CAUSES OF JUVENILE INSTABILITY OF PINUS RADIATA IN NEW ZEALAND

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ABSTRACT

The effects of root configuration and soil cultivation on stability of juvenile **Pinus radiata** D. Don were studied in New Zealand plantations. Roots of toppled and stable trees were excavated, and morphological features of the two sets were assessed and analysed in pairs. It was concluded that straight-grained taproots and sinker roots reduced the likelihood of toppling. The amounts of toppling in seven cultivation trials were assessed between ages 1 and 5. Cultivation varied in its effect on toppling frequency, because of differences in tree size, soil strength, and vertical root development.

Keywords: toppling; cultivation; stability; socketing.

INTRODUCTION

Juvenile instability, or "toppling" as it is called in New Zealand, is a frequent occurrence in young plantations (Chavasse 1969; Mason in prep.). Stands have been found in which it occurred many years ago, including *Pinus nigra* subsp. *laricio* (Poir.) Maire in Dusky Forest, planted 1924, and *P. contorta* Loud. in Beaumont Forest, planted 1928 (Chavasse 1969).

Wind-induced toppling is quite different from snow damage as snow applies a relatively constant destabilising load whereas wind places trees under periodic stress. Toppled trees do not usually fall over entirely (Fig. 1) – they acquire a lean from which they gradually recover. During the recovery process, large quantities of compression wood are formed, and the trees are left with butt sweep and sinuous stems (Harris 1977). Occasionally, 5- to 8-year-old trees snap entirely just below their root collars. This has also been labelled "toppling".

Another wind-related phenomenon is "socketing" – the swaying of trees in the wind leading to the formation of a funnel-shaped depression in the ground around the stem. This has been reported in various countries (Clarke 1956; Nanni 1960; Bergman & Hagstrom 1976).

Chavasse (1969, 1978) described a survey of toppling in the South Island of New Zealand. Many species of pine were affected, along with eucalypts. Trees involved were generally between the ages of 2 and 6 years, and in some stands all the trees were affected. Managers offered various opinions about the cause of the phenomenon, including quality of tree stocks, method of planting, soil and site conditions, fertility (low root : shoot ratios), exposure, weed competition, and low stocking.

FIG. 1—An area of **Pinus radiata** toppled at age 2 years.

Very high rates of toppling have been noted on fertile farmland sites (Chavasse 1969). Although fertility generally encourages root production (Lutz *et al.* 1937), Nambiar (1980) found that this increase in root production did not match the above-ground production.

A tree depends on its root system not only as a means to absorb water and minerals from the soil but also for anchorage in the soil. The quantity and quality of root growth therefore determine stability.

Previous studies of root configuration related to toppling fall into three groups:

(1) Those in which the roots of toppled trees were excavated and assessed but not those of stable trees for comparison. Not surprisingly, the results of such studies are qualitative and inconclusive (Gruschow 1959; Clarke 1956; Huuri 1978; Klawitter 1969; Schultz 1973);

(2) Those which examined the force required to pull over several different types of stock (Burdett 1979; Hulten & Jansson 1978; Lindgren & Orlander 1978; Somerville 1979);

(3) Those in which the roots of toppled trees were compared with adjacent stable trees, with the same soil environment and above-ground dimensions (Edwards *et al.* 1963; Pfeifer 1982; Hetherington & Balneaves 1973; Somerville 1979).

The studies reported here were planned with the following questions in mind:

(1) Is there a relationship between socketing and toppling?

(2) What kind of root development is most likely to ensure tree stability during the first few years?

(3) Does cultivation prior to stand establishment increase or decrease the likelihood of toppling?

METHODS

Socketing

Two permanent sample plots were planted in Kaingaroa State Forest (Fig. 2). The incidences of socketing and toppling were assessed annually for 3 years in one plot (778 trees) and for 5 years in the other (284 trees).

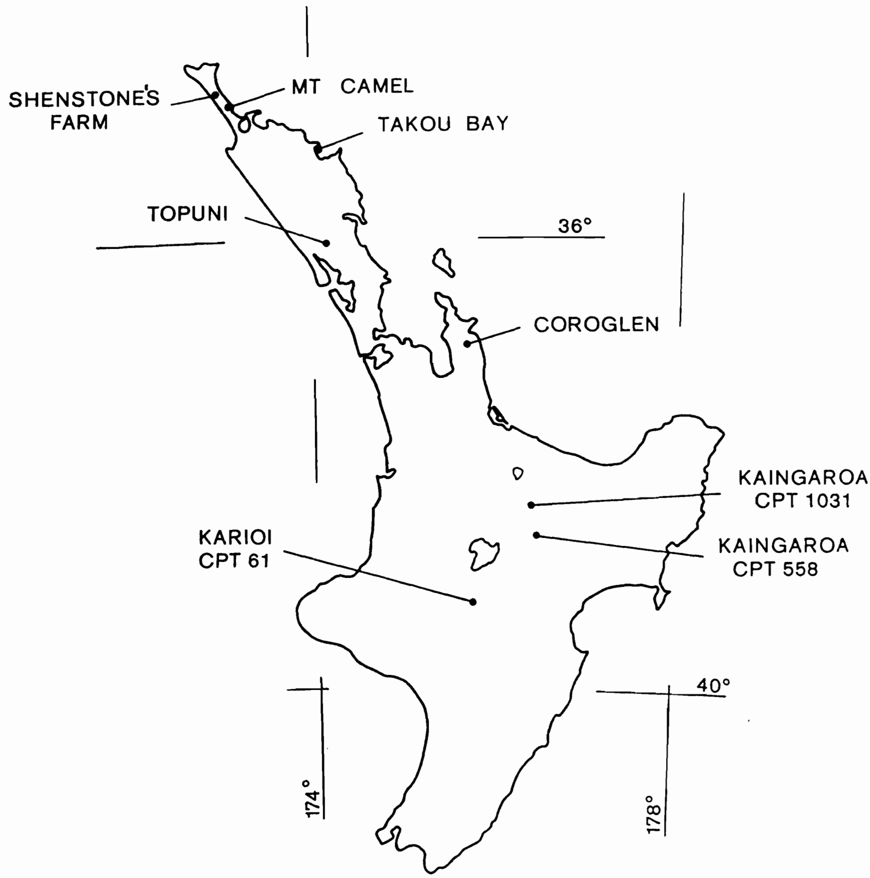


FIG. 2—Location of the trials assessed during this study.

A tree was considered to be socketed if the space between the root collar and the surrounding soil was 5 mm or greater. Since the assessment was on an annual basis, the incidence of socketing may be under-estimated as for a few trees the gap may have closed between assessments.

Trees were considered toppled if they acquired a lean greater than 15° from vertical or if they were butt swept. If a tree leans to 15° as a juvenile then it is likely to retain some residual stem distortion (Mason in prep.). Contingency tables were constructed for each plot so that the correlation between socketing and subsequent toppling could be computed.

Root Form

Ninety-eight 2- and 3-year-old *P. radiata* were selected in pairs from a variety of central North Island pumice sites, cultivated and uncultivated, with the following constraints:

(1) One of the pair was toppled but the other was completely stable (no trees with strangled and snapped stems were assessed);

(2) The soil type and the establishment regime were the same for both trees;

(3) The two trees were of similar dimensions above ground, were growing within 10 m of one another, and were similarly exposed to prevailing winds.

Height, root collar diameter, and diameter at breast height (where possible) were measured on each tree. Roots were carefully excavated with a spade to a distance of 60 cm on all sides and brought into a field room for cleaning. The following were measured or assessed:

(1) Diameter of each root at a point 10 cm from its origin on the bole. From these measurements the cross-sectional area of roots at 10 cm was computed, and the results summed per tree;

(2) Area of taproots and sinker roots only. Sinkers were defined as roots more than 45° from horizontal;

(3) Total area of lateral roots;

(4) Cross-sectional area of the laterals in Quadrants 1 and 3, Quadrant 1 being in the direction of topple and Quadrant 3 on the opposite side;

(5) Area of roots in Quadrants 2 and 4 (at right angles to the toppling direction);

(6) Difference in lateral root area between Quadrants 1 and 3;

(7) Standard deviation of areas in each quadrant – effectively an index of "balance" of the lateral roots;

(8) Some of the above parameters using diameters instead of areas of roots at 10 cm;

(9) Distance from ground level to the first lateral root – a measure of planting depth, assuming that no ground movement has taken place and that no adventitious roots have formed;

(10) Taproot distortion, using Menzies' Taproot Score (Fig. 3) (Chavasse 1978);

(11) Lateral root system, using Menzies' Lateral Root Score (Fig. 4);

(12) Number of sinkers greater than 2 mm in diameter 10 cm from their origin.

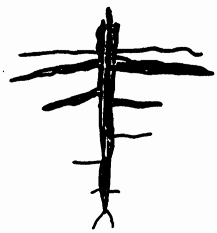
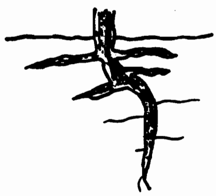
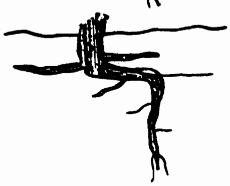
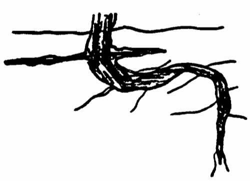
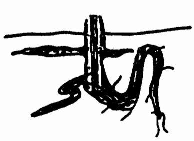
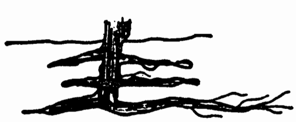
SCORE	DIAGRAM	DESCRIPTION
0		Strong, dominant, well developed taproot
2		Stunted, slightly malformed, but still a definite taproot
4		Taproot distinctly hooked
6		Taproot quite badly hooked, but downward development still present
8		Taproot severely deformed into two or more fracture zones, but growth still downward
10		Taproot does not come below a horizontal plane, or no taproot at all. Subtract one point for each strong sinker present.

FIG. 3—Menzies' Taproot Score. The score ranges from 0 for a good taproot system, to 10 for a poor one.

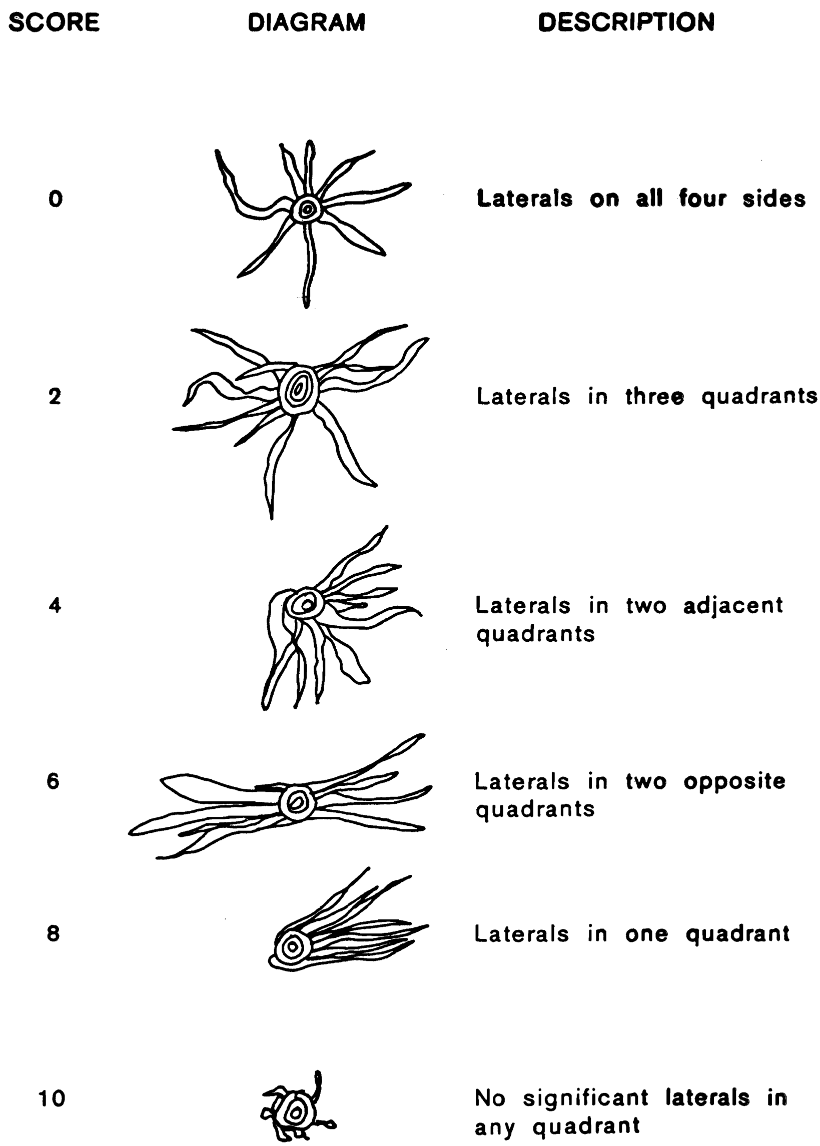


FIG. 4—Menzies' Lateral Root Score. The score ranges from 0 for a good lateral root system, to 10 for a poor one.

Measurements were tabulated and a discriminant analysis was performed to identify those variables which were most highly correlated with the likelihood of toppling.

Two experiments were designed to validate the results from the discriminant analysis:

(a) A "box" pruning trial was laid out in Cpt 482, Kaingaroa Forest. Box pruning is a nursery conditioning technique which replaces wrenching with periodic cutting of the laterals of each tree on all four sides, and begins with a deep undercut. In addition, the box pruned trees in this trial had a final undercut (Chavasse 1978) but the wrenched trees used as a comparison were not given this final treatment. The two stocks received identical treatments, apart from the conditioning, to the point of establishing 10 replications in a precision-sown nursery bed and transferring these same replications to the field site. Forty trees of each stock type were planted in each replication. Root assessment was carried out at age 3 years on a subsample of the trees within each plot, and the percentage of trees toppled was also recorded.

(b) In an experimental block in Karioi State Forest (Fig. 2) two lots of seedlings were planted in paired 10-tree plots, replicated 36 times. The roots of one lot were untrimmed and difficult to plant, while those of the other had been well trimmed (to 10 cm from the root collar) and could be planted with little distortion. Two years after planting, one tree was excavated from each plot and the roots were assessed. The plots were revisited 2 years later, by which time some toppling had occurred.

In addition, roots of four trees with stems snapped below ground-level were excavated. This snapping of stems is infrequent, but it is often labelled "toppling" as well.

Cultivation Study

Seven experimental plots containing a variety of ripping and discing treatments were located around the North Island (Fig. 2) – four were north of Auckland (Mount Camel, Shenstone's Farm, Topuni, and Takou Bay), one in Coromandel (Coroglen), and two on the central North Island pumice land (Kaingaroa and Karioi) (Table 1). All were replicated in randomised complete blocks of 10-tree plots which were assessed annually. In addition to the usual survival and growth measurements, assessors noted which trees in each treatment were toppled – i.e., had a lean greater than 15° from vertical or were butt swept. Differences between treatments were subjected to analysis of variance.

At Coroglen, direction of toppling was also noted. North was defined as the direction of the rip lines (it was close to true north), and frequency of toppling in each treatment was plotted.

In Cpt 558 at Kaingaroa Forest, measurements of toppling were much more extensive. Two years after planting, two trees per plot were excavated and assessed on Menzies' Taproot Score. A year later the angle from vertical of each remaining stem was measured with a ruler and a clinometer. These data were plotted according to cultivation treatment. Five years after planting, sinuosity of each stem was measured by placing a height pole against the tree so that it intersected the bole at 30 cm above the ground (stump height) and at the top of the tree (*see* Fig. 5). The horizontal distances between the pole centre-line and the centre of the whorls which were furthest from the pole in each direction were measured. Heights at which these measurements were taken were also recorded.

The effect of the sinuosity on the final crop was assessed by projecting growth and log characteristics of each tree, as outlined in Appendix 1. Projections were performed

TABLE 1—Cultivation treatments used for toppling assessment

Plot location	Treatments	No. of replications	No. of remeasurements
Mt Camel	Control Ripping Bedding (small) Bedding (large)	10	3
Shenstone's Farm	Ripping Bedding	16	3
Topuni	Ripping Ripping/bedding Bedding	10	4 (not measured at age 4)
Takou Bay	Control Ripping/discing Ripping Ripping/bedding	12	4 (not measured at age 4)
Kaingaroa Cpt 558	Control Ripping/centre planting Ripping/edge planting	16	5
Karioi Cpt 61	Control Ripping Ripping/bedding } and { two stocks from different nurseries (factorial design)	12	5
Coroglen	Control Ripping	14	3

twice for each treatment – once on all trees (assuming a random thinning), and once on the best possible selection, based on stem form, which would leave a final-crop stocking of 370 stems/ha.

A more detailed analysis of the relationship between cultivation and toppling was carried out in Cpt 1031, Kaingaroa Forest. Fourteen paired plots, five planting rows wide and 20 m long, were established in two adjacent blocks. One block was bedded with discs and a roller and the other was not cultivated. In each plot the trees were counted and all toppled trees were measured for height, diameter, topple angle, and topple direction. In addition, heights and diameters of five, randomly selected, stable trees per plot were measured. In all, 1042 trees were counted and 273 were measured.

RESULTS

Socketing

Results are presented in Table 2. More trees which had socketed were toppled than those which had not. This relationship was statistically highly significant ($p < 0.01$).

TABLE 2—Incidence of toppling in two trials where socketing was recorded

Socketing	No. trees toppled subsequently	No. trees not toppled	Percentage toppled	
Kaingaroa Cpt 482				
Socketing recorded	82	185	49	
No socketing recorded	82	429	15	Chi square = 22.7 ($p < 0.001$)
Kaingaroa Cpt 558				
Socketing recorded	104	26	80	
No socketing recorded	174	80	68	Chi square = 5.7 ($p < 0.02$)

FIG. 5—Measuring sinuosity - the distance from the centre of the pole to the centre of the whorl represents the degree of sinuosity.

Root Form

Paired root systems

As individual analyses, all measurements related to vertical roots (taproots and sinkers) were significantly different between the toppled and stable groups of trees. Lateral root measurements did not differ significantly between the two groups, nor did planting depth.

The single most discriminating factor between the roots of toppled trees and stable trees was Menzies' Taproot Score (Fig. 6). Stable trees exhibited consistently better vertical root form than toppled trees. Another factor which was significant, but not highly correlated with the taproot score, was the number of sinker roots. These two factors have been combined into a discriminant function which can be used to estimate the relative likelihood of toppling between 2- or 3-year-old trees of equal size growing with the same soil conditions and with similar exposure:

$$TI = 1.844 - 0.07\ (MT) + 0.01827\ (NS)$$

where TI = topple index
MT = Menzies' Taproot Score
NS = number of sinkers > 2 mm in diameter

The index ranges between 1.8 for a stable tree and 1.2 for an unstable tree. While the coefficients are highly significant for the two parameters, the r^2 is only 0.19, so the index should be used only to predict likelihood of toppling between large groups of trees.

Validation

In the box pruning validation experiment in Cpt 482, 25% of the wrenched stock and 17% of the box pruned stock had toppled after 3 years. Excavation of the roots

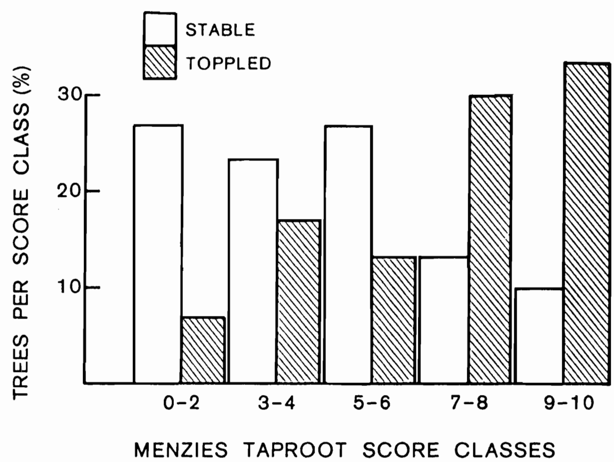


FIG. 6—Menzies' Taproot scores for toppled and stable trees in the root form study at Kaingaroa Forest.

revealed that the box pruned stock had significantly ($p < 0.05$) more sinkers than the other stock. In all other respects, the two stocks were identical at age 3.

In the paired plots of two stock types, the long-rooted stock had a topple index of 1.44 at age 2 years and 57% of the trees had toppled by age 4. Stock with trimmed roots had a topple index of 1.57 at age 2 and 33% had toppled by age 4. Statistical analysis showed that the means were significantly ($p < 0.01$) different.

An excavated root system from a tree which had snapped below ground level is pictured in Fig. 7. All four excavated trees displayed the same constriction by lateral roots around the bole. This strangulation is most likely to have occurred during planting.

FIG. 7—The lateral roots of this tree were wrapped around the stem during transplanting, resulting in stem fracture.

Cultivation

Three sets of plots (Topuni, Shenstone's Farm, and Mt Camel) showed no significant differences with respect to stability.

Results from three other plots are shown in Tables 3 and 4. At Coroglen cultivation reduced toppling frequency, but at Karioi it increased toppling frequency. At Takou Bay cultivation initially appeared to increase toppling (age 3), but by age 5 the trees in the control plots had grown to a susceptible size, and there was no significant difference in toppling frequency.

TABLE 3—Effect of cultivation type on frequency of toppling during the first few years after planting (values followed by the same letter are not significantly different $p < 0.05$)

Trial	Age (years)	Treatment	Toppling (%)
Coroglen	1	Control	18.8 a
		Rip	12.3 b
Karioi	6	Control	24 a
		Rip	38 b
		Rip, 6 discs, roll	32 b

TABLE 4—Toppling frequency and height v. cultivation at Takou Bay (values followed by the same letter are not significantly different $p < 0.05$)

Cultivation	Age 3		Age 5	
	Height (m)	Toppling (%)	Height (m)	Toppling (%)
Rip, 6 discs, roll	2.4 a	9 a	4.8 a	11 a
Rip, 4 discs	1.8 b	15 a	3.3 b	18.a
Rip	1.6 b	14 a	3.3 b	14 a
Control	1.3 c	2 b	2.4 c	8 a

At Coroglen trees in rip lines toppled predominantly at right angles to the rips (Fig. 8). This difference was highly significant.

In Cpt 558 at Kaingaroa, toppling during the first 3 years was greatest among trees planted in loose soil in the centre of the rip (Fig. 9). Those planted in the control plots, however, toppled to a greater angle than the other two treatments. In addition, toppling continued to occur up to age 5 in the control because the roots were confined to the top 20 cm of soil. By this age trees in the ripped plots were stable. The taproot form of the control trees was significantly ($p < 0.05$) worse than that of trees in the rip lines.

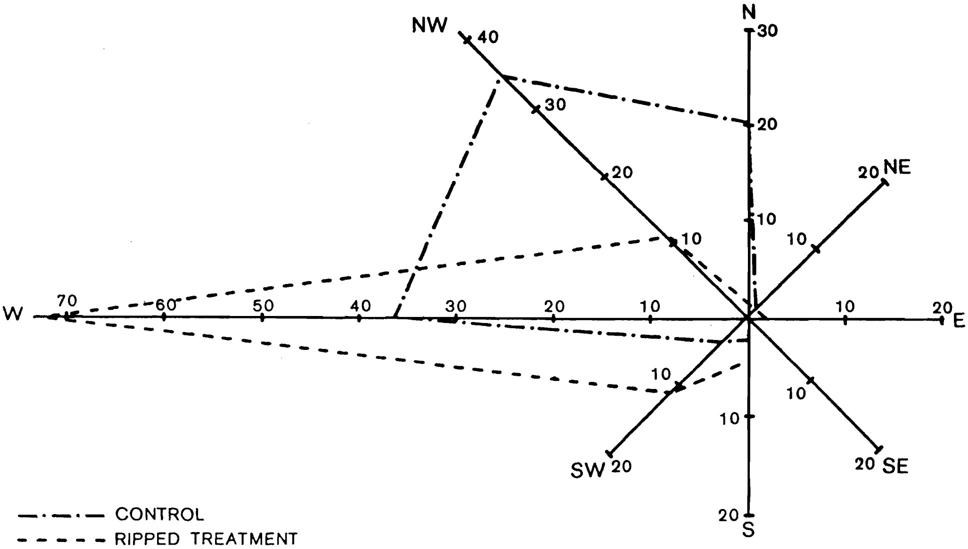


FIG. 8—Direction of topple (%) in the ripped and control treatments at Coroglen. Rip lines ran north.

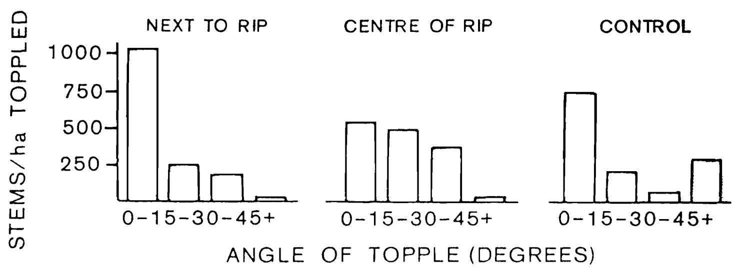


FIG. 9—Frequency and angle of topple, compared with position in relation to rip at Kaingaroa.

The results of the sinuosity analysis (Appendix 1) are shown in Table 5. The control has more sinuosity than the two ripped treatments, and the losses could be as high as 36% of potential No. 1 Clears and $7000 per hectare if thinning selection is poor.

TABLE 5—Projected long-term effect of toppling v. cultivation and thinning practice

		Next to rip	Centre of rip	Control
Reduction in No. 1 clears (%)	Poor thinning	22	26	36
	Good thinning	4	9	10
Revenue reduction due to sinuosity ($/ha)	Poor thinning	$4,876	$5,339	$7,170
	Good thinning	$869	$1,759	$2,159

Direction of toppling in Cpt 1031 at Kaingaroa did not vary between treatments or replications, so the measurements were combined for each treatment. Only trees in the middle and upper height range toppled in each treatment (Fig. 10). In addition, a chi square analysis demonstrated conclusively that, for any given size of tree, more trees toppled in the bedded area than in the control. Likewise, in a comparison of a ripped block with a ripped and bedded block on the other side of the same compartment, more trees toppled in the ripped and bedded block.

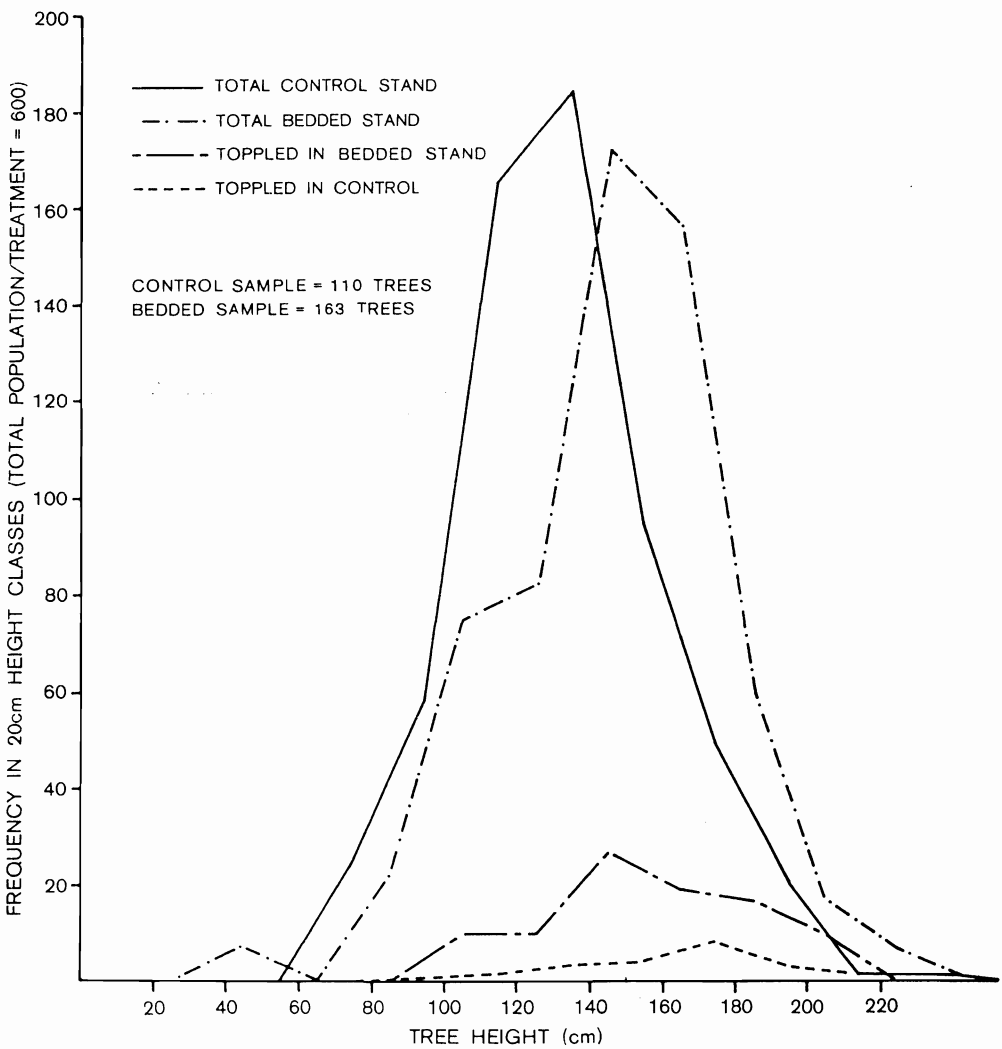


FIG. 10—Frequency of toppling, by height class, in bedded and control treatments of Cpt 1031 at Kaingaroa.

DISCUSSION

Toppling is often preceded by socketing, but not all socketed trees subsequently topple. This finding is important, because if, as results suggest, toppling occurs after a period of tree sway, studies which employ tree pulling techniques may be of limited use since they place a constant strain on the roots. Roots placed under periodic strain are likely to behave differently from those placed under a constant strain.

The discriminant function, while significant, explained only 19% of the variation in stability. Rigorous attempts were made to control all factors other than roots which might affect stability, but there are three possible reasons for the small r^2 value:

(1) Factors which the experiment was designed to control, such as exposure or soil conditions, may have varied slightly within pairs. Many of these factors were not measurable.

(2) Factors not controlled by the experimental design may have affected stability.

(3) The root measurements selected, while adequate for the purposes of the study, are probably not the best possible if variation in stability is to be explained completely.

Menzies' Taproot Score measures the straightness of grain within the taproot, and it makes good sense, from an engineering point of view, that straightness of grain in the taproot should be inversely correlated with toppling propensity. When a tree sways, the roots are placed under periodic stress. If the roots contain a bend, then the stress will be concentrated at the bend, and the root will fail after a period of sway. All lateral roots have a bend in their grain at the point where they are attached to the bole. This suggests that, to reduce toppling, management practices should be adopted which encourage development of straight-grained vertical roots. Edwards *et al.* (1963) reported that a lack of vertical root development in trees growing on a compact soil between plough furrows predisposed *Pinus contorta* to toppling. It should not be forgotten, however, that distortion of the lateral roots can induce root strangulation and stem fracture.

The validation studies support the use of the topple index; however, the effect of root configuration could be masked by differences in soil, exposure, or tree size, between treatments. For instance, the experiment with two stock types at Karioi also included three cultivation treatments and, while the three treatments produced trees with different topple indices, the actual toppling rates recorded were not strongly correlated with the index values. Both tree size and soil strength varied between the cultivation treatments, and no doubt these factors also affected the toppling rates.

The trial at Coroglen was on a grassed clay site. It is interesting that the toppling direction in the rips was almost always westerly, at right angles to the rip lines, while the trees in the control toppled mostly between west and north (Fig. 8). This suggests that development of lateral roots may have influenced toppling as the trees did not possess good taproots at this age; the average score, using Menzies' system, was 7 for both stocks. Pfeifer (1982) showed lateral roots can influence juvenile stability if the taproot is absent.

The Takou Bay trial illustrates how effects of cultivation and tree size on toppling can easily be confused. By age 3 years, more toppling had occurred in the cultivated treatments than in the control. However, the control trees averaged only 1.3 m tall, and many would have been too small to topple. By age 5, when the control trees averaged 2.2 m, there were no significant differences in toppling rate between treatments. Although there were some large differences in toppling frequency, these were not consistent throughout the replications.

At Karioi, on the other hand, there was a much greater incidence of toppling in the cultivated plots during the first 6 years. On this very exposed pumice site it is likely that the loose soil created by cultivation allowed more trees to topple. By age 6, the trees had established much deeper root systems in the cultivated plots, and may be less prone to subsequent windthrow.

CONCLUSIONS

Trees which have socketed are more likely to topple than trees which have not, as toppling usually occurs after a period of tree sway.

Trees with straight-grained taproots and plenty of sinkers are less likely to topple at ages 2 and 3 than trees with twisted or no vertical roots, at least on pumice sites. A kink in the grain of a taproot may be a point of stress which fatigues as the tree sways.

Cultivation can increase the likelihood of toppling. This may be because trees on such treatments grow rapidly and larger trees can be more topple-prone. Also, some cultivated soils lack mechanical strength and a combination of loose soil and poor planting methods will promote instability. However, ripping on sites with compact soils can improve vertical root development, reducing the likelihood of toppling.

The rare form of toppling in which trees snap below ground-level results from constriction of the stem where lateral roots are wrapped around the bole.

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REFERENCES

BERGMAN, F.; HAGGSTROM, B. 1976: Some important facts considering planting with rooted forest plants. **Forestry Chronicle 52(6):** 266–73. [Tr. R. A. Hellenius.]

BURDETT, A. N. 1979: Juvenile instability in planted pines. **Irish Forestry 36(1):** 36–47.

CHAVASSE, C.G.R. 1969: Instability in young stands. **Farm Forestry 11(3):** 70–7.

——— 1978: The root form and stability of planted trees, with special reference to nursery and establishment practice. Proceedings of Symposium on "Root Form of Planted Trees". **British Columbia Ministry of Forests/Canadian Forest Service Department Report No. 8:** 54–64.

CLARKE, R. W. 1956: Wind damage in planted stock and natural regeneration of **Pinus radiata** at Mount Stromlo, A.C.T. **Australian Forestry 20(1):** 37–9.

EDWARDS, M. V.; ATTERSON, J.; HOWELL, R. S. 1963: Wind loosening of young trees on upland heaths. **Forestry Commission Forest Record No. 50.**

ELLIOTT, D. A.; GOULDING, C. 1976: The Kaingaroa growth model for radiata pine and its implications for maximum volume production. **New Zealand Journal of Forestry Science 6:** 187.

GRUSCHOW, G. F. 1959: Observations on root systems of planted loblolly pine. **Journal of Forestry 57:** 894–6.

HARRIS, J. M. 1977: Shrinkage and density of radiata pine compression wood in relation to its anatomy and mode of formation. **New Zealand Journal of Forestry Science 7:** 91–106.

HETHERINGTON, M. W.; BALNEAVES, J. M. 1973: Ripping in tussock country improves radiata growth. **Forest Industries Review 4(12):** 2–7.

HULTEN, H.; JANSSON, K. 1978: Stability and root deformation of pine plants (**Pinus sylvestris**). Proceedings of Symposium on "Root Form of Planted Trees". **British Columbia Ministry of Forests/Canadian Forest Service Department Report No. 8:** 145–9.

HUURI, OLAVI 1978: Effect of various treatments at planting and of soft containers on the development of Scots pine. Proceedings of Symposium on "Root Form of Planted Trees." **British Columbia Ministry of Forests/Canadian Forest Service Department Report No. 8:** 101–7.

INGLIS, C. S.; CLELAND, M. R. 1982: Predicting final branch size in thinned radiata pine stands. **New Zealand Forest Service, FRI Bulletin No. 3.**

KLAWITTER, R. A. 1969: Wind damages improperly planted slash pine. **Southern Lumberman 218(2709):** 24.

KNOWLES, R. L.; WEST, G. C.; KOEHLER, A. R.: Predicting "diameter over stubs" as a method of evaluating pruning schedules (in prep.).

LINDGREN, O.; ORLANDER, G. 1978: A study on root development and stability of 6- to 7-year-old container plants. Proceedings of Symposium on "Root Form of Planted Trees." **British Columbia Ministry of Forests/Canadian Forest Service Department Report No. 8:** 142–4.

LUTZ, H. J.; ELTIR, J. B.; LITTLE, J. 1937: The influence of soil profile horizons on root distribution in white pine. **Yale University, School of Forestry Bulletin 44.**

MASON, E. G.: Toppling - what it does to the crop and what you can do about it (in prep.).

NAMBIAR, E. K. S. 1980: Root configuration and root regeneration in **Pinus radiata** seedlings. **New Zealand Journal of Forestry Science 10:** 249–63.

NANNI, V. W. 1960: Root distortion of **Pinus radiata** trees at Cathedral Peak. **South African Forestry Journal 34:** 13–22.

PARK, J. C. 1980: A Grade Index for pruned butt logs. **New Zealand Journal of Forestry Science 10:** 419–38.

——— 1982: Occlusion and the defect core in pruned radiata pine. **New Zealand Forest Service, FRI Bulletin No. 2.**

PARK, J. C.; PARKER, C. E. 1983: Regional validation studies of pruned radiata pine butt logs sawn to boards. **New Zealand Forest Service, FRI Bulletin No. 51.**

PFEIFER, A. R. 1982: Factors that contribute to basal sweep in lodgepole pine. **Irish Forestry 59(1):** 7–16.

SCHULTZ, R. P. 1973: Site treatment and planting method alter root development of slash pine. **U.S.D.A., Forest Service Research Paper SE109.**

SOMERVILLE, A. R. 1979: Root anchorage and root morphology of **Pinus radiata** on a range of ripping treatments. **New Zealand Journal of Forestry Science 9:** 294–315.

WEST, G.G.; KNOWLES, R. L.; KOEHLER, A. R. 1982: Model to predict the effects of pruning and early thinning on the growth of radiata pine. **New Zealand Forest Service, FRI Bulletin No. 5.**

WHITESIDE, I. D. 1982: Predicting radiata pine gross sawlog values and timber grades from log variables. **New Zealand Forest Service, FRI Bulletin No. 4.**

APPENDIX 1

METHOD USED TO PROJECT LOSSES DUE TO SINUOSITY OF THE KNOTTY CORE

A simulation of growth on the site was conducted using models developed at the Forest Research Institute, Rotorua. For descriptions of these models *see* West *et al.* (1982), Park (1982), Inglis & Cleland (1982), Elliott & Goulding (1976), Knowles *et al.* (in prep.), and Whiteside (1982). The models work with averages, allowing the user to nominate a thinning and pruning regime. A regime was selected which produced a pruned, 6-m, butt log with a near-cylindrical knotty core. This was necessary since the available mill conversion models do not yet take into account the practice of docking for clear lengths.

At the end of the growth sequence of the models, output can be obtained which describes the distribution of tree sizes within the stand at harvest. These data, and the data from the sinuosity measurements, were entered into the following routine which predicted effects of toppling-related pith deviation on the sawn value of each tree.

(1) The future sizes of individual trees were predicted:

$$\text{d.b.h. (future)} = (\text{d.b.h.}_{yr\,5} - \overline{\text{d.b.h.}}_{yr\,5}) \times \overline{\text{d.b.h.}}_{yr\,30}/\text{d.b.h.}_{yr\,5} \times \text{COV}_{yr\,30}/\text{COV}_{yr\,5} + \overline{\text{d.b.h.}}_{yr\,30}$$

COV = coefficient of variation of the diameters. Those variables with a subscript of yr 5 were measured in the field, while those with a subscript of yr 30 were predicted by the FRI models.

(2) Individual diameter over stub (DOS) size was predicted from mean estimates given by the models by the function used in subsequent routines of the FRI models for the same purpose (M. McGregor, pers. comm.):

$$\text{DOS}/\overline{\text{DOS}} = 0.7314 + 0.2686 \times \text{d.b.h.}/\overline{\text{d.b.h.}}$$

(3) Diameters over occlusion were estimated as a function of DOS with a relationship derived by Park (1982).

(4) The diameter of the defect core was increased by 0.5 of the measured sinuosity at the height of the sinuosity (which occurred in only one plane).

(5) The percentage of round log actually converted to timber was calculated using a function (J. Park, pers. comm.) which relates conversion to d.b.h., and gives estimates which are virtually identical to the highest level of conversion calculated with subsequent portions of the FRI models. The estimates are based on the levels actually achieved during sawing studies at the Timber Industry Training Centre mill (Park & Parker 1983).

(6) Grade index (Park 1980) was computed from the d.b.h., conversion, and defect core estimates for each tree. The percentage of clear grades and the log value were predicted from grade index, using functions described by Park & Parker (1983). Log volume was estimated as a function of d.b.h., with a relationship derived from the same data used to derive the grade index relationship.

(7) The analysis was repeated for each tree, to determine the value of the butt log if the tree had no sinuosity.