New Zealand Journal of Forestry Science Vol. 10 No. 3 (1980): 476-501

WIND STABILITY: FOREST LAYOUT AND SILVICULTURE

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A study was made of aerial photographs that showed wind damage in **Pinus radiata** stands on the Canterbury Plains and in Kaingaroa State Forest. This study revealed a consistent and characteristic pattern of wind damage associated with exposed stand edges of closed canopy stands. These exposed edges resulted from forest margins, abrupt increases in stand height of at least 5 m, and breaks of at least 40 m confronting the oncoming damaging wind. The associated damage was usually concentrated in the first 100 m or 200 m of the stand downwind from these edges. This pattern of damage calls into question the safety of laying out stands in narrow strips with abrupt changes in height confronting a potentially hazardous wind, viz the "strip system" in Canterbury.

Additionally, it was observed that in widely spaced stands, before canopy closure, there was no apparent fall off in damage downwind from exposed edges; wind forces acting on trees evidently remain high over the whole stand. The adoption of wide spacings on sites prone to wind damage could result in stands being less wind stable for at least part of the rotation.

Where clearfelling in closed canopy stands has exposed a new face to a damaging wind, the consequent damage has often been severe, extending in long drives downwind. In some instances there appears to have been an upwind as well as a downwind exposure from clearfelling.

Thinning temporarily increases risk of damage. This, and increasing vulnerability with stand height, indicates that thinning should be done as early as practicable.

Butt log pruning can affect wind stability of young stands, but whether it has an advantageous or detrimental effect may depend on wind, stand, and site characteristics.

INTRODUCTION

Wind is a serious risk factor to conifer plantations in New Zealand. It also has serious implications for selection management of indigenous forests because growth rates are very slow and even slight losses can negate increment (Herbert 1980; A. E. Beveridge, I. James, and A. Griffiths, pers. comm.).

Some losses due to wind are never quantified or even recognised; for example, losses resulting from:

(a) Toppling of recently planted trees and consequent butt sweep.

(b) Stem malformation from leader loss.

(c) Changes in wood properties, including reaction wood and resin pocket formation, although the association of the latter with wind is not definitely proven (Clifton 1969; Cown 1973).

Received 7 January 1980; revision 2 September 1980

(d) Growth retardation.

(e) Increases in other risks such as fire.

(f) Attritional windthrow and stem breakage in stands.

Gale damage to forests, in the form of windthrow and stem breakage has occurred over much of New Zealand and the potential for future damage is high particularly in the Wellington, Canterbury, North Auckland, and Manawatu regions (Thomson 1976). Other regions also suffer significant losses; for instance, Chandler (1968) estimated that between 10 and 15% of the annual yield is lost as unsalvaged windthrow in the Tapanui district. Canterbury forests have suffered the most serious wind damage. In light of the catastrophic gales of 1945, 1964, 1968, and 1975 further gales causing up to thousands of hectares of wind damage could be anticipated every 10–20 years. Canterbury's problem stems mainly from the Föhn-type north-west wind. The problem is to some extent compounded by the region's relatively small-scale harvesting and processing capabilities which are inadequate to utilise quickly large quantities of wind-damaged material.

The shallow rooting soils of the Canterbury Plains restrict vertical root development and this limiting of root deevlopment has long been thought to increase stand vulnerability to wind damage. However, tree anchorage studies at Eyrewell State Forest (Somerville 1979) indicated that deeper rooting could result in a change in the type of wind damage from windthrow (or uproot) to stem breakage and would not effectively lessen overall vulnerability of trees to wind damage. Wilson (1976) observed increased breakage on the Canterbury Plains on the deeper soils closer to the inland foot hills. On the Canterbury Plains, wind damage is characteristically windthrow rather than breakage and trees often live for many years allowing a lengthy utilisation period. The longer this period is, the less upheaval there is to future supply. Deep ripping on these sites is aimed at increasing tree vertical root development. This may be a harmful practice as it seems likely that it will result in an increase in the potential for stem breakage. Wind damage in other parts of New Zealand is often characterised by a high proportion of stem breakage and degradation by insects and fungi is rapid. Where there is much stem breakage, harvesting of wind-damaged material may have to be completed within months.

This paper examines tree–wind stability aspects of forest layout and silviculture, reviewing appropriate literature and reporting relevant examples of wind damage. As background to this work, some broad concepts of wind behaviour in relation to the ground surfaces are firstly presented.

WIND BEHAVIOUR — SOME BROAD CONCEPTS

Properties of the large-scale wind system, the surface wind, and the effects of surface friction over a surface without mountainous relief, as reported in Gloyne (1968), are diagramatically presented in Fig. 1. Winds tend to follow the ground contours where slopes are gentle. Gloyne (1968) has suggested approximate limits for these slopes: windward slopes 20–25° and lee slopes 5–10°.

In Bull & Reynolds' (1968) discussion of wind structure over surfaces of varying roughness the following concepts are presented:

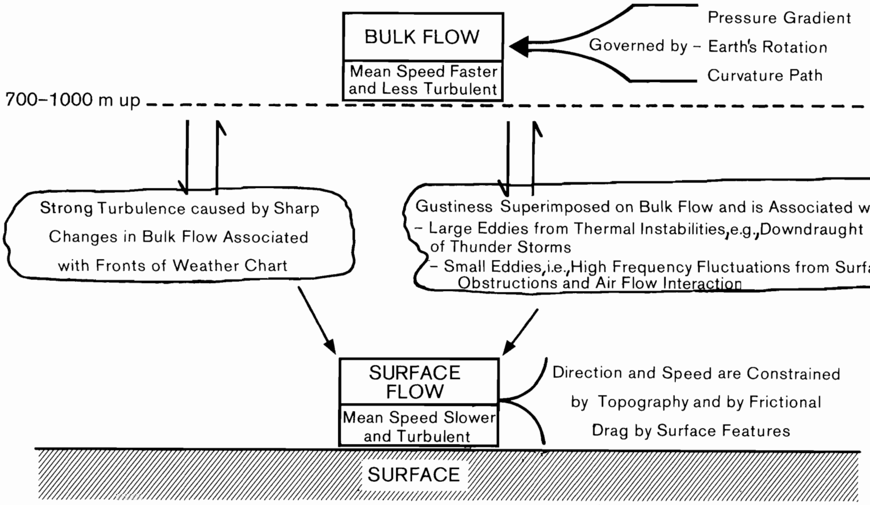


FIG. 1—Large scale wind system over a surface without mountainous relief (see Appendix 1 for definitions).

Any surface exerts a drag on the air stream. In a forest this arises primarily from "form drag" in which an obstacle produces a turbulent wake on its lee side. Wind applies force to the surface it contacts because of its momentum and the more turbulent the wind the greater this force. Air is naturally turbulent and the rougher the surfcae the more turbulent the air becomes. Eddies resulting from this turbulence are very effective at transferring energy vertically. Bull & Reynolds (1968) contend that windthrow is more affected by the turbulence component of wind structure than pure linear velocity; however, the two are closely related as eddies will quickly attenuate unless they are supported by a strong wind. The greater the turbulence generated by a rough surface, the more interplay there is between successive layers of air and the more effective the transfer of momentum downwards from the bulk flow above. The effect of a rough surface inducing turbulence is reflected in the wind velocity profile by a greater rate of increase of wind speed with height above that surface.

A. FOREST LAYOUT, THE "EDGE EFFECT"

A number of workers have examined forest edges with regard to the behaviour of wind and of trees under wind stress.

Fraser (1964) used wind tunnel simulations to examine static wind forces on model trees behind several edge types. Constant velocity wind was used and static force was measured by the bending moment at tree base. He found that forces on trees fell off rapidly in the first tree height back from the edge (or first 4 rows of trees) and by 2 tree heights back, had stabilised at a low level with foci of slightly higher forces near the front of the stabilised zone. Model stands with a thinned stand margin, a wedge margin, and a dense margin all showed a similar stabilising of forces downwind but without the foci behind the margin. The dense margin resulted in lower bending moments throughout the whole of the model stand.

Wind velocities near ground level were measured in a 600-m wide stand at the Affolter Forest in Solothurn canton, Switzerland (Nageli 1954, quoted by Mitscherlich 1974). There was a damming up of wind before the edge, a slight "jet effect" through the edge, a fall off in wind velocity through the stand, and an increase in wind velocity in the downwind margin. Changes in wind velocity within the stand are explained by air movement upwards in the stand's windward side and downwards near the leeside margin.

Mitscherlich (1974) presents a model of wind movement through and over a forest edge. In front of the edge there is a dammed up zone. Wind moves up over and also though the edge with strong eddies falling down on trees immediately behind the edge. Trees leaning leeward are more exposed to diagonal movements of air and are consequently pushed further groundward.

Eling & Elon (1978) examined wind damage in strips of *Picea mariana.* From 1949 to 1969 alternate strips, up to 40-m wide, had been removed to allow regeneration. Wind damage was assessed in 1972. Damage was correlated with length of exposed edge and normally occurred within the first 8 m of the stand.

Neustein (1971) examined wind damage in hilly Scottish forests. Of 115 recognisable starting points of damage, 51% could be attributed to some factor. Plantation edges, extensions of previous damage, roads, rides, and increases in height class accounted for this 51%.

McKenzie (1974) highlighted the danger associated with edge zones after conducting a survey of attritional damage that occurred from 1965 to 1969 and in 1974 in *Picea sitchensis* in Northern Ireland.

The "Redesdale Experiment", set up by the British Forestry Commission in Kielder Forest, examined changes in the structure of wind over a forest edge. Data recorded in 1970 and 1971 were analysed and interpreted by A. J. Papesch (pers. comm.). The study examined wind patterns in and above approximately 14-m high *Picea sitchensis* (Bong.) in two adjacent areas stocked at 2760 and 2220 stems/ha. Arrays of anemometers on towers were located outside the stand and approximately 13 m and 80 m behind the stand edge. Some of the relevant observations are given in Table 1. At the "open ground" tower upwind from the stand, wind speeds were greater over the full gust frequency range than at the within-stand towers. Wind at tree top level moved in from the edge, mean wind speed slowed down, and drag lessened. However, the wind also

TABLE 1—Changes in the structure of wind at 13 m and 80 m in from a stand edge

Wind	13 m downwind from edge	80 m downwind from edge
Drag	Higher than at 80 m downwind	
Mean wind speed near tree top level	Higher than at 80 m downwind	
Increase in wind speed with height above canopy	Sharp increase near surface	Slower increase
Energy and frequency of gusts		Shift towards higher frequency gusts and higher wind speeds associated with these gusts

assumed a more "excited" structure with more frequent gusts. It is not known if the wind structure reported at the 80-m towers persisted further downwind and the significance of the change to higher frequency gusts is uncertain.

Both White *et al.* and Papesch (pers. comm.) stress the significance of gust frequencies that correspond to the natural sway period of a tree. Such frequencies occur as wind moves over a stand and they are more likely to result in damage. Mayhead (1973) found the natural sway period of a tree increased with increasing tree size.

Downwind from the windward edge of a closed canopy stand, the mean wind speed and drag decrease and if energy transfer processes are stabilising, we might expect a fall off in wind damage potential. The following section examines this hypothesis.

STUDY OF WIND DAMAGE DISTRIBUTION

An initial examination of vertical aerial photographs recording wind damage in the Canterbury Plains forests from 1945 onwards revealed that certain stand edges had a characteristic pattern of wind damage that was consistently associated with them. The study involved recording the intensity and distribution of wind damage (from aerial photographs) behind these edge types, for all *P. radiata* stands that had partial wind damage and that met various homogeneity requirements.

Sites

This study examined wind damage in the following Canterbury Plain forests: Eyrewell and Balmoral State Forests, and the North Canterbury Catchment Board (NCCB) and Selwyn Plantation Board (SPB) forests totalling approximately 20 000 ha (Fig. 2). The following characteristics of these forests made the survey possible:

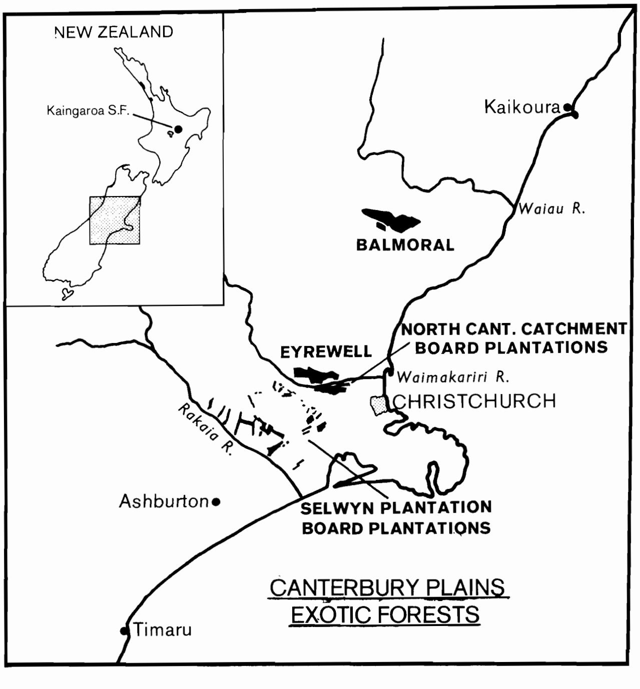


FIG. 2—Location of the Canterbury Plains exotic forests and Kaingaroa State Forest.

(1) There were large areas of untended *P. radiata.* Stands were planted at approximately 2000 stems/ha. Natural mortality reduced stockings to around 600 stems/ha by age 25–30 years.

(2) Aerial photographs were available of many instances of partial wind damage to stands. Table 2 outlines the events of wind damage that were examined.

(3) The topography was flat.

(4) Soil types within stands were constant.

(5) The stands were in large, homogenous, rectangular blocks, clearly outlined by roads, breaks, and changes in height class.

(6) Wind damage was from a relatively constant NW direction.

The western end of Balmoral Forest abuts a hill and gorge system and, because patterns of wind damage have reflected this topography, it was excluded from the study.

Observations were also made of storm damage in Kaingaroa Forest, in the central North Island, where a NW wind severely damaged 800 ha on 11 April 1979. Topography was generally flat to rolling and the pumice soil was apparently uniform within affected areas.

TABLE 2—Examples of wind damage examined in the "distribution of wind damage study"

Storm date	Wind direction	Maximum wind speed at Christchurch (km/hour)	Forest surveyed for damage	Available damage data
13.7.45	NW	145	Eyrewell, Balmoral, SPB	Several thousand ha scattered damage; 1500 ha with 70–80% damage at Balmoral
14, 21, 24, 26.3.64	NW	103, 111, 106, 56	Eyrewell, SPB	5200 ha damaged at Eyrewell
9–11.4.68	SW to W to NW	130 from W	SPB	Approaching 1000 ha partial damage, SPB and Eyrewell
1.8.75	NW	170	Balmoral, SPB, NCCB	2.2 million cu. m sawlogs windthrown. Around 11 000 ha damaged

Method

Three types of exposed windward edge were all associated with the same characteristic pattern of wind damage. These edges were created by:

(1) Open ground upwind (forest edge situation).

(2) A windward stand at least 5-m shorter than the damaged stand.

(3) A break at least 40-m wide with a similar stand upwind.

For the Canterbury Plains, stands of edge type 1 above were further stratified into younger than 25 years, and 25 years and over. On the better sites on the Plains, this corresponds to an approximate height boundary of 25 m.

The sample included only those stands of *P. radiata* uncomplicated by variations in relief, treatment, stocking, species composition, age composition, and other obvious infringements of the homogeneity constraint. It omitted stands that were totally damaged, previously damaged, and those exposed by recent clearfelling.

The downwind projection of each straight windward edge defined the study area in each stand. Each study area was divided into sections by projecting the windward edge, at 10-m and thereafter at 100-m intervals, measured downwind from the windward edge. The approximate percentage of windthrown trees was recorded (in categories of 0, 2, 10, 25, 50, 75, and 100%) for each section at least 250-m wide. Fig. 6A illustrates the definition of a sample area and the assessed percentage damage, by section, downwind from the edge. Grouping of data was complicated by the different levels of severity of damage between sample stands. However, since the study examined only the relative distribution of damage within stands and not absolute values, the problem was solved by accumulating data as follows:

For each section (or 100-m "distance interval") for a particular stratum:

$$\begin{array}{l} \text{Relative intensity of damage} \\ \text{(based on n stands' strata)} \end{array} = \frac{1}{n}\sum_{1}^{n}\frac{\text{Observed \% damage for section}}{\begin{array}{l}\text{Mean \% damage (based on first 5 100-m} \\ \text{intervals for that stand)}\end{array}}$$

Results

The distribution of wind damage within stands, by edge type and age stratum for Canterbury and for Kaingaroa, is illustrated in Figs 3 and 4, together with the number of stands and total length of edge on which each graph is based. Figs 5, 6, and 7 are examples of actual damage for each stratum.

Each edge type is identified as consistently inducing a high level of damage in the immediate edge zone of these closed canopy stands. There is a fall off in damage further downwind. In stands less than 25 years old, windthrow often began with the edge trees. In stands 25 years and over, there was often an intact margin of trees and the high damage zone extended up to several hundred meters downwind from the edge. These are mean patterns of damage and have been repeated with each gale, but exceptions certainly occur.

SPB and other forest owners on the Canterbury Plains have many narrow strips of stands, from 100-m wide upwards, that have been damaged by north-west winds. "Edge effect" patterns of wind damage were clearly evident in aerial photos, independent of strip width.

Eyrewell 1945 gale

The Eyrewell 1945 gale warrants special consideration as it proved to be a major source of data with large homogenous stands of partially damaged *P. radiata*. Fig. 8 outlines the wind damage: the solid line indicates edges that met the criteria as damage-inducing edges.

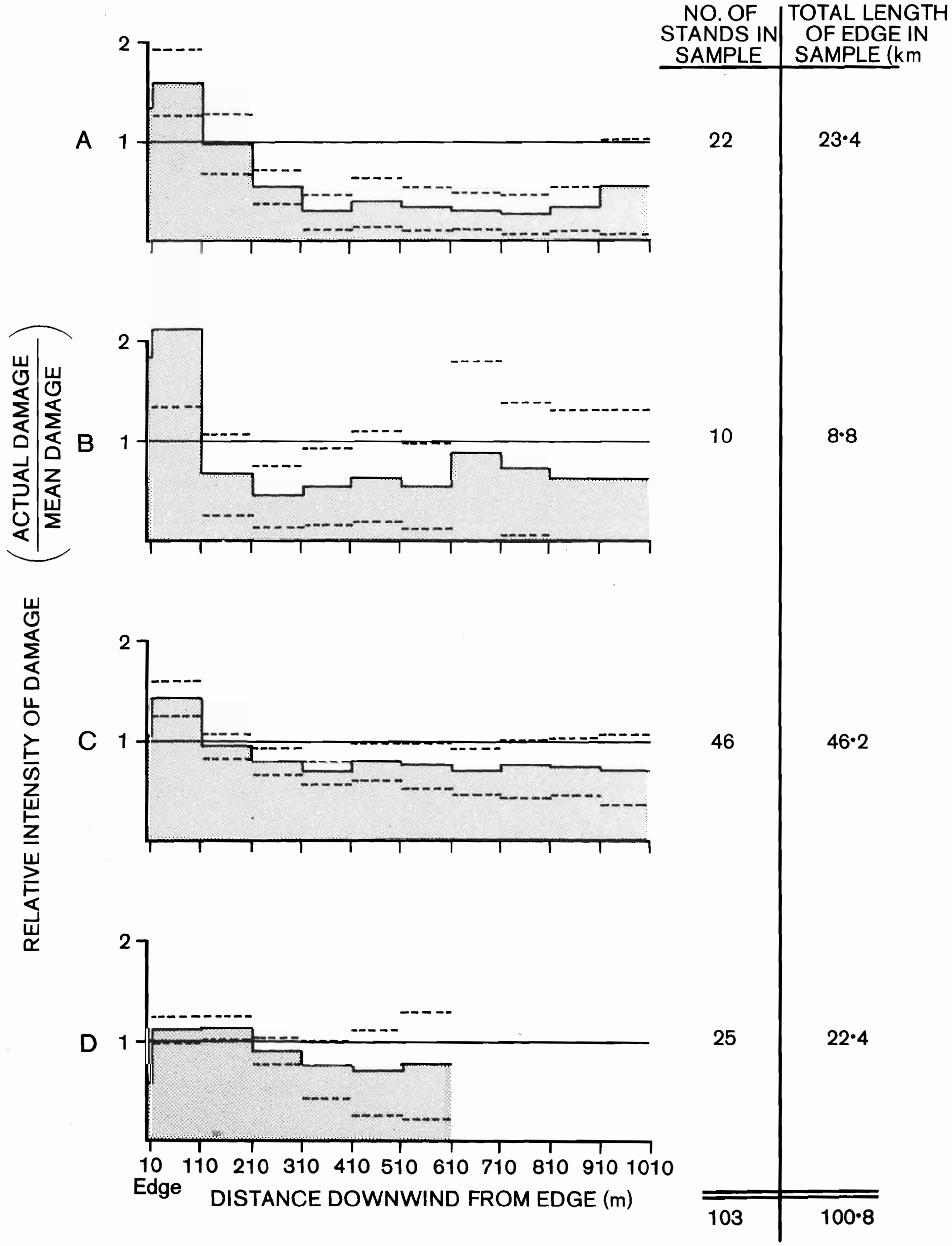
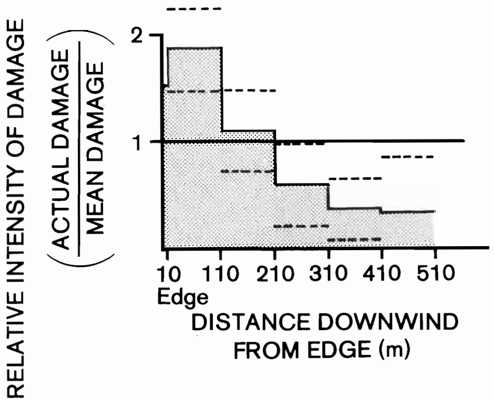


FIG. 3—Distribution of wind damage in Canterbury Plains forests in relation to exposed edges for the following strata: stands less than 25 years old with (A) open ground to windward, (B) windward stands at least 5-m shorter, (C) a break at least 40-m wide with windward stands of similar size; and stands over 25 years old with (D) open ground to windward. Means for strata and confidence limits, P = 0.05.



NO. OF STANDS IN SAMPLE	TOTAL LENGTH OF EDGE IN SAMPLE (km)
6	3·6

FIG. 4—Distribution of wind damage in relation to exposed edges for the 1979 gale in Kaingaroa State Forest. Means for stratum and confidence limits, P = 0.05.

An analysis was carried out on the % damage data, transformed by arc sin $\sqrt{x}$, for the 3 edge type strata, over the first 5 100-m intervals. Stands that did not have observations extending back for the full 500 m were omitted. A total of 43 stands with 54 km of edge and 215 sections or "distance intervals", with percentage damage observations, remained.

Sources of variation were examined in an analysis of variance (Table 3). The variation due to "study areas" and "section or distance interval downwind from the edge" accounted for most of the variability of the data. The latter source of variation was investigated further with the Least Significant Difference Test. The results are given in Table 4.

The 3 edge types are identified as causing high levels of damage in the first and second 100-m intervals downwind from the edge. No significant differences between edge types could be established.

Kaingaroa 1979 gale

For the Kaingaroa 1979 gale only 6 stands met the criteria for analysis; their mean relative distribution of damage is given in Fig. 4 and an example of damage is shown in Fig. 7. The heavy concentration of damage behind the edge is consistent with observations in Canterbury.

OTHER EDGE OBSERVATIONS

Clearfelling

There are numerous instances of wind damage downwind from clearfelling. Forest managers are very aware of the risk of exposing new edges. Such damage is often severe and can extend hundreds of meters downwind in long swathes. Fig. 9 shows wind damage in the 1964 storm at Eyrewell associated with clearfelling. Wind damage to previously damaged stands is not shown. Damage is severe and not bound by "edge effect" so that it occurs in long runs downwind. Damage links up clearfelling coupes in

FIG. 5—(A) 1945 wind damage in Eyrewell Forest. Open ground to windward. (B) 1945 wind damage in Balmoral Forest. Shorter stand to windward.

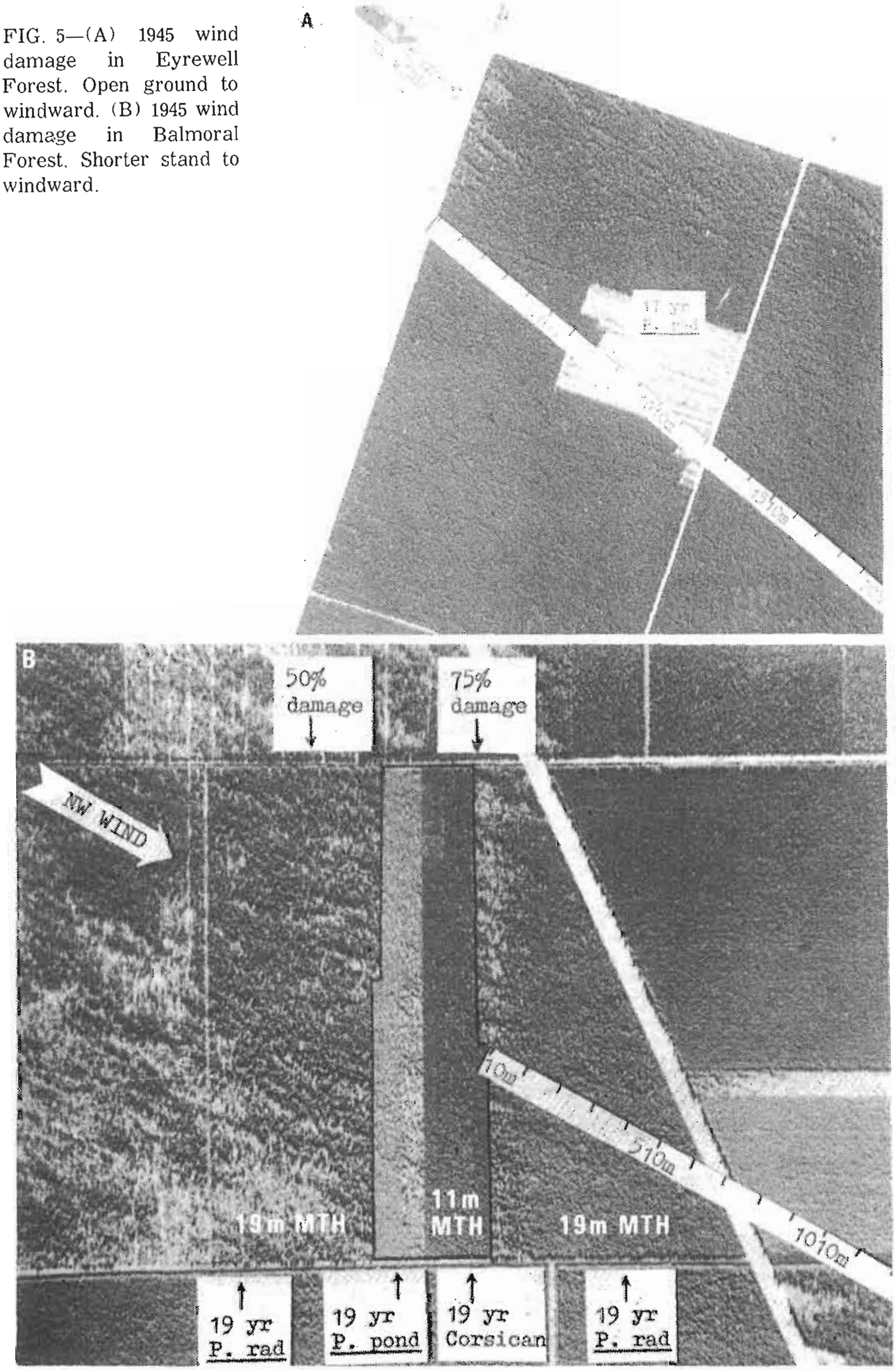


TABLE 3—Analysis of variance of distribution of wind damage data for Eyrewell Forest, 1945 storm

Source of variation	Degrees of freedom	F	Significance*
1. Edge type	2	1.5	NS
2. Study areas within types	40	11.6	0.001
3. Section or distance interval downwind	4	25.4	0.001
4. Interaction between (1) and (3) above	8	0.9	NS
Residual	160		
Total	214		

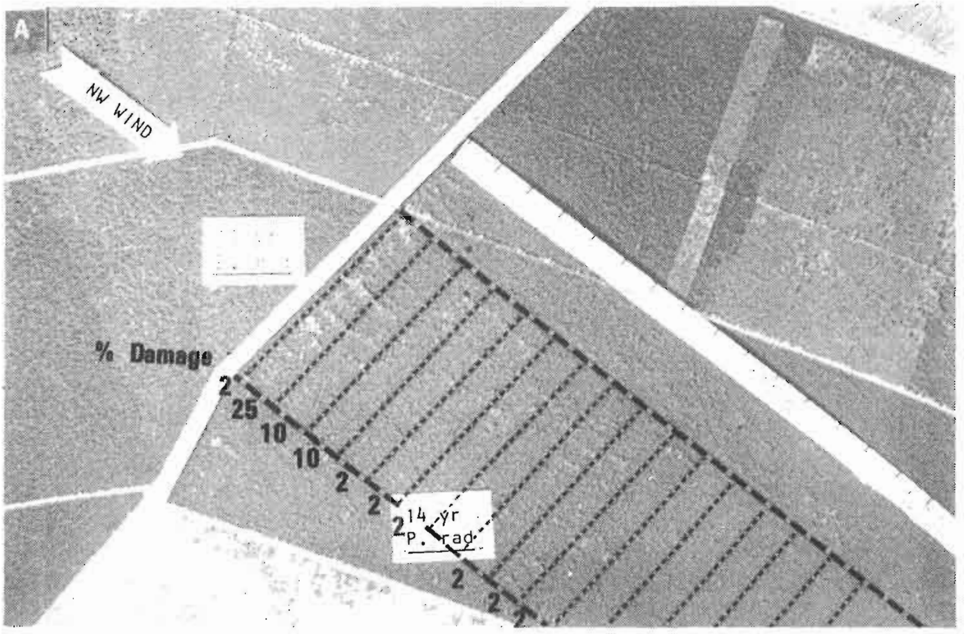
* NS — non-significant ($P > 0.05$)
0.001 — significant level of variation due to this source at 0.1% probability level.

TABLE 4—Variation in % damage observations by section or distance interval downwind from edge

100-m interval downwind from edge	Actual mean % damage for 43 stands	
1	25.4	a
2	16.4	b
3	12.0	c
4	9.9	c
5	11.4	c

Means followed by different letters are significantly different at 0.05 level.

Compartments 1, 6, 10; 5, 8, 9, 11, 12; 27, 32, 33; 28, 33; and 42, 43, 53, and extends upwind from clearfelling coüpes in Compartments 28 and 58, suggesting an upwind exposure as well as a downwind exposure from clearfelling. Fig. 10, although not an example of clearfelling, shows upwind exposure in *P. nigra* laricio (Poiret) at Kaingaroa, damaged in the 1979 storm. Damage radiates around the upwind side of a logging bay. Nageli (1954, quoted by Mitscherlich 1974) observed increases in wind speed in a stand, before the lee edge. This would be accompanied by air movement down into the stand which could help to explain this damage zone.



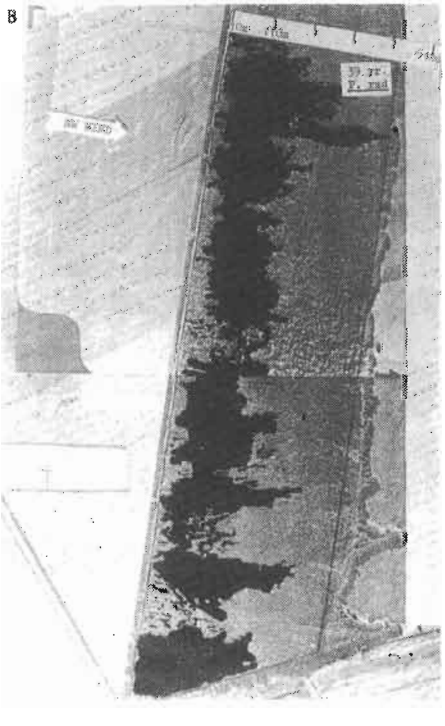


FIG. 6—(A) 1945 wind damage in Eyrewell Forest. Similar stand to windward. (B) 1954 wind damage in SPB. Open ground to windward. Stand over 25 years old.

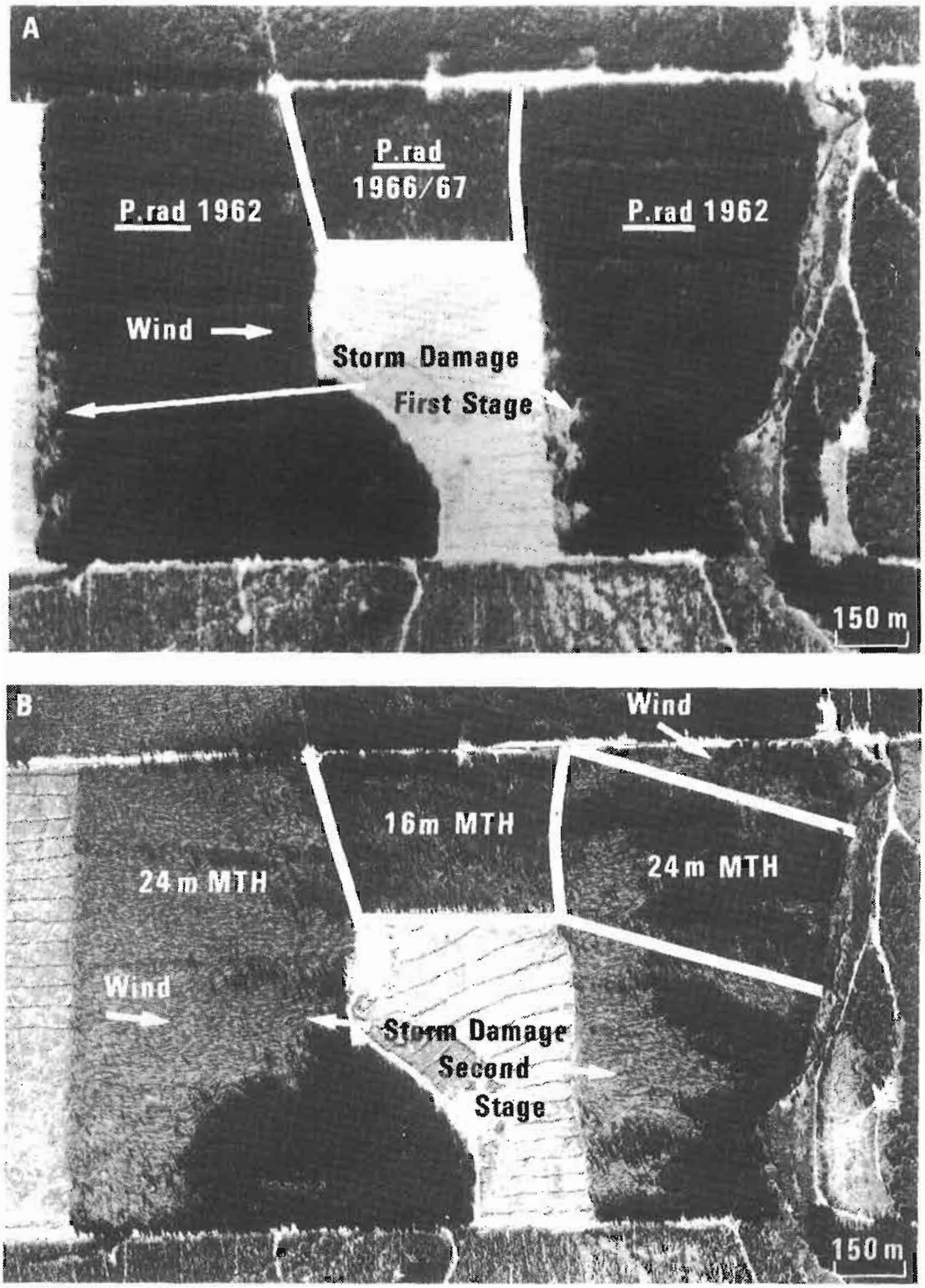


FIG. 7—Wind damage in **P. radiata** in Cpt. 161, Kaingaroa Forest, after two consecutive gales, A and B. B also shows damage downwind from a change in height class.

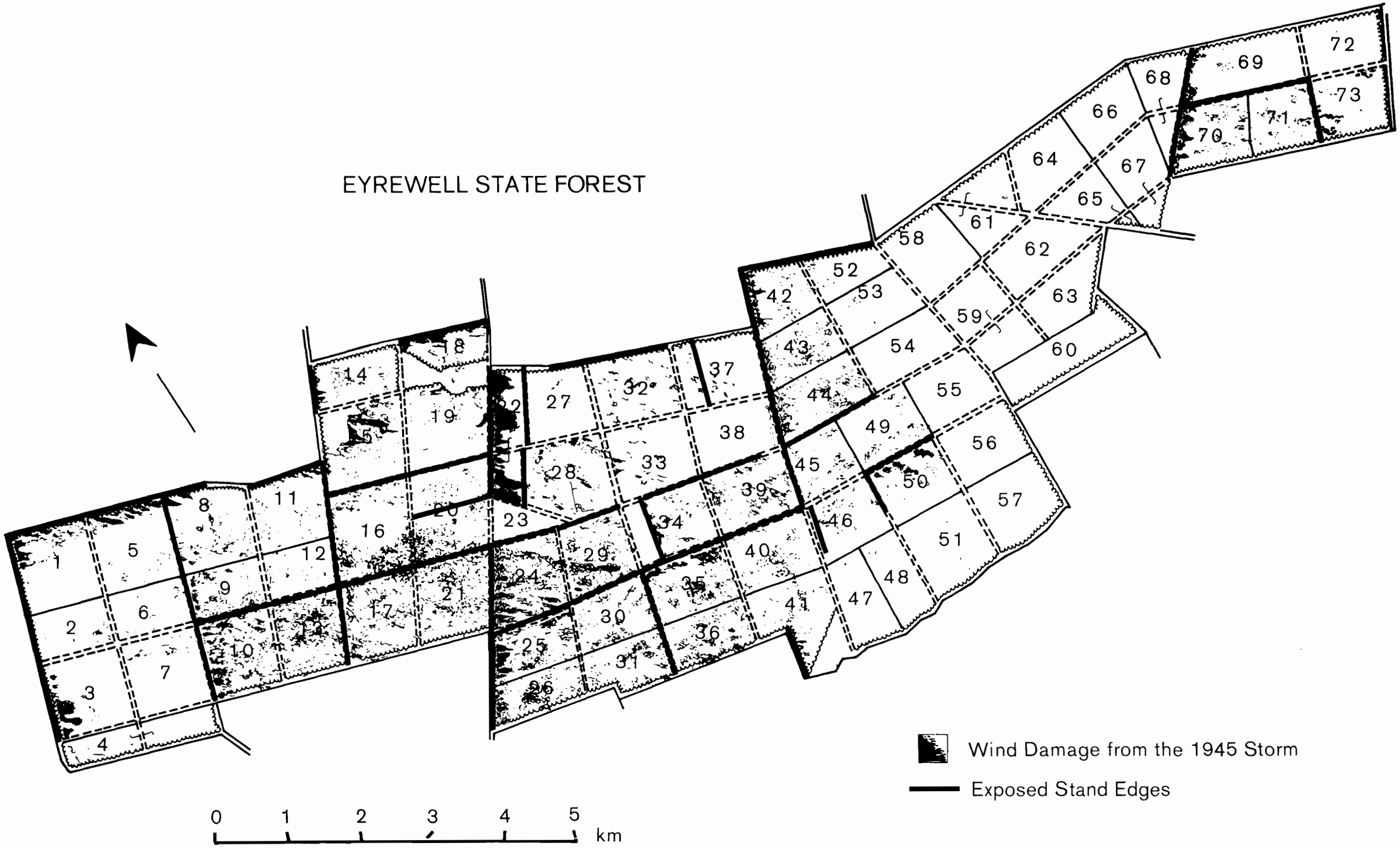


FIG. 8—1945 wind damage to **P. radiata** and exposed stand edges in Eyrewell Forest.

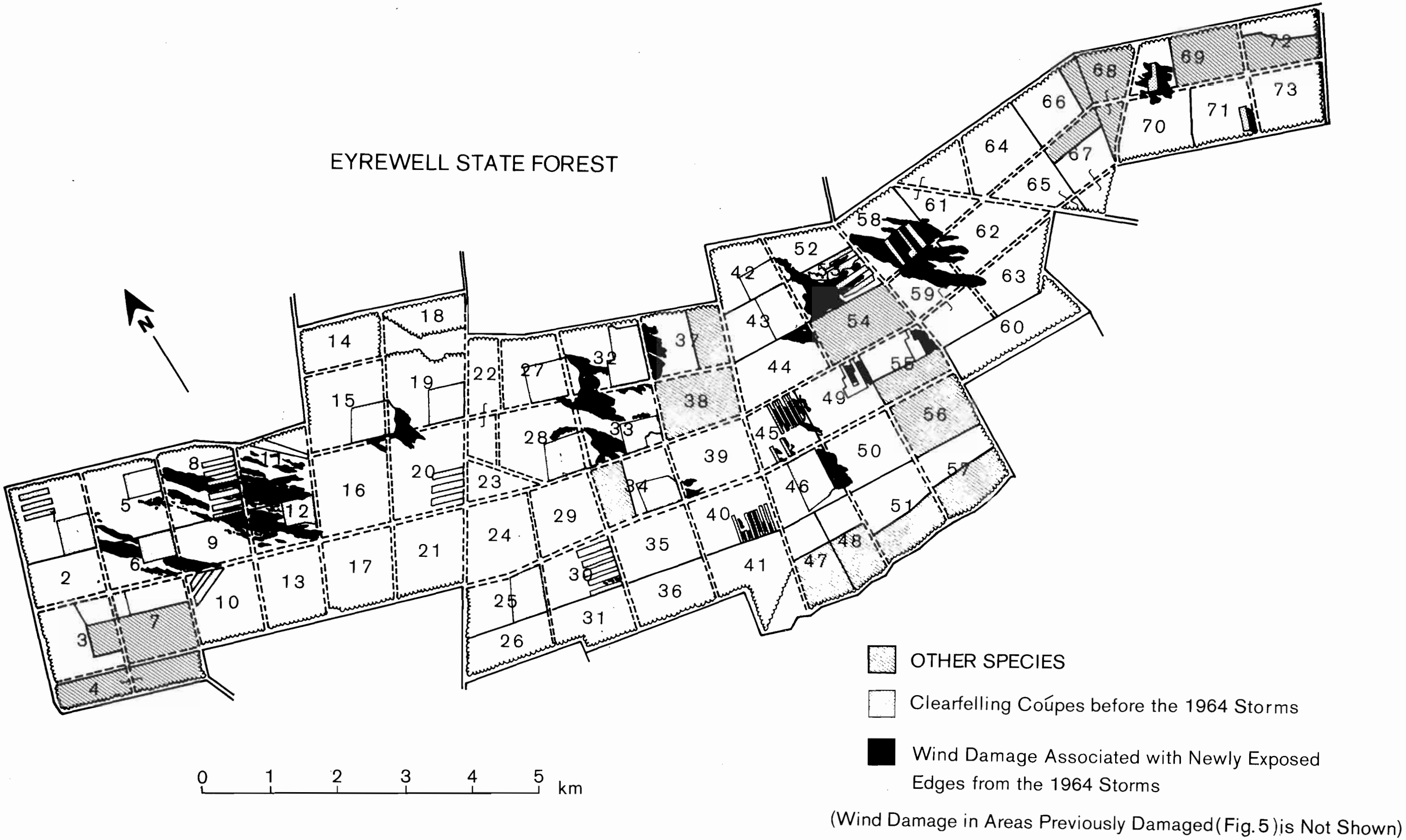


FIG. 9—Wind damage in **P. radiata** associated with clearfelling in the 1964 gales in Eyrewell Forest. Much of the damage shown occurred on 14.3.64 and so does not include subsequent extensions of this damage.

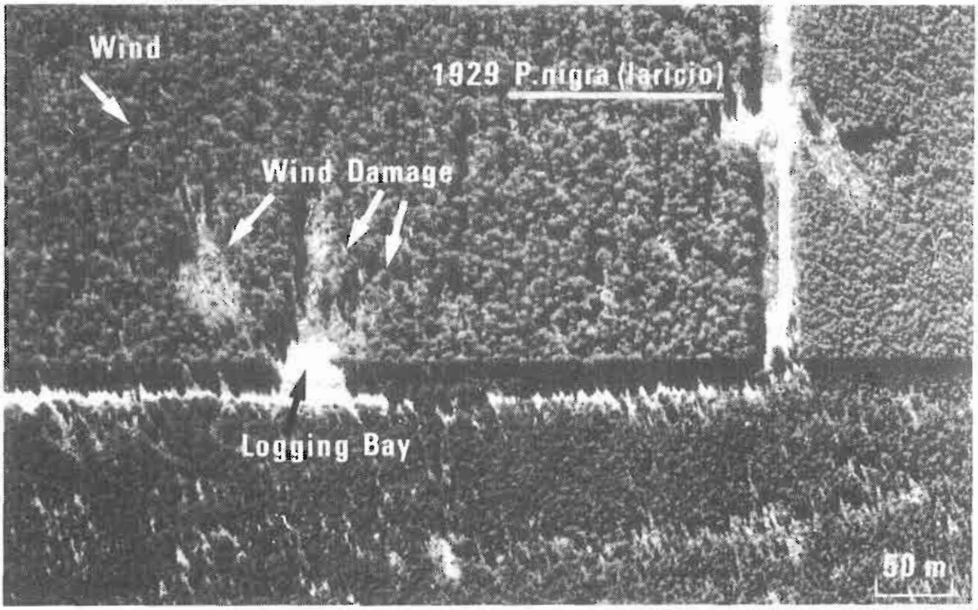


FIG. 10—Wind damage upwind from a logging bay in Cpt. 380, Kaingaroa Forest.

Taller stands upwind

In the 1979 gale in Kaingaroa Forest there were instances where tall stands appeared to have caused associated damage in shorter stands several hundred metres downwind. Fig. 11 shows 3 such instances. This phenomenon was not examined in other forests.

Wider spacings

Fraser (1964), using constant velocity wind tunnel experiments, found that the static force on model trees, measured by the bending moment at the tree base, doubled with an increase in the distance between trees of 25% tree height to 40% tree height (this corresponds to final thinning from 710 stems/ha to 280 stems/ha at a stand height of 15 m). In addition, the edge effect was lost and forces were irregularly distributed throughout the whole stand, depending more on distance upwind to nearest neighbour than distance upwind to the edge.

Actual observations appear to be consistent with these wind tunnel results. In widely spaced young stands, before canopy closure, there is no apparent edge effect and wind damage is widely distributed, hence there is no indication of a lessening of the forces on individual trees with distance downwind. In the edge zone, widely spaced stands appear to suffer similarly to closely spaced stands. The differences in stability behaviour between the two occur further downwind where the more closely spaced stand has less potential damage. The stability of widely spaced young stands is discussed in detail in Section B, Silviculture, Spacing effect.

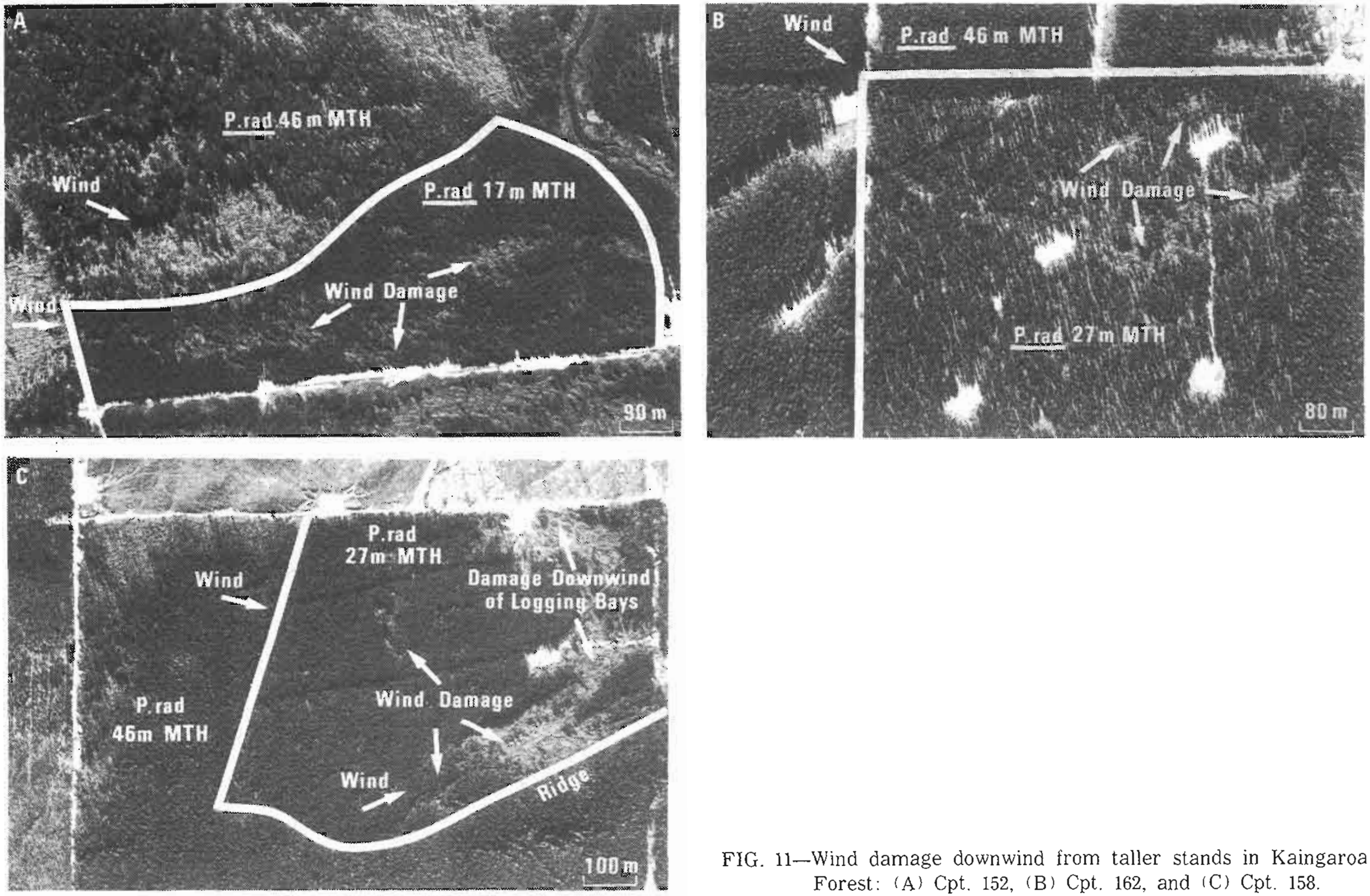


FIG. 11—Wind damage downwind from taller stands in Kaingaroa Forest: (A) Cpt. 152, (B) Cpt. 162, and (C) Cpt. 158.

At some stage of canopy development, at a particular stand height and spacing, the edge effect phenomenon becomes apparent and the potential for damage further downwind is lessened. The following example gives some indication of this boundary:

> In the 1975 storm at Balmoral 800 ha of 19-year-old *P. radiata,* approximately 18-m high and stocked at 300–375 stems/ha, were mostly windthrown without any apparent "edge effect" distribution of damage. Among these stands, 5 ha in Trial C283 were stocked at 580 and 870 stems/ha (Fig. 12). In these 2 treatments, survival was 68% and the incidence of damage was higher in the exposed edge zone.

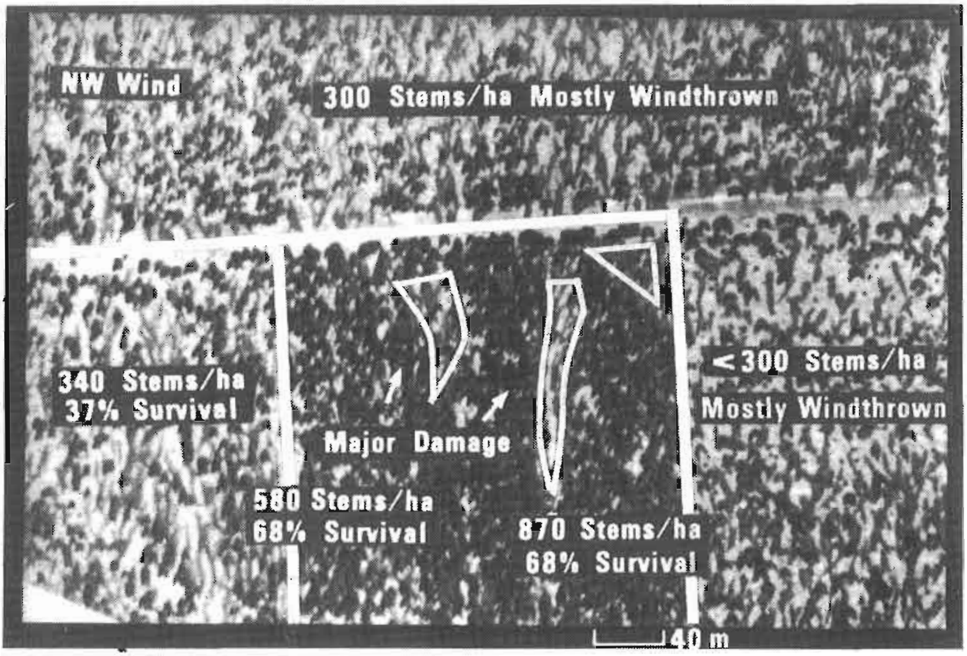


FIG. 12—Percentage survivals over a range of stockings after wind damage in 1975 in Balmoral Forest.

DISCUSSION OF FOREST LAYOUT

A strong wind over a forest is an immense and relatively unlimited source of energy that potentially may be transferred downwards into the forest. With a closed canopy forest there is an unavoidable transfer of this energy along the windward boundary. It is a localised effect and if there is no further disruption to the wind's movement by new "edges" then these energy transfer processes stabalise and damage potential lessens (this analysis ignores wind movement and wind turbulence as they are affected by topography and the other factors depicted in Fig. 1). Where new "edges", created by wide breaks or height changes of at least 5 m, further disrupt the wind's progress, turbulence results, more energy is transferred downwards, and the potential for wind damage increases.

This study did not include totally damaged stands. It is not generally practicable to reconstruct the spread of damage in such stands; however, it is assumed that damage spreads from concentrations associated with the edge zone. Fig. 7 shows such a sequence in Kaingaroa.

"Edge effect" patterns of wind damage appear to persist independently of stand width. In a 200-m wide closed canopy, immature stand confronting a damaging wind, potential damage could be expected to abate in the second 100-m. If the stands were mature, a margin of windward edge trees may prove to be relatively safe but potential damage elsewhere would be comparatively high.

The strip system

In the Canterbury Plains State Forests, each compartment is prescribed to be divided into 4 equal, parallel strips running at right angles to the damaging NW wind. At Eyrewell these strips are 120-m wide. Each array of 4 strips is designed to confront the NW wind with an ascending step profile. Strips are one-quarter of a rotation apart in date of establishment. As the oldest strip is felled the youngest is exposed downwind.

Thinning to final crop stocking is at around age 13 years of a nominally 32-year rotation. Young stands are widely spaced and wind exposure will be high and similar over the whole strip. With canopy closure in the latter third of the rotation, the edge effect will become apparent. The approximately 8-m height difference between stands will be enough to result in an exposed edge and could induce "edge effect" damage to the whole strip. Each strip could repeat the high damage zone shown in Fig. 3 and thus increase several-fold the overall damage potential for mature and semi-mature stands when compared to a forest layout with large stands extending well downwind.

Fig. 5B shows this phenomenon in Balmoral in 1945. Wind caused 50% damage in 19-year-old *P. radiata,* travelled over several hundred metres of shorter strips, then over an 8-m higher edge back into the *P. radiata.* This edge caused 75% damage for around 100 m and then damage ceased further downwind.

Fig. 7B shows an example of the same phenomenon in Kaingaroa in 1979. The 1962 stand is divided by a 1966–67 stand, 400-m wide and 8-m shorter. The resulting edge induced a high damage zone immediately downwind and in appearance is identical to the adjacent damage zone behind the "open ground" edge.

The above examples differ from the "strip system" in two respects: (i) "Strips" are likely to be more exposed to wind through the whole rotation. This will result from high wind exposure associated with wide spacing until canopy closure (unless there is a net sheltering effect of the taller strips upwind), and subsequently from the "edge effect". (ii) The above examples do not have ascending age classes between oldest strips. This configuration may have some advantageous effects (Papesch, pers. comm.). In the 3 examples in Fig. 11, however, wind travelled over older age classes and inflicted damage up to several hundred metres downwind from the boundary in the younger stands. If this proves to be the case in the "strip system", a large body of wind will miss the smaller stands and have the greatest impact around the edge of the next mature strip.

Wind over a smooth continuous canopy has to some extent stabilised. When this canopy is broken by exposed edges which generate turbulence, we can expect increases in potential damage. Over parts of Eyrewell Forest there will be up to 40 significant changes in height classes confronting a NW wind. Each edge will generate turbulence which might in turn be fed from the successive air layers above, bringing more and more energy downwards. In the Eyrewell 1945 storm (Fig. 8) the damage on the leeside of the forest, downwind from several exposed edges, was greater than on the windward side. This may be a coincidence or it may be the product of increased turbulence fed into the system from several exposed edges.

B. SILVICULTURE

Thinning effect

We may think of thinning effect on tree wind stability as solely the difference in stability between a stand recently thinned to a given spacing and a stand already at that spacing for a number of years. When risk of wind damage increases with stand height, any effect of thinning on tree stability is reduced by early thinning. The questions of wind behaviour, forces acting on trees, and energy losses from trees deal with the spacing effect and are considered in the following section.

New Zealand forest managers are generally very familiar with the relative instability of recently thinned stands. We tend to speak of "late" thinning as resulting in unstable stands.

The British Forestry Commission has recognised the wind instability aspects of thinning. *Picea sitchensis* is the main species planted in the British Isles and thinnings tend to be light and frequent compared to the New Zealand silviculture of *P. radiata.* The Commission has devised a "Windthrow Hazard Classification" which comprises 6 hazard classes defined by a scoring system based on: (i) wind zoning from "tatter" flags, (ii) elevation above sea level, (iii) exposure, (iv) soil type. The hazard rating for an unthinned stand is weighted upwards by 1, to a more stable class. In the greatest hazard class, there is reluctance to thin at all.

Spacing effect

The spacing effect is reflected in the wind stability performance of a stand as it is affected by its own relative spacing. Relative spacing largely determines the growth and form of the tree from canopy to root system. Spacing also governs the wind movement through and immediately over the canopy which in turn defines the forces acting on the tree and the way in which energy put into the tree by the wind is dissipated. Some of these processes are shown diagrammatically in Fig. 13.

Stability is a function of the force on a tree and energy loss from that tree.

Fraser's (1964) wind tunnel experiments indicated that the static forces acting on trees doubled when the spacing between trees was altered from 25% tree height to 40% tree height, and that the distribution of these forces became irregular over the whole stand due to the loss of the "edge effect". An irregular canopy fell between the thinned and unthinned crop in terms of force on trees and edge effect.

In the Redesdale Experiment wind structure was examined as the wind moved over and through 2 adjacent stands of *Picea sitchensis,* approximately 14-m high and stocked at 2760 and 2220 stems/ha (Table 5). At the wider spacing (2220 stems/ha),

TABLE 5—A comparison of the structure of wind over 2 differently stocked stands

Wind behaviour	Stocking	
	2220 stems/ha	2760 stems/ha
1. Mean wind speed at tree top	Higher	
2. Surface drag		Higher
3. Energy and frequency of gusts	Higher gust frequency and higher wind speed associated with gusts	
4. Assumed danger from windthrow	Higher	

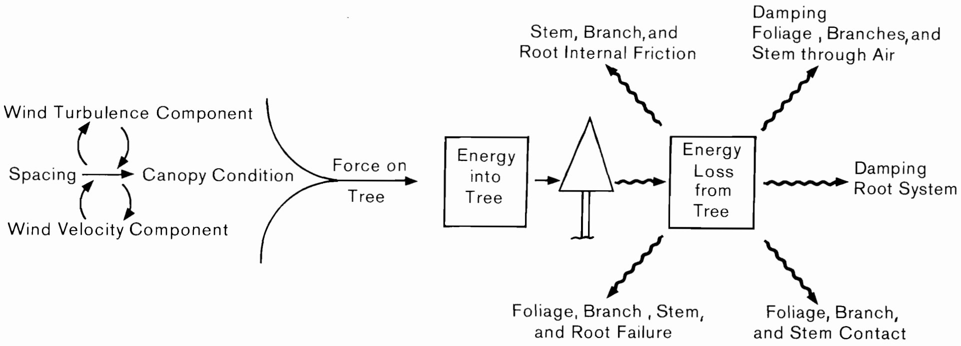


FIG. 13—Processes of energy gain and loss for a tree under wind stress.

the wind at tree top level had a greater speed and was more turbulent. This implies greater forces acting on these wider spaced trees with a consequently larger energy transfer into the stand.

At wider spacings, increased forces acting on trees are further compounded by a larger crown for the wind to act upon. There are also different processes of energy loss from the tree, since tree to tree contact can account for large amounts of energy loss and there is less contact between wider spaced stems (White *et al.).* More energy must be dissipated through other mechanisms such as damping by movement of the above ground parts of the tree and through the root system. This may be reflected in greater stem movement. Mitscherlich (1970–71, quoted by Mitscherlich 1974) found that the amplitude of oscillation in a stand of *Pseudotsuga menziesii* (Mirb.) increased 2–3-fold after heavy thinning. However, these processes are counteracted to some extent; wider spaced stems have more extensive root systems to absorb energy and provide anchorage, larger branch systems which give increased damping, and greater taper, restricting tree bend.

Researchers have tended to concentrate on only a part of the whole system when considering spacing and stability. For instance, Fraser & Gardiner (1967) examined the anchorage properties of root systems of *Picea sitchensis* and recommended wider spacing to promote better root growth and resistance to windthrow. Fraser (1962) and

Papesch (pers. comm.) correlated tree weight and tree volume respectively with root anchorage as measured by bending moment. Day (1950) recommended early thinning to promote crown depth and hence lower the centre of gravity to reduce windthrow.

The wind stability performance of edge trees, solitary trees, and shelterbelts has little to do with the stand situation, but their relatively wind stable behaviour has often prompted the recommendation for wider spacings. Observations of the stability of different spacings are compounded by treatment variables, stand layout, relief, soil type, edge effect, etc. Comparing the stability of two differently-spaced stands is comparing treatments as a whole, since the component trees are likely to be different in size and form. It is unclear what effect spacing has on the incidence of stem breakage compared to windthrow

Windthrow and breakage after thinning suggest one or more of the following:

(a) The structure of the wind is of a more damage-causing nature.

(b) Forces on trees have increased.

(c) The processes of energy dissipation have been altered (primarily due to less tree-to-tree contact).

The following examples give an indication of the change in the nature of wind forces acting on trees and the stability behaviour of trees with regard to spacing:

(1) Thinning trial C283, Balmoral (Fig. 12). This trial consisted of 22 ha of 6 different stockings of 19-year-old *P. radiata* and was thinned 3–5 years before windthrow in 1975 (height approximately 18 m). Stocking before wind damage and percentage survival were as follows: 870 stems/ha — 68% survival, 580 stems/ha — 68% survival, 340 stems/ha — 37% survival, and lower stockings almost total failure.

(2) Thinning trial C158, Balmoral. This trial consisted of 6 thinning plots in 19-year-old *P. radiata* regen. at the time of storm damage in 1975. Plot number, stocking, and percentage survival were as follows: (1) 10 646 stems/ha — 100% survival, (2) 988 stems/ha — 82% survival, (3) 966 stems/ha — 84% survival, (4) 655 stems/ha — 58% survival, (5) 439 stems/ha — 30% survival, and (6) 341 stems/ha — 6% survival. Plot 1 was unthinned; plots 2, 4, and 5 were last thinned 4–5 years before damage; and only plots 3 and 6 were recently thinned before wind damage.

(3) In Compartment 375, Kaingaroa Forest, 2 adjacent stands of 1966 *P. radiata* were damaged by windthrow in the 1979 storm (Fig. 14). Both were thinned in 1977, 37 ha thinned to 180 stems/ha and 28 ha thinned to 250 stems/ha. The wider-spaced stand had 54% damage and the more heavily stocked stand only 4% damage. However, parts of the 250 stems/ha stand were more exposed and some of the damage could be attributed to this exposure.
In these examples the fact that damage occurred may be in part a "thinning effect" but the differences in stability performance of stands reflect the "spacing effect".

(4) Prior (1959) observed that overstocked stands were less susceptible to wind damage than lightly stocked stands and offered 3 examples to support his observation. One

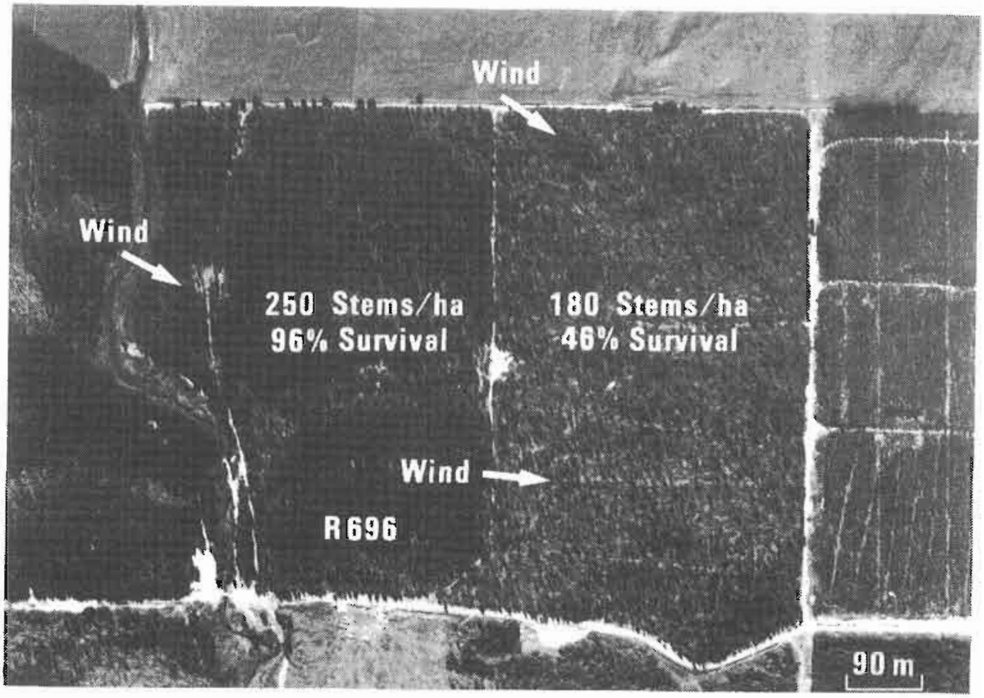


FIG. 14—Wind damage in 18-m tall stands in Cpt. 375, Kaingaroa Forest.

of these examples was at Eyrewell in 1957 where 29 ha of unthinned 26–28-year-old *P. radiata* were windthrown. Of this windthrow, 18 ha were part of 100 ha planted at 4.9 × 4.9 m. The remaining 11 ha were part of 5261 ha planted at 2.4 × 2.4 m. Wendelken (1955) and Chandler (1968) also observed better stability with heavier stocking.

The above examples show differences in wind stability behaviour with differences in stocking or after changes in stocking. Evidently, the wider-spaced trees have had greater forces acting on them without there being a corresponding increase in capacity to deal with these forces. This is apparently not always so. On some sites, trees may more than compensate for this increased exposure. Cyclone "Alby" damaged radiata plantations in Western Australia in 1978. In a thinning trial in an 18-year-old stand at Bussels plantation, plots stocked at 200 stems/ha received minimal damage, plots at 750 stems/ha were moderately damaged, and unthinned plots at 1200 stems/ha were severely damaged. In the two heavier stocked plots damage was mostly in the form of severe stem bend rather than windthrow (F. H. McKinnel, pers. comm.).

Pruning effect

In New Zealand, the butt logs of selected trees are pruned to around 5.5 m. Pruning is usually done in three stages at top heights of approximately 6, 9, and 12 m.

Within stands in the latter third of the rotation, pruned trees differ in appearances only in that they have a few less dead branches. Unless there is some long-term conditioning effect from early wind porosity, this slight difference is unlikely to have any significant consequence in wind stability behaviour.

In the young stand, pruning could have the following effects:

(i) Reduce the surface area on which a force can act and hence reduce the bending moment resulting from a wind.

(ii) Increase the permeability of a stand, allowing more air movement particularly below the canopy. It is uncertain what effect this has.

(iii) Restrict the energy loss processes of tree-to-tree contact and damping by branch movement in relation to air.

(iv) Elevate both the centre of gravity and the centre of pressure on which the wind works.

(v) Alter the natural sway period of a tree and hence its response to a wind of a particular structure.

The force on a pruned tree may be less but there will be an increased propensity to oscillate once energy is put into the tree.

Where a non-turbulent constant wind acts, the pruned stem may be more stable. The reverse may be true in gusty conditions where tree oscillation is encouraged. The following examples of the relative wind stability of pruned trees are conflicting:

1. At Eyrewell Forest in 1975, 8- and 9-year-old *P. radiata* stands, stocked at 1500 stems/ha were damaged. These stands had alternate row treatment in which trees in every second row, containing one-third of the total stems, were pruned. Pruned trees were very significantly less damaged than unpruned trees. (T. Brummer, pers. comm.). However, at Balmoral Forest, the reverse occurred although corresponding damage was light and hence data were limited. These observations were complicated by stands being a mixture of pruned and unpruned trees, row orientation differing between the two forests, and the stocking in the pruned rows was one-half of that in the unpruned rows.

2. Trial R696, part of an 18-m tall *P. radiata* stand in Kaingaroa Forest, was damaged by strong NW winds on the 11 April 1979. A set of four 0.27 ha plots lay at right angles to the damage-causing wind along an exposed edge. Three plots, butt log pruned and stocked at 200, 290, and 800 stems/ha, had 15%, 40%, and 27% damage respectively. The fourth plot, unpruned and stocked at 400 stems/ha, remained completely intact.

There is a general lack of information and actual experiences regarding the stability performance of pruned trees. The answer appears to be complex and stability behaviour may vary with wind structure, pruned *versus* actual height, stocking, position within a stand, form, or other stand and site parameters.

CONCLUSIONS

Silviculture in New Zealand is determined by reasons other than wind stability. In some localities the actual timing of silviculture is affected by wind stability considerations. Young stands will be widely spaced with canopy closure generally occurring in the latter third of the rotation.

The following synthesis does not take into consideration the consequences of wind movement as it is affected by topography and the large scale weather system.

A. In young, widely spaced stands of *P. radiata,* before canopy closure, the following apply:

1. Forces on individual trees, beyond 100 m downwind from an exposed edge, will be higher than in a corresponding stand with canopy closure. The structure of the wind may be more conducive to stem sway and eventual dislodgement. Forces acting on trees are likely to be irregularly distributed over the whole stand. If windthrow does not occur, this increased exposure may result in an advantageous stability conditioning.
2. The risk of wind damage is likely to be higher beyond 100 m downwind from an exposed edge compared to a closely-spaced stand.
3. Pruning may affect stability. Whether it has a beneficial or detrimental effect is likely to depend on stand, site, and wind characteristics.
4. Exposed edges, other than those from recent felling, do not appear to affect the distribution of wind damage.

B. As stands age and the canopy closes, the following apply:

1. Forces on trees and risk of wind damage are greater in the first 100 m or 200 m downwind from an exposed edge. Further downwind, the forces on trees and the risk of wind damage are less than if the stand were at a wider spacing without canopy closure.
   Significant changes in height class and wide roads and breaks across a damaging wind can increase wind damage up to several fold. If the wind risk in a forest is high and the hazardous wind direction is predictable, then these edges can and should be avoided. It appears that a smooth continuous canopy will minimise risk.
2. Whether the stand is pruned or not is unlikely to make any difference to stability.

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APPENDIX 1

Terminology

Bulk flow:	the movement of the mass of air at around 700-1000 m above the earth's surface surface (subject to large variation in altitude). Highest velocity of gusts near the earth's surface is approximately equal to the bulk flow velocity (Gloyne 1968).
Damping:	dissipation of energy in a tree through movement and contact of branches, foliage, stem, and roots.
Drag:	the surface friction for trees and surface features in the boundary layer.