained by the long-term effect of stocking on tree development and by the immediate effect of thinning in opening the canopy to the wind.

Reduced stocking greatly increased stem diameter and crown and root growth, but had little or no influence on the height of the dominant trees, except at extremely high or extremely low stockings. The height/diameter (H/D) ratio was thus greatly reduced at lower stocking. The H/D ratio, calculated from the mean height and diameter at breast height (1.3 m) over bark (d.b.h.o.b.) of the 200 largest diameter trees/ha, was identified as a valuable index of the risk of wind damage, at least with respect to stem failures. It was found that H/D values are influenced by growth at various stockings and after various thinning regimes. The most important conclusion reached is that trees should be allowed as much growing space from as early in their life as can be reconciled with other silvicultural and economic constraints.

INTRODUCTION

This paper deals with the influences of initial stocking rates and subsequent thinnings on the incidence of wind damage in terms of root or stem failure, i.e., tilting and uprooting of trees, or bending and breakage of tree stems. It focuses on plantations of *P. radiata*, but we believe that the main relationships noted probably apply, in broad terms, to most tree species grown in stands of even age.

Published and new information were examined in order to identify (a) how wind damage is related to stocking and thinning, (b) which stand and tree characteristics affect stability, (c) how stocking and thinning influence these characteristics, (d) how degrees of risk might be quantified, and (e) how stocking/thinning strategies might be designed to reduce risks of wind damage.

Relationships Between Stocking or Thinning and the Incidence of Wind Damage

Trees grown at low stocking or in relative isolation commonly appear superior in resistance to both stem and root failures. Trees grown in isolation, in wind breaks, or at the edges of stands often survive far better than trees grown within stands (Curtis 1943; Wilson 1976; Cremer *et al.* 1977; Mitscherlich 1972, 1974).

Reukema (1970) reported that in a 40-year-old Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) spacing trial the proportion of stems bent or broken in the previous 20 years ranged from 12% at the lowest stocking (750 stems/ha) to 22% at the highest stocking (6800 stems/ha). Uprooting ranged from 0% at the lowest stocking to 1–3% at the three highest stockings. Similarly, in another spacing trial with Douglas fir (van Tuyll & Kramer 1981) the proportion of trees uprooted shortly after thinning ranged from 4% at the lowest stocking (1100 stems/ha) to 10% at the highest stocking (4400 stems/ha).

Somerville (1980) described several examples where lower initial stocking rates had led to higher incidence of uprooting, but these stands had been thinned within the previous 5 years. Increased incidence of wind damage soon after a thinning has been observed many times in Australia and elsewhere. In Australia, for instance, the extensive uprooting of 30- to 40-m-tall *P. radiata* in July 1974 near Canberra was virtually confined to stands downwind of recent clearcuts or stands which had been thinned within the preceding 4 years (Cremer *et al.* 1977). Similarly, most of the 500 ha of *P. radiata* uprooted at Flynn Creek, Victoria, in 1968 involved stands which had recently been thinned the first time (O. Raymond pers. comm.). The widespread bending and breakage of *P. radiata* stems caused by Cyclone Alby in Western Australia during 1978 occurred predominantly in stands which had been overdue for their first thinning or had been thinned belatedly within the preceding 2½ years (McKinnell in prep.). Increased wind damage after recent thinning has been observed also in natural eucalypt forests of even age (Incoll 1977; F. H. McKinnell pers. comm.).

These Australian experiences are consistent with those reported from Europe and America (e.g., Busby 1965). Booth (1974) reported that the heavier and more recent the thinning of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland, the greater is the risk of windthrow. Similarly, Mayhead *et al.* (1975) reported that in Scottish conifer plantations any type of thinning reduces stability, especially if the thinning is heavy and if the larger trees are removed; the reduction in stability is related to the increase in roughness of the canopy surface. Leibundgut (1969) emphasised the danger of thinning conifers in Switzerland, especially if tall dense stands are thinned heavily. He stated that frequent light thinning commencing at an early age, however, had reduced windthrow. Ruth & Yoder (1953) observed that certain conifer stands in Oregon suffered little wind damage after low-intensity thinnings (when only 16–24% of the stand's volume had been removed), while severe damage occurred in stands where most of the dominant trees had been cut.

The time needed for thinned stands to regain considerable stability depends on growth rate, on stand age, and on the state of the stand at the time of thinning. It may be as little as 3–5 years in *P. radiata* (*see* McKinnell (in prep.) re stem failure; Cremer *et al.* (1977) re root failure).

In some situations, however, no relationship has been found between stability and recent thinning, e.g., in Australia by Incoll & Baker (1980) and in New Zealand by Irvine (1970). There are indications that on sites where roots are restricted to shallow depths (e.g., by poor drainage or an impermeable layer) low stocking results in decreased resistance to uprooting (SWOAC 1972). On certain sandy, shallowly rootable soil types *P. radiata* is highly vulnerable to windthrow even without prior thinning (Turvey 1980).

STAND AND TREE CHARACTERISTICS WHICH INFLUENCE STABILITY

Stand Configuration, Wind Loading, and Swaying

The configuration of a stand greatly affects both the local gustiness of the wind and the wind loads imposed on the trees. However, only superficial information is available on this important subject.

Removal of trees by thinning opens the canopy, allows more wind to penetrate, increases the aerodynamic roughness of the canopy surface, and increases turbulence. The over-all wind load has to be shared by the reduced number of remaining trees. Their crowns are less likely to touch and thus dampen each other's sway (Mitscherlich 1974; Brünig 1974; White *et al.* 1976). Fraser (1964) observed with model forests in a wind tunnel that the wind load per tree was doubled when the spacing between trees was increased from 25% to 40% of tree height.

Great importance is attached to gustiness and swaying. It has been suggested that a most dangerous situation arises when the wind spectrum includes strong gusts whose frequency coincides with the natural frequency of oscillation of the trees (Roschke 1977; Holbo *et al.* 1980) or, worse still, when the oscillating crop itself causes a corresponding frequency of gusting (*see* Papesch (1976) for *P. radiata*; Finnigan & Mulhearn (1978) for a model wheat crop in a wind tunnel). Oliver & Mayhead (1974) observed the honami effect in a pine plantation, i.e., the tree tops swayed in unison during extreme gusts. We have found, however, that under most conditions trees sway largely at random, rarely in unison.

Our observations suggest that two other effects of gusting and swaying are probably of great importance. The first is the increased risk of uprooting when gustiness and swaying are prolonged since the grip of the roots on wet soil is loosened progressively (Hütte 1968; Mitscherlich 1974; Cremer *et al.* 1977). It is recognised in Europe that when shallow-rooted trees sway they may "pump" the wet soil, and cause it to liquefy and ooze out from under the roots. This could explain why shallow-rooted trees on wet soils have been uprooted by winds of much lower speeds than those predicted as necessary from tree-pulling experiments (Oliver & Mayhead 1974). Observations on uprooted *P. radiata* near Canberra have shown that progressive loosening of roots during swaying is important also when the roots penetrate reasonably deeply (1 m or more) and not only in wet clayey soils but also in rocky soils (K. W. Cremer, unpubl. data). The roots and the root-ball tend to sway and flex in response to the swaying of the tree. The roots which project below the root-ball are pulled loose from the ground, so that in wet soft clayey soil they form a slurry of puddled clay, and in rocky or gritty soil they are torn and abraded.

The second effect is that with more prolonged, largely random swaying, the risk is increased that a strong gust arrives just when the tree is in a most vulnerable situation, so that the kinetic energies of the gust and swaying crown combine. A study of the relative positioning of *P. radiata* trees uprooted in wet soil during prolonged wind indicated that most trees probably fell one by one in random sequence (Cremer *et al.* 1977). This is attributable to the above effect as well as to any random variations in soil and wind conditions.

Tree Characteristics

The crown

The drag, i.e., the load of the wind on the crown, depends on the speed of the wind (V), as well as the frontal area, permeability, and flexibility of the crown. With rigid structures, drag increases linearly with V^2. However, with certain 7-m-tall conifers with flexible branches the drag was found to increase in proportion to V, because the crowns became more and more streamlined as wind speeds increased (Fraser 1964). In these conifers, drag could be estimated satisfactorily from V and the weight of the crown.

Tree height

The incidence of wind damage tends to increase as tree height increases (Brünig 1974; Ford 1978). A. W. Simpson (cited by Mitscherlich 1972) found that in one situation the percentage of Sitka spruce uprooted increased from 0 at 10 m height to 100% at 25 m height. The critical height (below which only minimal damage occurs) varies with soil conditions, tree species, and wind speed (Fraser 1965).

Vulnerability to wind damage does not necessarily increase throughout the life (or height range) of a species (Ford 1978). In a study by Cremer *et al.* (1977) the vulnerability of *P. radiata* up to 45 m tall did not increase with height above 30 m. These trends could be due partly to thinning histories, partly to the fact that height growth declines faster than diameter growth as the trees mature, and partly to the fact that the strength of the wood increases with age (Harris 1981).

The increasing incidence of wind damage with increasing tree height is attributed to three factors. Firstly, as height increases, so does the turning moment at the base of the tree, and it is this which is critical, at least for uprooting. Secondly, as wind speeds increase with height above open ground and within and above the crown space of forests (e.g., Raupach & Thom 1981), so individual trees which are taller than their neighbours are subjected to more wind. Thirdly, and most importantly, trees in fully stocked plantations do not increase proportionately in diameter while they are growing rapidly in height, and their apparently increasing slenderness makes them more and more vulnerable to both stem and root failure (see below).

Stem strength

The strength of a cantilever of circular cross-section, i.e., its ability to support a static load at its free end, is directly proportional to the cube of its diameter (d^3) and inversely proportional to its length (l). The shape of the most economical cantilever, i.e., one of uniform resistance throughout its length, is that of a third-degree paraboloid, so that d^3 plotted against l forms a straight line (where l is the length between the free end and the point at which d was measured). K. Metzger (cited by Larson 1963) and others have argued that the shape of the stem from above the butt swell to the base of the crown does indeed approximate a cantilever of uniform resistance. This is consistent with our observation that when *P. radiata* is broken by wind, the break may occur anywhere above the butt swell. More detailed evidence indicates that the form of tree stems tends to most closely resemble a second-degree paraboloid (Gray 1956).

The stem's strength depends on the development of buttresses, butt swell, and stem eccentricity as well as the intrinsic strength of the wood. It is important to note in this context that the density (which is closely related to strength) of *P. radiata* wood is lowest near the pith (irrespective of age or height above the ground) and increases by about 50% in the first 15 to 20 growth rings (Harris 1981).

Defects which significantly diminish the strength of *P. radiata* stems in Australia are forks or double leaders, cankers caused by the fungus *Diplodia pinea* (Desm.) Kickx, and whorls of numerous large branches. Forks are by far the most important of these, and are the cause of much stem breakage.

In view of the importance of sway and the dynamic nature of the loading in gusty winds, the elastic properties of tree stems could be especially important. Little is known, however, on this aspect of stem strength (Papesch 1974; McMahon 1975).

Root-soil anchorage

The ability of a tree to resist uprooting depends on (1) its root system, (2) the way roots and soil have combined structurally in the given situation, and (3) the current condition of the soil, mainly its moisture content. Except in sands, trees usually form a "root-ball" when they grow large, i.e., the roots and soil tend to modify each other and form a structure which is considered to be important to anchorage (Mitscherlich 1974).

The development of the roots and of the root-ball are influenced by stocking, by the size of the tree, and by above- and below-ground growing conditions (especially drainage and depth of soil penetrable by the roots). The turning moment at the base of a tree required to uproot the tree has been found to be closely related, within a given soil type and moisture condition, to the amount of roots; for a given tree size, this turning moment was markedly higher on sites which were deeply penetrable by the roots than on sites where penetration was only shallow (Fraser & Gardiner 1967; Faulkner & Malcolm 1972). In some situations root grafting may also be important for anchorage. On some sites, deep ripping may improve the anchorage of trees planted in the rip lines (Somerville 1979).

Effects of Stocking on Tree Characteristics

Height growth

Despite its well-known sensitivity to site quality, the height growth of the dominant trees of a stand is not usually influenced by stocking, except at very low and very high rates of stocking. The subordinate members of a stand do, however, have their height growth suppressed progressively as competition increases with stocking and age. Because competition reduces diameter growth much more than height growth, suppressed trees look slender and give the false impression that they "reach for the light" or "are drawn up by the shade".

There is indirect evidence that the height growth of *P. radiata* can be markedly reduced at very low stockings, apparently as a result of increased exposure to wind. In three 30-m-tall stands, the trees at the edge were found to be 24% shorter than those growing within the stands (Cremer *et al.* 1977). Similarly, in a 9-m-tall stand, the trees at the margin facing the prevailing winds were 24% shorter than the interior trees, but the effect at the opposite margin was much less (K. W. Cremer, unpubl. data.).

The above observations are supported by six Australian spacing trials with *P. radiata* (Appendix 1) although these did not cover sufficiently high or low rates of stocking to produce marked variations in the height growth of dominants. In South African trials with four pine species, including *P. radiata,* heights of 12- to 15-m-tall stands were very little affected by stocking at 250–2000 trees/ha, except that mean heights were 11% lower at the very highest stocking (Craib 1947). Evert (1971) concluded from a wide-ranging review of relatively young conifer spacing trials, that dominant heights are usually little affected by stocking, except for some reduction at very high stocking rates on poor sites. Results from several spacing trials in Europe and America with Douglas fir up to 43 years old (24 m tall) also showed that top heights were not affected by stocking, except again on one very poor site where dominant heights were reduced at the higher stand densities (van Tuyll & Kramer 1981). In a number of spacing trials with conifers in Britain, top height was found to be marginally greater in the denser stands (Hamilton & Christie 1974).

Stem strength

The results of all the above spacing trials show that, once competition has started, the growth in stem diameters is markedly suppressed at higher stocking rates and that suppression becomes worse as competition increases with age or height. The effect is least on the dominants and greatest on the suppressed trees. As competition intensifies with age, the smaller trees are left more and more behind. In a row thinning experiment (Cremer & Meredith 1976) 3 years after thinning the average basal area of the smallest trees had increased by only 3% while the largest trees had grown 30%.

The increased diameter growth achieved at lower stockings is attributed not only to the fact that each tree gains better access to light (Fielding 1967), water, and nutrients, but also to the fact that its increased exposure to wind results in more swaying. Jacobs (1954) showed that the diameter growth of *P. radiata* stems was greatly reduced when these were guyed and thus prevented from swaying. Work with *P. taeda* and *Liquidambar styraciflua* L. (Telewski & Jaffe 1981) indicated that swaying increased diameter growth and decreased height growth. There is also some evidence that the development of buttresses and root brackets is enhanced by swaying, especially towards the lee of the stem in relation to the prevailing winds (Pryor 1937). Increased exposure to wind may even enhance the growth of roots at the expense of the shoots (Whitehead 1968).

Increased exposure to wind thus tends to result in growth responses which improve stem and root strength and tree stability.

Thinning or stocking level may also influence the intrinsic strength of the wood produced. However, this influence tends to be small, compared with the influence on the quantity of wood produced, and it may be either positive or negative. In Western Australia, where moisture supply in summer is extremely limiting in dense stands of *P. radiata,* reduced stocking results in denser wood (McKinnell 1981). Where moisture during summer is less limiting, the response by *P. radiata* may be to produce less dense wood after thinning (Wood & Siemon 1981). Whether the density of conifer wood rises or falls after thinning may also depend on age and crown size (Elliott 1970).

Crown size

The well-known sensitivity of the crown to stocking is illustrated by data from a *Pinus resinosa* Ait. spacing trial (Stiell & Berry 1977) (*see* Table 1). The weight of a tree's foliage (F) is in fact usually closely related to the diameter of its stem (D), provided the tree is not overmature. In the example given in Table 1, F was proportional to D^2. In a thinning trial with *P. radiata,* F was proportional to $D^{2.5}$ for all treatments (Siemon *et al.* 1980). On a stand basis, the weight of foliage of five pine species, including *P. radiata,* was found to be proportional to stand basal area, i.e., to D^2, except at basal areas below 20 m^2/ha, where the more open-grown trees carried higher proportions of foliage (Siemon *et al.* 1980). As drag may increase in proportion to crown weight, drag may therefore also increase in proportion to D^2.

TABLE 1—Stand characteristics in a **P. resinosa** spacing trial

	6000 stems/ha	500 stems/ha	Increase
Mean tree height (m)	9.4	9.7	Nil
Mean d.b.h.o.b. (cm)	9.9	21.3	× 2.2
Mean basal area/tree (cm^2)	77	356	× 4.6
Mean dry weight of foliage per tree (kg)	4.8	22.2	× 4.6
Mean crown length (m)	4.2	9.0	× 2.1
Mean crown width (m)	2.1	4.9	× 2.3

Root development

The influence of stocking on root weight seems to be much the same as that on stem diameter and crown weight. In two 36- to 39-year-old stands of *P. radiata,* root weights increased linearly with stem diameter (Heth & McDonald 1978). Jackson & Chittenden (1981) showed that in young *P. radiata* the weight of the roots was proportional to $D^{2.7}$.

The studies of Fraser & Gardiner (1967) on spruce in Great Britain indicated that root weight per tree increased strongly with decreased stocking, maintaining an almost constant ratio of about 0.3 to the weight of the stem plus crown. The ratio of root weight to stem weight did, however, vary markedly with soil type, from 0.38 to 0.61; the proportion of root weight **decreased** with increasing site productivity. It was also noted that root spread increased markedly with lower stocking, and that depth of rooting was on some sites related inversely to spread of rooting. Somerville (1979) reported that deep ripping in a gravelly soil increased the depth but did not affect the weight of the roots of 11-m-tall *P. radiata.*

These indications that root and stem development are closely related support the observations that stems resistant to bending or breaking also tend to be resistant to uprooting (Kennedy 1974; Cremer *et al.* 1977).

Breakage of stems and roots during wind is sometimes strongly related to the existence of decay at the point of breakage (Bazzigher & Schmid 1969) but, although extensive decay of massive sinker roots has been noted in uprooted *Pinus caribaea* Mor. var. *hondurensis* Barr. & Golf. at Byfield in Queensland (K. W. Cremer, unpubl. data), neither root nor stem rot has so far been identified as an important contributor to windthrow in Australian conifer plantations.

AN INDEX TO THE RISK OF WIND DAMAGE

The three classes of hazard which determine the risk of wind damage are weather, site, and stand conditions. Weather, specifically wind and soil moisture, may vary rapidly with time. Site conditions are mainly permanent and include (a) soil type (drainage, penetrability by roots, mechanical strength properties, fertility), (b) geographic location (i.e., general incidence of wind and precipitation), and (c) topography (i.e., local modification of wind because of altitude, aspect, slope, exposure). In the United Kingdom, where site conditions are particularly important, a windthrow hazard classification for sites has been developed (Booth 1977). No such scheme exists in Australia, though it is recognised that the risk of uprooting is particularly high on some soil types (e.g., Turvey 1980). In outlining the optimum thinning range for *P. radiata* in South Australia, Lewis (1963) provided a first guide to the risk of wind damage in relation to thinning. He warned against thinning overstocked stands and against reductions in stockings to excessively low levels.

The present paper deals only with stand conditions, i.e., with features subject to change with growth and silvicultural treatment. The important effects of stand configuration on wind loading can be dealt with only superficially at present, as too little is known about this. The following therefore deals mainly with variations in resistance to given wind loads. Moreover, unless otherwise specified, only resistance to stem failure is dealt with, because most of the information relates to this. Fortunately, the indications are that, except on sites where root development is extremely restricted, resistance to stem failure is at least broadly correlated with resistance to root failure.

European foresters (e.g., Erteld 1978) have used the height/diameter ratio as a measure of risk of wind and snow damage. Although they do not appear to have any detailed justification for this index, they have found lately that there is indeed some correlation with incidence of damage (Brünig 1974; Faber 1975; Johann 1981). They have calculated the height/diameter ratio in several ways, but mostly from the mean height and diameter of all the trees in the stand.

The Height/Diameter Ratio

In the present analyses, both height (H) and diameter (D) were calculated from the mean height and the mean d.b.h.o.b. of the 200 largest stems/ha, i.e., H_{200L}/D_{200L}. It would not have been appropriate to base the calculations equally on all the trees, because the smaller trees are far less significant than the dominant trees in determining the stability of the stand, and selective removal by thinning of the smaller trees would at once boost the ratio and thus wrongly suggest that the risk was lowered.

In Australian forestry practice it might be preferable to use H_{50T} (the mean height of the tallest 50 trees/ha) rather than H_{200L}, because data on the former are far more commonly available. However, we preferred H_{200L} for our calculations, because H_{50T} would have given us only four trees per plot. We have presented a correlation between H_{50T} and H_{200L} in Appendix 2 and have used this to give our conclusions in terms of H_{50T}/D_{200L} as well as H_{200L}/D_{200L}.

Alternative Indexes

The following ratios were examined: H/D^3, H/D^2, H/D, and $H^{3/2}/D$. The first, H/D^3, relates to the strength of a cantilever of uniform resistance (as described previously). The second, H/D^2, is more closely related to the shape of the tree's stem (Gray 1956). The third, H/D, is intended to take account of the fact that, although the strength of the stem decreases in proportion to H/D^3, the load of the wind increases with increasing crown size, and hence D^2. From an engineering analysis of conifers loaded with snow, Petty & Worrell (1981) identified the H/D ratio as "the most important factor likely to influence stability". This ratio has indeed shown good correlation with the actual incidence of stem bending or breakage due to snow damage (Cremer *et al.* in prep.). The fourth, $H^{3/2}/D$, gives the greatest relative weight to tree height; it may relate best to elastic strength properties (McMahon 1975) and might thus best reflect the tree's ability to withstand dynamic loads.

The merits of the above four indexes as measures of risk were examined by assessing the way their values varied with tree and stand conditions and how this variation matched expected variations in stability. Trends in the index values were examined with variations in (a) d.b.h.o.b. of open-grown trees, (b) d.b.h.o.b. of trees within a stand, (c) stand height and age, and (d) stocking. The values of H_{200L}/D_{200L} were correlated with actual experiences of wind damage.

Two indexes, H/D^3 and H/D^2, were clearly unsuitable. The first, H/D^3, is unsuitable even on theoretical grounds, as it takes no account of the increase of drag which accompanies increase in crown size, which accompanies increase in stem diameter. Neither index was in fact correlated with the incidence of stem damage observed by Nielson and Pataczek (see below). Both indexes showed trends inconsistent with known trends in risk: (a) open-grown trees are highly stable at all sizes, yet there were strong and extremely strong decreases, respectively, in the values of H/D^2 and H/D^3 with increases in tree size; (b) in unthinned stands, risk increases with height up to about 30 m, yet the values of H/D^2 and H/D^3 decreased with stand height.

The calculated trends in the values of H/D and $H^{3/2}/D$, on the other hand, were both consistent with expected trends in risk with stocking and age. The H/D index appeared to be preferable, however, on the basis of the observation that in open-grown trees H/D values remained constant with increase in d.b.h.o.b. while $H^{3/2}/D$ declined steeply.

Relations between H/D Values and Incidence of Stem Failure

As we preferred H/D to $H^{3/2}/D$ and as the height/diameter ratio had already been used in Europe, we decided to further test the H/D ratio as an index of risk.

W. A. Neilson and W. Pataczek (pers. comm.) of the Forestry Commission of Tasmania have made a valuable study relating stand parameters in a recently thinned plantation of *P. radiata* to the frequency of bent and broken stems after winds gusting up to about 100 km/hr during January 1980. Damage on the 35-ha area ranged from slight to complete. Dominant heights were 22–30 m. Thinning 5–24 months previously had reduced the stocking from about 1200 to about 300 stems/ha. From data on the mean height and the mean d.b.h.o.b. of all trees measured on ten 0.08-ha sample plots it was found that the percentage of severely bent and broken stems was not significantly related to H alone, nor to H/D^2 or H/D^3. However, significant positive correlations were obtained with $H^{3/2}/D$ alone, with H/D alone, and with H/D plus H. The last correlation was best ($R^2 = 0.80$) and indicated that the risk of wind damage increased both with the value of H/D and with H. A simple linear correlation between damage and H/D values indicated no damage at H/D values below 74 and complete damage at values above 90 with dominant height averaging 25 m.

In a spacing trial at Bussell's Plantation (Fig. 1) the intensity of damage in different plots ranged from 0 to 100%. The intensity of damage increased with rises in stocking and decreased with rises in stem diameters. A positive linear correlation was obtained between the percentage of trees badly bent or broken and H/D values ($R^2 = 0.85$). H/D values (or stem diameters) thus exerted a far stronger influence than stand configuration: in the four treatments, stockings were 747, 1076, 1682, and 2990 stems/ha; basal areas were 34, 37, 43, and 44 m^2/ha. respectively; and damage averaged 3, 25, 72, and 75%, i.e., damage was lowest where the canopy was least dense. These results are based on 12 sub-plots of 36 trees each. The corresponding results for the 12 full 0.08-ha plots were 12, 20, 38, and 70% damage, respectively, and show a more regular trend.

The distribution of damage within each of the above plots was ,however, not obviously related to either the diameters or the H/D ratios of the individual stems. For instance, the 17- to 20-cm-diameter trees exhibited 0, 33, 71, and 69% damage in stands where the over-all damage levels were 3, 26, 72, and 75% respectively. It was thus mainly the slenderness of the dominants (H_{200L}/D_{200L}) which determined the frequency of stem failures in this violent wind.

Results similar to those in Fig. 1 were obtained also with snow damage near Batlow (Trial B in Appendix 1). There was positive linear correlation between the

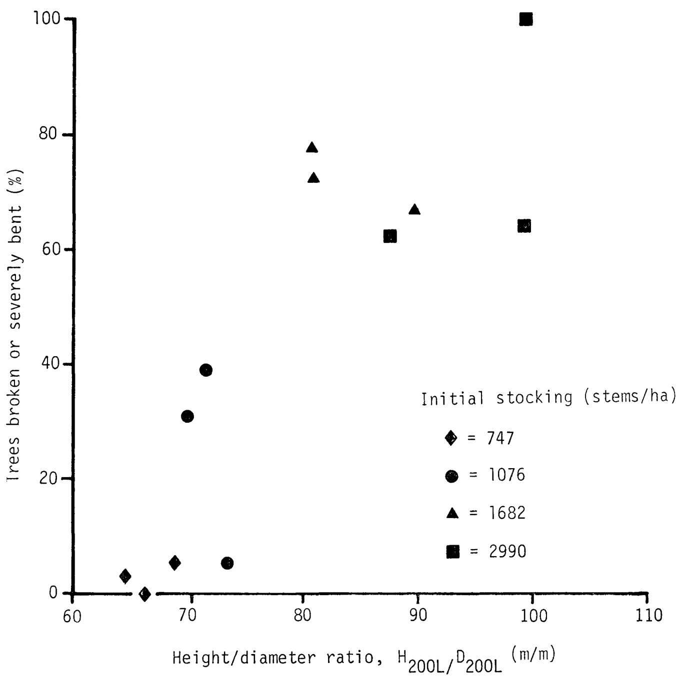

FIG. 1—Height/diameter ratios in relation to damage caused by Cyclone Alby in a spacing trial with ***P. radiata*** at Bussell's Plantation in Western Australia (Age 10 yr; Hd = 20 m; for other details **see** Trial C in Appendix 1)

percentage of trees badly bent or broken and H/D values ($R^2 = 0.86$) (Cremer *et al.* in prep.). Susceptibility to stem damage was thus correlated with H/D values, irrespective of whether the damage was due to wind or snow.

Another experiment in the Bussell's Plantation (Table 2) tested the effect of three regimes with and without thinning. Damage was 70% in the unthinned plots and negligible for the most intensive thinning regime, even though the canopy here was the sparsest and the last thinning had been done less than a year before the cyclone. Again, factors that were related strongly to H/D values were more important than the opening or roughness of the canopy in determining risk of stem damage.

The above results from small experimental plots are supported by observations of large-scale treatments in Western Australia.

The incidence of damage was related also to other parameters such as stem diameters, tree heights, crown size, root development, stocking, stand basal area, and canopy density or surface roughness. However, none of these other parameters taken individually could possibly provide a useful measure of risk of wind damage, though some combinations of them certainly would. The combination of height and diameter in the H/D value was proved to be valuable in providing a first indication. Better measures of such risk should be attainable with further work.

TABLE 2—Height/diameter ratios of 18-year-old **P. radiata** in three silvicultural regimes at Bussell's Plantation, and incidence of severely bent or broken stems after Cyclone Alby
(Means of 8 replications; Trial C in Appendix 1)

Silvicultural regime (stems/ha, and age at thinning)	Trees damaged (%)	Stand basal area (m^2/ha)	D_{200L}* (m)	H_{200L}/D_{200L} (m/m)
1. No thinning (1100 stems/ha)	70	38	0.25	109
2. Moderate thinning (1100→750 at 11 yr,→500 at 17 yr)	34	26	0.29	95
3. Heavy thinning (1100→750 at 6 yr, →200 at 11 yr, →125 at 17 yr)	7	13	0.36	80

* D_{200L} = mean d.b.h.o.b. (m) of 200 largest-diameter trees/ha
H_{200L} = mean height (m) of 200 largest-diameter trees/ha

Because risk of wind damage depends not only on the sturdiness of the tree population but also on the aerodynamic properties of the stand, as well as on wind and soil conditions, only broad correlations can be expected between H/D values and the incidence of wind damage. Conversely, H/D values by themselves can provide only broad indications of risk.

Figure 2 shows H/D values in relation to various experiences of stem failure. Table 3 presents our tentative conclusions on relations between H/D values and the risk of stem failure. The data in Fig. 2 are not sufficient by themselves to warrant the suggestion that H/D values for a given level of risk will change with age or height. It may well be, however, that since the wood's strength increases strongly

TABLE 3—H/D values (m/m) at low and high risk levels for stem failure (based on Fig. 2 and the observations that isolated trees are stable and have H/D value of 38)

	Low risk				High risk			
	H_{200L}/D_{200L}	Equiv. H_{50T}/D_{200L} values			H_{200L}/D_{200L}	Equiv. H_{50T}/D_{200L} values		
Height, H_{50T}, (m)	>10	15	25	35	>10	15	25	35
Isolated trees	<45	45	45	45	>60	60	60	60
Sparse canopy	<65	72	70	69	>85	94	91	90
Dense canopy	<80	88	86	84	>100	111	107	106

- Values of H_{200L}/D_{200L} are here assumed not to change with height or age.
- Equivalent values of H_{50T}/D_{200L} were calculated assuming that H_{50T} was 16.6, 26.8, and 27.0 m when H_{200L} was 15, 25, and 30 m, respectively.
- The above values assume that the subject stand is not adjacent to clearcuts. Risk of damage is greater downwind of clearcuts.

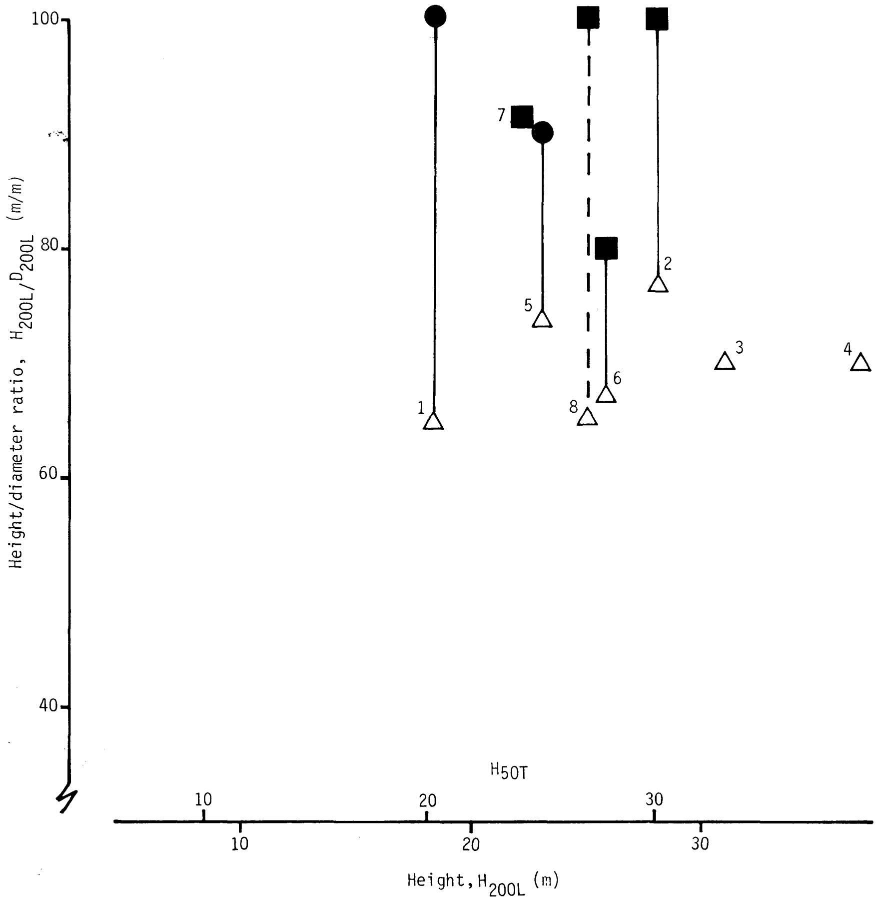

FIG. 2—Incidence of stem bending or breakage of **P. radiata** in relation to stand heights and height/diameter ratios

Δ = minimal damage

■ = 25–75% of trees damaged

● = nearly 100% trees damaged

1. Bussells' spacing trials (Fig. 1)
2. Bussells' thinning trials (Table 1)
3. Basal area trials at Grimswade and Mungalup in Western Australia (McKinnell, in prep.)
4. Well thinned, mature stands in south-west of Western Australia (McKinnell, in prep.)
5. Data from Tasmania (W. A. Neilson & W. Pataczek, pers. comm.)
6. Thinning trial at Carabost, New South Wales, damaged in January 1979
7. Routine plantations in Ovens Valley, Victoria, based on means in Table 2 of Sheehan **et al.** (1982)
8. Snow damage in thinning trial near Batlow (Trial B in Appendix 1). (In 1-7 damage was due to wind)

Wherever possible (i.e., items 1, 2, 5 and 8), the point of "minimal damage" was estimated by regression as the H_{200L}/D_{200L} value at which damage was 0-5%. Stands with minimal damage had sparse canopies. Stands with heavy damage had dense canopies, except for No. 5.

with age, H_{200L}/D_{200L} values indicating minimal risk will also change with age, e.g., from 65 at around 10 years to 75 at 30 to 40 years. Such a trend would be consistent with the results in Fig. 2.

Data relating H/D values with incidence of uprooting are far fewer. They suggest that the H/D values for a given risk of uprooting are lower than those for the risk of stem failure. The only substantial information on uprooting and H/D values is from a trial in Carabost State Forest, New South Wales. The three treatments (Table 4) were adjacent on a uniform site. The contrast between damage in Treatments 1 and 3 was ascribed mainly to influences related to H/D values. Treatment 3 had been thinned very heavily and very belatedly in 1980 and was uprooted entirely by wind when the soil was wet in winter 1981. Treatment 1, however, suffered no damage, even though it had a similar canopy. Its trees had become sturdier through earlier thinnings (including a light thinning just before the wind). Treatments 2 and 3, on the other hand, provided a big contrast in canopy density with only a slight difference in H/D values. Treatment 2 had never been thinned and suffered only slight damage. The rather high H/D value of 78 associated with no uprooting in Table 4 contrasts with occurrences of extensive uprooting near Canberra when H/D values in sparse stands were about 60–80.

TABLE 4—Uprooting (in winter 1981) of 23-year-old **P. radiata** in relation to thinning treatment and H/D values (means of five 0.024-ha plots assessed in 1981)

Treatment	Stocking (stems/ha)	BA (m^2/ha)	Height H_{40T} (m)	H_{200L}/ D_{200L}	Trees uprooted (%)
1. Thinned in 1974 and 1981	450	38	30	78	0
2. Never thinned	1500	54	29	88	5
3. Thinned in 1980 only	325	23	30	93	100

Variations of H/D Values with Age and Stocking

The value of the H/D ratio changes in time because of the relative changes in the increments of H and D. One factor in these changes is competition — as noted previously, competition has far more effect on D than it has on H. The second influence is developmental patterns. In mature trees height growth stops but diameter growth continues, and on poor sites the height of mature trees is less than that on good sites. Figures 3 and 4 illustrate typical patterns.

The H/D values were lowest in open-grown trees (Fig. 3), i.e., in the absence of competition, and these values did not change with age. At higher stockings, however, the H/D values increased strongly with both stocking and age, reflecting the effects of increasing competition. The increases in H/D values were most pronounced up to dominant heights of 20 or 25 m, i.e., to about the time of the first commercial thinning. At greater heights, stocking had little or no further effect, and the H/D values levelled off and even declined with further growth (*see also* Fig. 4). At this stage, growth patterns and site evidently exerted the major influence. The height at which H/D values reached their peak varied with site quality (*see* Appendix 1). It is emphasised

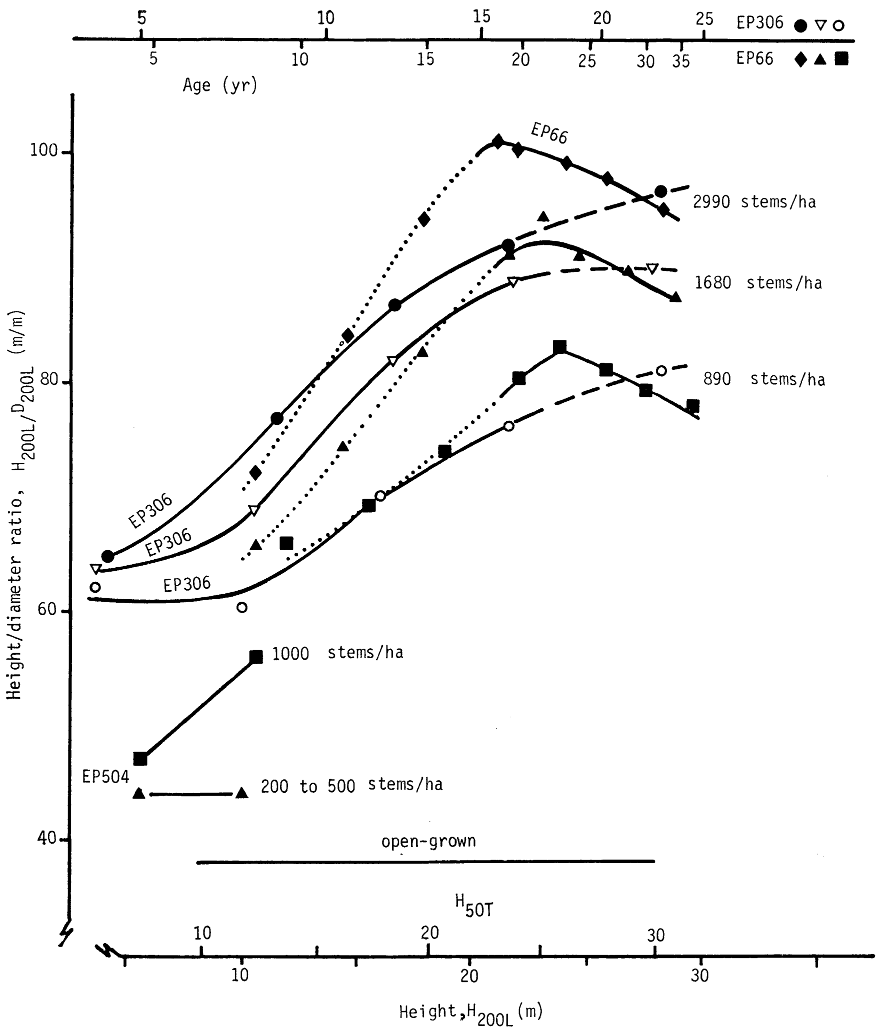

FIG 3—Variation of H/D values with age and stocking

For experimental details **see** Appendix 1. The open-grown trees were at corners of compartments in Uriarra forest. The dotted lines represent the interval when H_{200L} was estimated from Hd. The broken lines represent development after thinning to 25 m^2/ha; elsewhere, stockings are as shown.

that the maximum H/D values reached depended not on the ultimate intensity of competition (all of the stands would eventually be "fully stocked"), but on initial stocking, i.e., on competition during the early years of growth.

It is apparent that H/D values are affected also by thinning (Fig. 4). Heavier thinning naturally had a stronger effect than lighter thinning, but the timing of the thinnings was most important. The earlier the thinning, the more powerful was its influence on H/D values. Once dominant heights exceeded about 20 m, the effect of thinning was comparatively slight. Thinning according to the conservative schedules

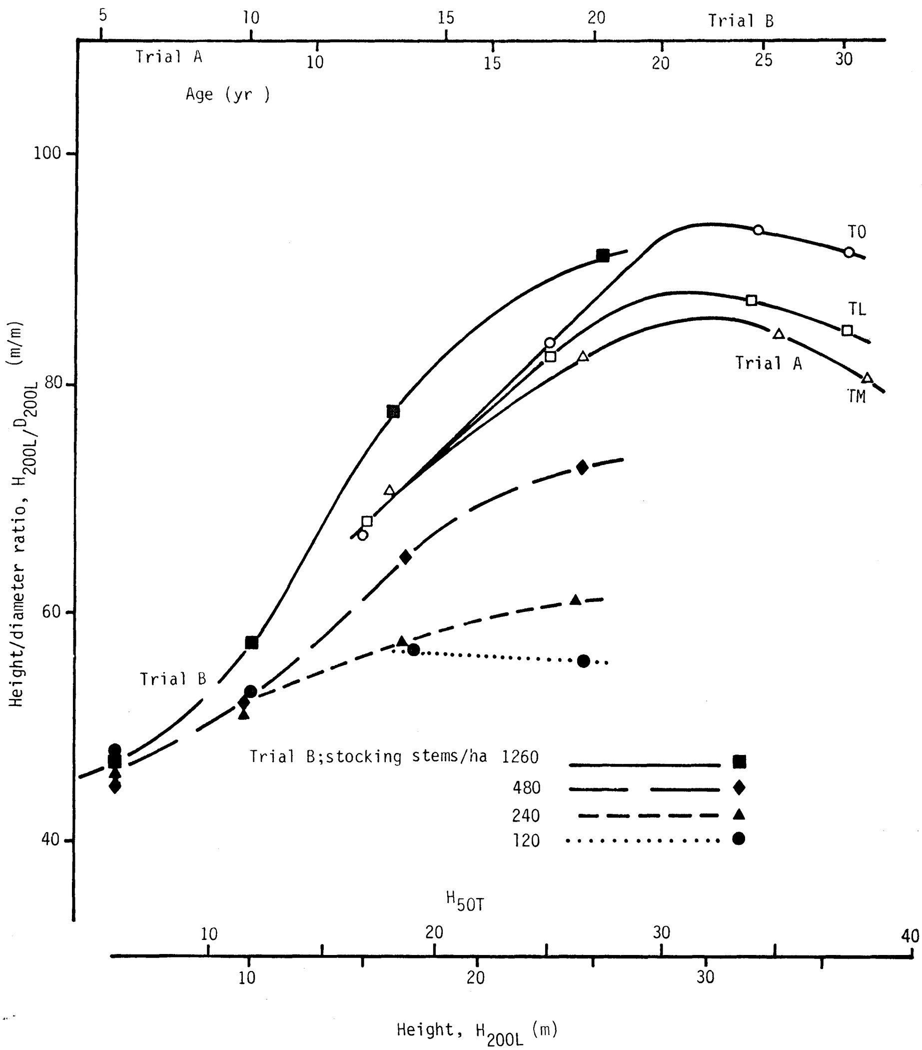

FIG. 4—Variation of H/D values with age and thinning treatments

Trial A: TO = not thinned, 1600 stems/ha

TL = lightly thinned, in four steps to 480 stems/ha*

TM = medium thinned, in four steps to 260 stems/ha*

Trial B: The final stockings, of 120 to 1260 stems/ha, were achieved by a series of much earlier thinnings, after planting at 2500 stems/ha (see Appendix 1).

* Conventional schedules, according to Lewis (1963)

most widely used in Australia (curve TM in Fig. 4) thus results in far higher H/D values than thinning by more radical schedules (e.g., Trial B, 240 stems/ha, in Fig. 4) which rely on earlier, heavier, non-commercial thinnings and aim primarily at sawlog production.

Thinning regimes aimed at specific H/D values may need to be varied according to site quality or fertility. The indications are that increasing nitrogen and phosphorus supplies lower the H/D ratio of young *P. radiata* by boosting diameter growth more than height growth (Will & Hodgkiss 1977; Snowdon *et al.* 1980).

DISCUSSION AND CONCLUSIONS

Thinning entails risk of wind damage in the short term. Thinning may indeed be totally inadvisable in stands which are already weak because of overstocking, and perhaps also in stands where root development is extremely restricted.

Except on sites where root growth is seriously restricted, the safest course is probably to give the trees as much growing space from as early as is compatible with other objectives of management. Growth at wide spacings also reduces the length of the rotation, and hence the over-all risk of wind damage, as damage tends to occur mainly with advanced height. Thinning after the stands have grown more than 20 m tall should preferably be light and frequent or should be avoided altogether.

Dominants have lower H/D ratios than suppressed trees, and are less likely to suffer wind damage when exposed after thinning than are retained suppressed trees. Thinning should therefore aim to remove suppressed trees and retain dominants. Because of this, and because of the difference in the roughness of the canopy, unselective thinning (e.g., row thinning) results in greater losses of stability than does selective thinning from below and cannot be recommended for sites where the hazard is high (Hamilton 1980).

Clearing should be avoided upwind of unstable stands (Cremer *et al.* 1977). Margins of stands should probably be especially pruned and thinned to make them highly permeable to wind and thus avoid extreme turbulence and promote wind firmness through growth responses to swaying Mitscherlich 1974; Fraser 1964).

The risk of wind damage is subject to very complex factors, including the stature of the trees, the aerodynamic properties of the stand, the general and local incidence of winds, and soil conditions. More work is needed on how to identify and quantify the sources of risk. Within the limitations described, the H/D ratio, calculated from the 200 largest diameter trees/ha, appears to provide a useful index of the level of risk (at least with respect to stem failure) at all heights and stockings. Probably the two most significant factors not accounted for in the H/D ratio are the aerodynamics of the canopy and the 50% increase in wood density (and hence in wood strength) which develops in the first 20 annual growth rings.

If, with the above provisos, the observed trends in H/D values (such as those in Figs 3 and 4) do indeed reflect trends in levels of risk of stem failure, then a number of interesting conclusions emerge:

(1) The benefits of growth at low stocking during the early years are permanent. Stands raised at low stocking do not attain H/D values as high as those raised at high stocking, no matter how long they are left unthinned.

(2) The trends in H/D values emphasise the paramount importance of growing space early in the stand's life (before 20 m height, in *P. radiata*). This importance had previously not been sufficiently appreciated. It is consistent with recent experience of wind damage in Western Australia. The earlier the thinning, the more effective it will be in keeping risk low.

(3) Risk increases with stand height, in agreement with general experience. However, risk does not rise greatly beyond about 25 or 30 m dominant height; this was previously only suspected. Indeed, risk may even decline at still greater height or age as H/D ratios decline and the intrinsic strength of the wood improves. This conclusion is also consistent with experience of wind damage, but was not previously suspected.

(4) Once H/D values have reached high levels, thinning is unlikely to reduce them; H/D values continue to climb to their peak, though thinning does reduce the amount of climb.

(5) Field experience (e.g., Cremer *et al.* 1977, McKinnell in prep.) suggests that *P. radiata* stands thinned after they have reached 20–30 m do regain considerable stability, and may do so in as little as 3–5 years. This is consistent with the H/D trends observed after medium and light thinnings only after the peak H/D values have been passed. Considerable stabilisation can, however, also be due to increase in wood strength with age, and due to increase in the canopy's density and smoothness with time after thinning.

(6) The most widely used stocking/thinning practice in Australia's *P. radiata* plantations has been to plant 1700 seedlings/ha and thin only after the dominant heights have reached about 20 m, or even 25 m. This leads to fairly high levels of the H/D ratio and risk. In some areas with high survival rates after planting, extensive serious wind damage has actually occurred, even before thinning and without extremely violent winds (e.g., Sheehan *et al.* 1982).

(7) The recent adoption in some areas of lower initial stockings and of much earlier and much heavier thinnings, aimed at producing mainly sawlogs in shorter rotations, leads to far lower H/D values and much lower risk, a conclusion well supported by experience in Western Australia.

(8) As a rule of thumb, we suggest that a thinning regime aimed at high stability, as well as high sawlog production, should seek to provide the trees with a minimum average growing space (in square metres) equal to the dominant height (in metres) of the stand. This stocking range lies just below the optimum thinning range advocated by Lewis (1963). Lewis' warning about "risk of severe wind damage" applies only if the soil greatly restricts root development or if the stocking rates advocated by us are achieved by thinning after the stands have grown overdue for thinning.

In view of the widespread similarities in observed relationships between wind damage and stocking or thinning, and since responses to stocking are qualitatively similar in most tree species, we suggest that the conclusions presented in this paper on relations between risk of stem failure due to wind and the influences of thinning, stocking, and stand development probably apply, at least in broad principle, to even-aged stands of many tree species.

Finally, to retain perspective, it must be said that the risk of wind damage in Australian plantations is generally not very high, compared, for instance, with England or the Canterbury Plains in New Zealand. In Australian plantations, the winds, poor soil drainage, and high stocking are rarely extreme, and *P. radiata* is a very flexible species. Though consideration of the risk of wind damage is clearly needed, a wide range of stocking/thinning options does remain available.

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APPENDIX 1

DETAILS OF *P. RADIATA* SPACING AND THINNING TRIALS

(all plot sizes are net, i.e., excluding buffers)

Trial		Location	Year planted	Site			Design			Treatments	
No.	Name			Ann. rainfall (mm)	Site index (Hd at 20 yr)	Site qual. (S.A. scale)	Plot area (ha)	No. of replications	No. of treatments	Stocking established (stems/ha)	Thinnings (AT = after thinning)
A	AFS plots Uriarra Cpt 135	Uriarra near Canberra	1941	1200	29	II	0.08	1 or 2 unreplicated, adjacent	3	1600	Year 1953 1958 1963 1971 Hd (m) 17 26 32 38 Stems/ha AT 1600 1600 1600 1600 Stems/ha AT 1090 870 620 480 Stems/ha AT 840 610 360 260
B	CCT Trial Green Hills	Green Hills Batlow, NSW	1960	1300	27	III	0.09	3 randomised block	8	2000	2470→1260 (at Hd = 2 m)→940(6)→730(8) →480(10)→360(13)→240(17)→120(18). Mortality negligible, except at the highest stocking (= 17% deaths).
C	Bussell Brook Spacing Trial	near Collie, WA	1968	1050	32+	I+	0.09	4 latin square	4	749 1077 1683 2990	No thinning; negligible mortality. The data presented are based on sub-plots of 36 trees each. The fourth replication was lost because of premature salvage logging.
D	EP66	Mount Burr SA	1940	700	23	VI	0.08	3 randomised block	6	890 1076 1329 1682 2197 2990	No thinning; mortality by age 35 ranged from 4% at 890 stems/ha to 15% at 2990 stems/ha.
E	EP360	Corree near Canberra	1958	1200	29	II	*	3 randomised block	6	890 1076 1329 1682 2197 2990	All plots thinned in 1974 to uniform basal area of 25 m^2; negligible mortality. *25 trees/plot
F	EP306	Kowen near Canberra	1971	600	25?	V?	>0.5	3 to 6 not random, adjacent	5	1000	Thinned at 3 years to 100, 200, 300, 500, 1000 stems/ha. No mortality. Planted on fertilised pasture site of low quality.

APPENDIX 2

CONVERSIONS BETWEEN DIFFERENT MEASURES OF STAND HEIGHT AND DIAMETER

This is to assist in the estimation of H_{200L}/D_{200L} from alternative information.

A. Heights

(1) Definition of "dominant height", Hd

We calculated this as H_{50T}, i.e. the mean height of the 50 tallest trees per hectare, following the practice of the forest services in Victoria, Tasmania, Western Australia, and Queensland. However, A.C.T. and New South Wales use 40 trees/ha, and South Australia 75 trees/ha. In Victoria the tallest 50 are identified from the heights of the 75 largest diameter trees.

If, in our plots, the number of trees needed to estimate H_{50T} came to a fraction, e.g., 9.6 trees per plot, we added 0.6 of the height of the tenth tallest tree to the sum of the heights of the nine tallest trees, and divided the total by 9.6. (H_{200L} and D_{200L} were calculated similarly, using fractions as above.)

In field practice, it would be sensible to estimate H_{50T} at each sampling point by measuring the heights of the three tallest looking trees per 400 m² sample area and then averaging the height of the two tallest individuals.

(2) H_{50T} **v.** H_{200L}

$[H_{50T}] = 1.55 + 1.017\ [H_{200L}]$ ($R^2 = 0.99$; 60 pairs of observations)

Data from spacing trial EP136A, Uriarra, site quality IV, based on measurements at four ages (heights 15–35 m) on each of 15 plots; three replications × five spacing treatments. As the net plot area was only 0.04 ha, 50 and 200 stems/ha represented only two and eight trees per plot, respectively.

H_{50T} at 15–35 m was thus about 2 m taller than H_{200L}. The horizontal scales of Figs 2 to 4 show the conversion graphically. Data from Western Australia indicate that the difference in heights may be less, about 1.5 m.

B. Diameters

(1) D_{50T} **v.** D_{200L}

$[D_{50T}] = -6.87 + 1.26\ [D_{200L}]$ ($R^2 = 0.91$; 60 pairs of observations)

Data from trial EP136A, as above, for diameter range of 20–60 cm.

(2) Estimation of D_{200L} from mean D of all trees.

Figure A1 presents harmonised results, based on data from spacing experiments EP63 and EP306 (**see** Appendix 1) obtained from measurements at eight ages.

Linear regressions of D_{200L} on mean D at each of six spacings (with 24 data pairs for each spacing) were calculated ($R^2 = 0.93$). The values from these of slope and Y-intercept were plotted against stocking, and fitted with straight lines to yield the parameters used in plotting Fig. A1.

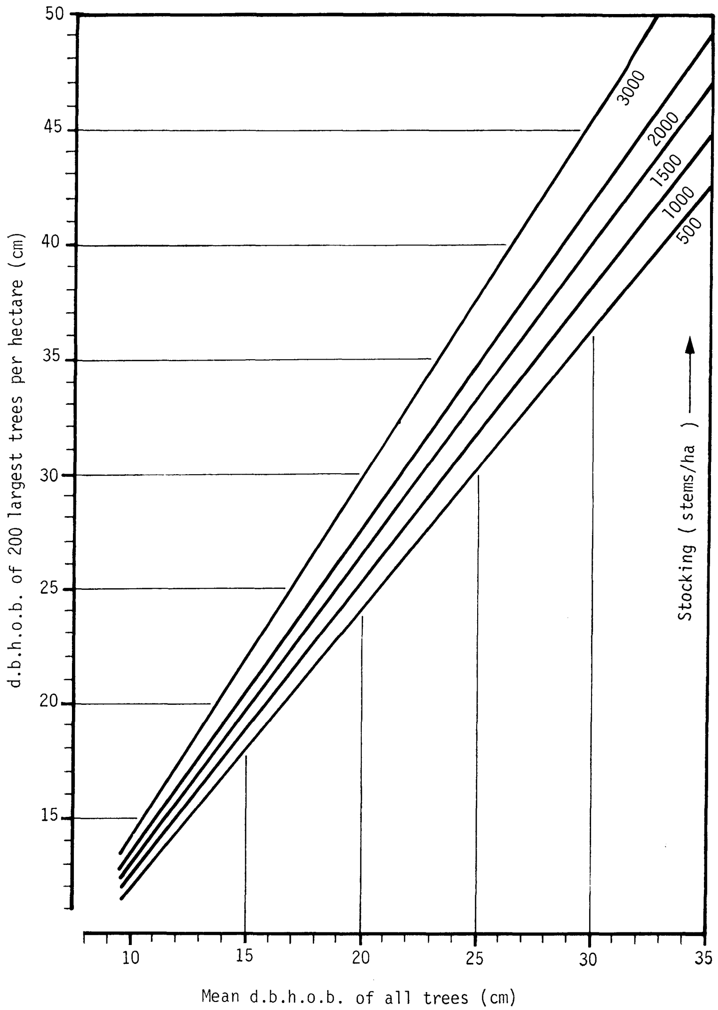

FIG. A1—Estimation of mean diameter of 200 largest stems/ha from mean diameter of all trees in plantations of **P. radiata** established at stockings of 500 to 3000 stems/ha.