# ROOT ANCHORAGE AND ROOT MORPHOLOGY OF *PINUS RADIATA* ON A RANGE OF RIPPING TREATMENTS

ALAN SOMERVILLE

Forest Research Institute, New Zealand Forest Service, Rotorua

(Received for publication 9 October 1979)

## ABSTRACT

The root anchoring properties of 11½-year-old **Pinus radiata** D. Don, grown at Eyrewell State Forest after a range of ground preparation treatments, were tested by winching over sample trees and recording resistance with a strain gauge. The study included naturally regenerated and hand-planted stock on unripped ground, and machine-planted stock on ripped ground that had been treated in four different ways. Altogether 62 trees were winched over during February and March 1978. An increase in anchoring ability of roots in deep rips (to 120 cm) resulted in a tendency towards stem failure rather than the uprooting that characterised other treatments and which is the usual mode of failure in windthrow on the Canterbury Plains.

Sixty-one root systems were excavated in April and May 1978 and measured to examine the main differences between treatments. Natural regeneration had a greater total root weight than did planted stock. Laterals contributed two-thirds of the total root weight in all treatments and were mostly located near the surface. Deep ripping treatments markedly altered root distribution but not total root weights. The greatest differences between treatments were in the sinker roots. Increased depth of ripping resulted in redistribution of sinker roots downwards which accounted for the increased root anchorage of the trees in these treatments. While regeneration tended to form large straight-grained tap roots where soil conditions permitted, nursery stock (particularly 2/0 stock) formed few tap roots and a number of smaller diameter sinkers which often fractured at the base of the stem when under stress. Roots were significantly aligned along rips. Some treatments showed evidence of a slight asymmetrical root development associated with the north-west wind.

## INTRODUCTION

Afforestation on the Canterbury Plains has been largely on the poorer sites where shallow soils overlie compacted gravels that inhibit deep root penetration. On unripped ground, trees characteristically form a shallow root-plate of laterals and a central core of sinkers that penetrate slightly deeper but end abruptly in another matted plate. The total rooting depth usually ranges from 50 to 100 cm.

Windthrow occurred in *Pinus radiata* stands as early as 1914; severe damage occurred in 1945, 1964, 1968, and 1975 with lesser instances in other years. Windthrow, with the intact root plate lifting out of the ground, is the usual type of wind damage on the

N.Z. J. For. Sci. 9(3): 294-315 (1979).

Plains. In the 1975 storm, the incidence of stem breakage was higher where soils were deeper and root development greater (Wilson, 1976).

Ripping, nominally to either 45 cm (shallow) or 120 cm (deep), was introduced in the Canterbury Plain State forests* in 1966 and since then has been used as a standard site-preparation technique. To date around 5000 ha have been shallow ripped and around 2000 ha deep ripped. The local-body forest owners† have generally not adopted the practice.

Originally it was hoped that ripping would make hand and machine planting easier, increase survivals, and improve growth rates. The first two objectives have been largely fulfilled but the effect on growth rates is not yet clear. It was also anticipated that ripping would lead to the development of more extensive root systems, and consequently improve tree anchorage.

Brummer (unpubl. data) carried out a survey in Eyrewell Forest of young *P. radiata* damaged in the 1975 north-westerly storm, comparing wind damage in areas subjected to a range of treatments. The survey indicated that, in age classes 5 and 8 years, trees on the intersection of deep and shallow rips were less stable than trees on shallow rips only. Toppling of young trees up to age 3 years is a problem on ripped ground at Eyrewell.

This paper presents the findings of an investigation into the differences in root anchoring properties and root morphology of (i) trees growing on sites with different levels of disturbed ground from ripping, and (ii) natural regeneration compared with planted tree stock.

## SITE AND SAMPLE

The sample trees came from an area about 300 × 700 m and running into compartments 30, 34, and 35 of Eyrewell Forest. The soil type (Lismore) is a stony silty loam. Of the 62 trees in the sample, 52 were on sites that had less than 30 cm of clay and duff over compacted soil/gravel layers. On the remaining sites clay and loose soil were up to 50 cm deep over compacted soil/gravel. All other site factors appeared to be constant.

The area was planted in 1929, windthrown in the 1964 north-westerly storm, recovery logged in 1965, and windrowed, ripped, and replanted in 1966. Windrows were parallel and running in a north-east/south-west direction. An early ripping trial established in 1966 provided the range of treatments examined in this study (*see* Table 1). Regeneration from an adjacent stand of similar development was included as a further treatment.

In the ripped treatments, 2/0 *P. radiata* was machine planted with a Lowther. The No rip treatment was hand planted with 1/0 stock.

The planted crop was established at 2000 stems/ha and thinned to around 1100 stems/ha in 1974. The 1975 north-westerly storm resulted in a natural thinning. In 1976 the final thinning to about 300 stems/ha tidied up the damage and the crop was pruned to 4.5 m. The regeneration remained unpruned and had a stocking of about

* Eyrewell and Balmoral State Forests.

† Ashburton County Council, Selwyn Plantation Board, and North Canterbury Catchment Board.

TABLE 1—Ground preparation treatments

| Treatment | Name | Rip in NE-SW direction | Rip in NW-SE direction |
|---|---|---|---|
| Natural regeneration | Regen | — | — |
| Not ripped | No rip | — | — |
| Shallow | S | S at 2.4-m intervals | — |
| Deep | D | D at 7.3-m intervals | — |
| Shallow × deep | S × D | S at 2.4-m intervals | D at 10-m intervals |
| Deep × deep | D × D | D at 7.3-m intervals | D at 10-m intervals |

Shallow = rip to 45 cm
Deep = rip to 120 cm

1000 stems/ha in the sample area. The root anchorage study was carried out in January and February 1978 when the trees were 11½ years old.

The location and depth of all rips under potential sample trees were tested with a crow bar, as ground shattered by ripping had remained in a loose condition. Original trial pegs assisted in the selection of sample trees. Trees on cross rips were not always planted at the exact rip intersection and those greater than 0.6 m from the centre of either rip were rejected. Ten trees per treatment were selected, and height, diameter at breast height (d.b.h.), and root-collar diameter measurements taken. Sample trees were selected within a narrow range of heights and diameters so that the investigation tested the root anchorage of similarly developed trees and was not unnecessarily confounded by differences in growth characteristics. Regeneration showed greater variability than other treatments in anchorage behaviour and two further trees were added to the sample.

## ROOT ANCHORAGE

### *Method*

The selected trees were winched over and their resistance was recorded using a strain gauge.

The direction of pull was kept at north-west within the range ± 20°, i.e., in the same direction as tree fall under north-westerly winds. The pull was across the north-east to south-west rips and along the direction of the deep rips in the two cross-rip treatments.

The process of winching a tree over is different from the oscillating behaviour of a tree under actual high wind conditions. This part of the study was primarily concerned with the performance of the soil/root bond of the various treatments and did not examine the behaviour of trees under wind stress.

A hand winch was used for winching and the loads were measured with a load cell. The angle of the tree was recorded on an improvised topplemeter consisting of a pendulum over a large protractor. The topplemeter was attached as low as practicable to the base of the tree so that it measured the angle the base of the stem was being pulled through and not stem bend. At 2° intervals the winching was halted and the load recorded. In addition, distance measurements (*see* Fig. 1 — A, B, C) were taken so that the load could be converted into the bending moment (torque) at ground level, at the base of the stem*, with the following equation:

$$\text{Bending moment at ground level (torque)} = \text{Load} \times B \sqrt{1 - \left[\frac{A^2 + B^2 - C^2}{2AB}\right]^2}$$

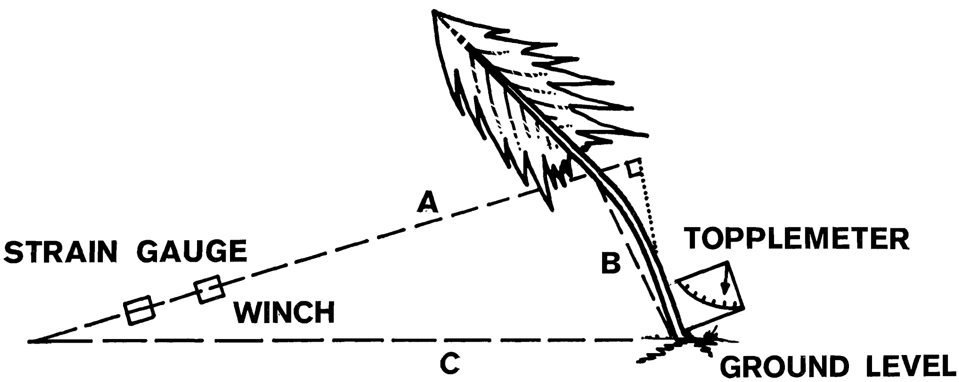


FIG. 1—Placing of strain gauge, winch, and topplemeter in relation to testing of root anchorage. Distance measurements taken along lines A, B, C were used in calculating torque.

*Data Analysis*

Computer program TEDDYBEAR (Wilson, 1976) was used for analysis of variance and covariance of the following:

(1) *Form:* To gain some appreciation of significant between-treatment or between-site variations in stem form, a crude form factor of d.b.h. over root collar diameter outside bark was tested by analysis of variance.

(2) *Angle at which maximum torque occurred:* To test whether treatments allowed different levels of tree movement before reaching maximum torque, the means of the sine-transformed angles at the maximum torque were compared by analysis of variance.

(3) *Torque:* Analysis of covariance was used to compare the adjusted mean torque (or bending moment) values of treatments at maximum torque and at 10°, 16°, and 20°. This type of analysis took into consideration the differences in size of sample trees and gave a more accurate comparison of sample means. Covariates of tree height (H), diameter at breast height outside bark (d.b.h.o.b.), root collar diameter (r.c.d.), and a volume index (VI) of H × d.b.h.o.b. × r.c.d. were tried. The latter proved most suitable.

* This point was as close as practicable to the true pivot point of the tree.

Results are given as means per tree by treatment, together with an indication of significant differences in means by Duncan's Multiple Range Test at the 5% level.

## Results

### *Sample Size*

To obtain an indication of the required sample size for statistically adequate results the sample size equation

$$n = \frac{t^2 \; s^2}{E^2}$$

where

n = size of sample required

t = Student's t test at 5% level

$s^2$ = variance of the initial sample

E = is the required 5% confidence limit about mean

was used on the adjusted mean maximum torque values, with volume index as covariate.

The initial sample size was sufficiently large to give actual confidence limits of ± 12% of the mean at the 5% probability level.

### *Sample Data and Form*

Table 2 gives the treatment means and standard deviation of height (H), d.b.h., root collar diameter outside and inside bark (r.c.d.o.b. and r.c.d.i.b.), and a simple form factor of d.b.h./r.c.d.o.b. (F).

There were no significant size or form differences among treatments.

### *Visible Failing Properties*

Three types of root anchorage failure were recognised. Table 3 gives the number of trees in each failure category by treatment. Fig. 2 shows an example of each.

(1) *Uproot:* This type of failure was characterised by the appearance of cracks in the ground on the north-west side of the tree at about 0.5-1.5 m from the stem when the lean was on average 14°, followed by the lifting of the intact root plate and the falling of the tree under its own weight. In appearance this failure was identical to the actual windthrow that is characteristic of the Canterbury Plains.

(2) *Root failure:* The tree was pulled over without lifting of the root plate and without stem failure. There was often a slight mounding to the north-west of the tree, accompanied by the sounds of roots breaking. After excavation it was found this failure was characterised by fractures at the base of the stump and by a breakdown in the bond between soil and large roots, with roots being dragged through the earth. Roots tended to remain intact where only a direct pull acted.

Some of the 8- and 9-year-old *P. radiata* appeared to fail in this manner in the 1975 storm at Eyrewell.

(3) *Stem failure:* This was visible as a break, failure under compression and tension, or splits usually from the root system up. The angles at which stem failure became apparent ranged from 6° to 40°. If stem failure were the sole factor contributing to loss of root anchorage then it would be logical to assume that it began at or before the

TABLE 2—Means and standard deviations of tree measurements in all treatments

| Treatment | $\bar{H}$ (m) | s.d. | $\overline{\text{d.b.h.o.b.}}$ (cm) | s.d. | $\overline{\text{r.c.d.o.b.}}$ (cm) | s.d. | $\overline{\text{r.c.d.i.b.}}$ (cm) | s.d. | $\bar{F}$ | s.d. | ANOVA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Regen | 11.5 | 1.1 | 18 | 1 | 23 | 1 | 20 | 1 | 0.76 | 0.03 | NS |
| No rip | 10.8 | 0.8 | 18 | 1 | 23 | 1 | 20 | 1 | 0.76 | 0.03 | NS |
| S | 11.2 | 0.6 | 18 | 1 | 23 | 1 | 20 | 1 | 0.77 | 0.03 | NS |
| D | 11.4 | 0.7 | 18 | 1 | 23 | 2 | 20 | 1 | 0.78 | 0.03 | NS |
| S × D | 11.4 | 0.7 | 18 | 1 | 23 | 1 | 21 | 1 | 0.77 | 0.03 | NS |
| D × D | 10.9 | 0.8 | 17 | 2 | 22 | 2 | 21 | 2 | 0.77 | 0.04 | NS |

NS = a non-significant difference between treatment means at the 1% level

TABLE 3—Numbers of trees in each root-holding failure category

| Treatment | Total trees | Type of failure | | |
|---|---|---|---|---|
| | | Uprooting | Root failure | Stem failure |
| Regen | 12 | 8 | — | 4 |
| No rip | 10 | 9 | — | 1 |
| S | 10 | 9 | — | 1 |
| D | 10 | 2 | 3 | 5 |
| S × D | 10 | 2 | 6 | 2 |
| D × D | 10 | 2 | 7 | 1 |

angle at which maximum torque occurred. Visible failure was often a combination of stem and root failure and such samples were categorised by visual assessment according to the dominant mode of failure.

Deep ripping resulted in roots so well anchored as to cause structural failure of the next weakest point, usually the stem or base of stump.

*Angle of Maximum Torque*

During the winching process, torque values increased rapidly and usually reached a maximum while the tree was within 10° of vertical. The mean angles at which maximum torque occurred in each treatment are given in Table 4. Means of the sine-transformed angles were compared by Duncan's Multiple Range Test.

Treatments fall into two sets that are significantly different at the 5% level — those with deep ripping and those without. The zone with deep ground disturbance allowed more movement in the tree before the maximum torque was reached and as a result more energy was used in winching the tree through to this threshold.

Roots in the confined and compacted rooting space available without deep rips had a rigid root/soil bond compared to roots in the looser soil and greater rooting space of deep rips. Assuming the root anchorage tested in this study and actual tree stability are related, then the relative instability of trees in deep rips to age 8 (refer Introduction) is apparently reversed by age 11½. This would be due to the development of sinker

TABLE 4—Mean torque values (Nm) adjusted by covariate VI and mean angles of maximum torque

| Treatment | Mean angle of maximum torque | Torque at | | | |
|---|---|---|---|---|---|
| | | Maximum | 10° | 16° | 20° |
| Regen | 6.3 x* | 12 396 NS | 10 597 x | 8 931 x | 7 673 xy |
| No rip | 6.0 x | 13 049 NS | 11 087 x | 8 225 x | 6 761 x |
| S | 5.2 x | 12 977 NS | 10 359 x | 7 921 x | 6 417 x |
| D | 8.2 y | 13 427 NS | 13 143 y | 11 794 y | 10 157 y |
| S × D | 8.6 y | 13 998 NS | 13 781 y | 11 965 y | 10 341 y |
| D × D | 8.4 y | 13 129 NS | 12 514 xy | 11 271 y | 10 001 y |

* In this table and hereafter, means followed by the letter x are not significantly different but are significantly different at the 5% level from means followed by y. Means with y are not significantly different at the 5% level. NS = not significantly different at the 5% level.


FIG. 2—Visible modes of failure. **A** — Uprooting; **B** — Root failure; **C** — Stem failure.

roots in the deep rip zone (refer Root Morphology section). As these roots develop further and the loosened soil settles, then we can anticipate more rigidity in the root/soil bond of trees on deep rips.

*Root Anchorage*

In order to examine the between-treatment variation in root anchorage, the torque values were compared by analysis of covariance, with volume index as covariate, at maximum torque and when the angles from the vertical were 10°, 16°, and 20°. The torque values beyond 20° from the vertical are not particularly important as this is well past the anchorage failing point.

The adjusted mean torque values and an indication of significant levels of differences are given in Table 4 and are illustrated in Fig. 3.

Maximum torques are not significantly different but beyond this point the anchorage behaviour falls clearly into two sets of treatment that reflect the mode of failure.

(1) Trees in deep rips retain relatively high anchorage beyond the maximum torque.

(2) Other treatments with zero or a minimum of ground disturbance result in a rapid fall-off of torque as the trees uproot.

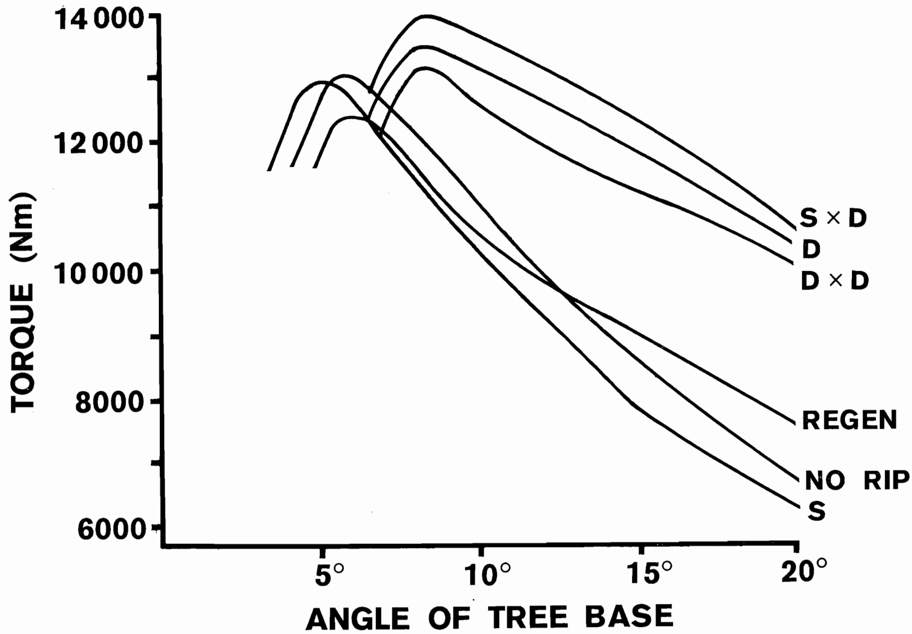


FIG. 3—Torque v. angle of tree base.

## ROOT MORPHOLOGY

### *Method*

The root systems of 61 trees from the winching study were manually excavated in April and May 1978 (one tree in the S × D treatment showed advanced decay and was discarded). The root systems were photographed and then quantitatively described using oven-dry weights and root diameters in a complex zonation system that accounted for lateral and vertical root distribution. Treatments were compared to isolate the differences between naturally regenerated and planted trees, and differences associated with various levels of ground disturbance from ripping.

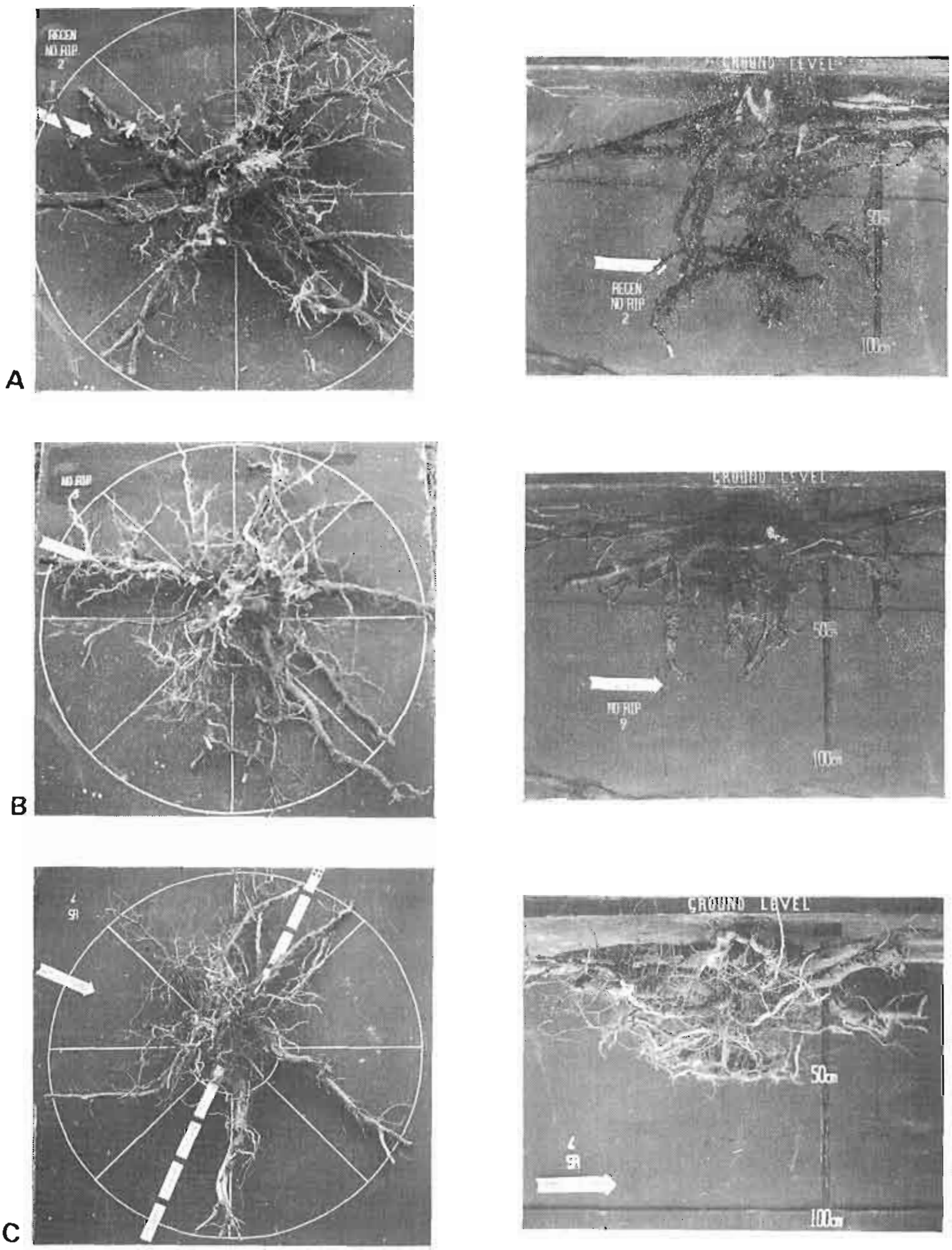


FIG. 4—View from below (left) and side view (right) of a root system from each of **A** — natural regeneration, **B** — unripped ground, **C** — ground shallow-ripped to 45 cm.

FIG. 5

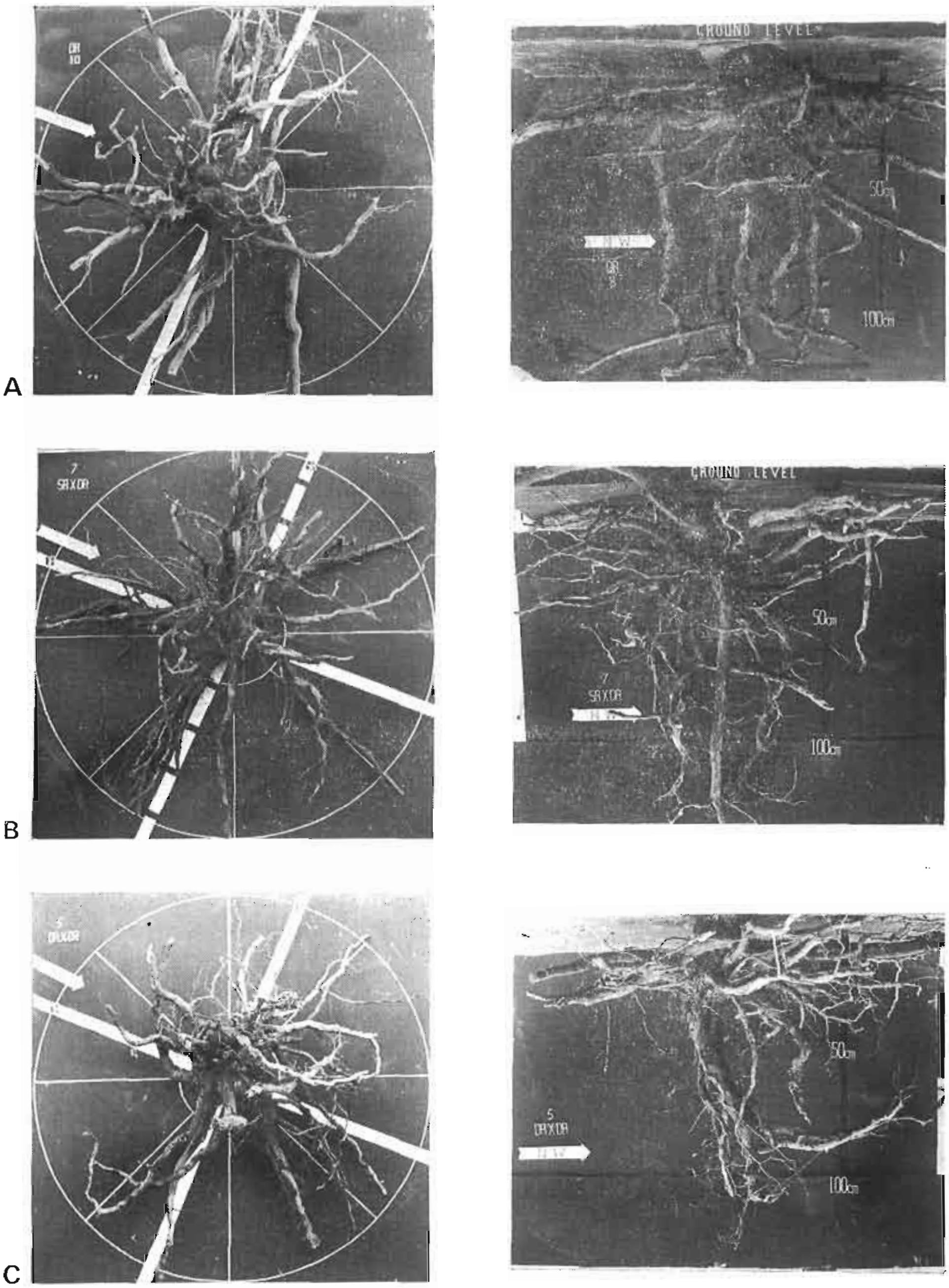


FIG. 5—View from below (left) and side view (right) of a root system from each of **A** — ground deep-ripped to 120 cm, **B** — ground cross shallow-ripped to 45 cm and deep-ripped to 120 cm, **C** — ground cross deep-ripped to 120 cm in both directions.

Characteristic examples of each treatment are shown in Figs. 4 and 5.

Only roots exceeding 1 cm small-end diameter and within 100 cm of the central tree axis were assessed.

*Zonation*

Root systems were zoned in three dimensions as follows:

(1) *Central core:* The cylinder within a 25-cm radius about the central axis. The cylinder was further divided by the ground depths 50 cm and 100 cm (horizons) (Fig. 6).

(2) *Sectors:* The space outside the central core to a radius of 100 cm about the central axis was divided vertically into eight equal sectors and then further divided horizontally by the 25-cm, 50-cm, and 100-cm horizons (Fig. 6). The mid point of sector 1 lay north-west, so rips ran through sectors 1 and 5, 3 and 7.

*Root Classifications*

Roots in the arc 0-30° from the horizontal were described as laterals, in the arc 30°-60° as obliques, and in the arc 60°-90° as sinkers. If an obviously main sinker was present it was further classified as a tap root (Fig. 7).

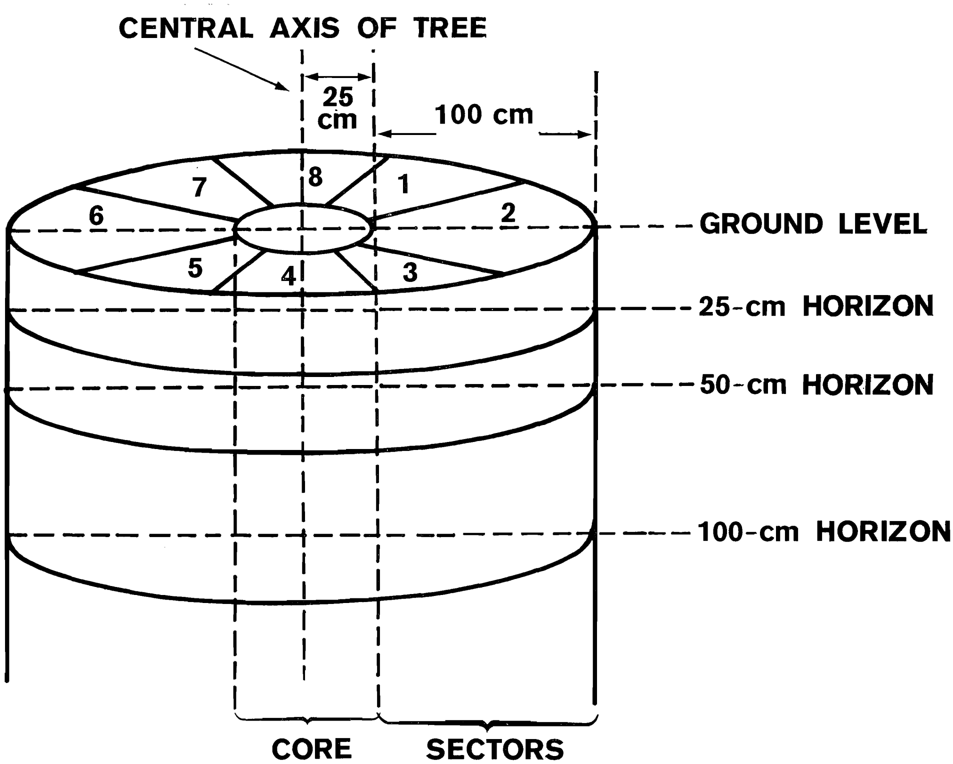


FIG. 6—Root zonation.

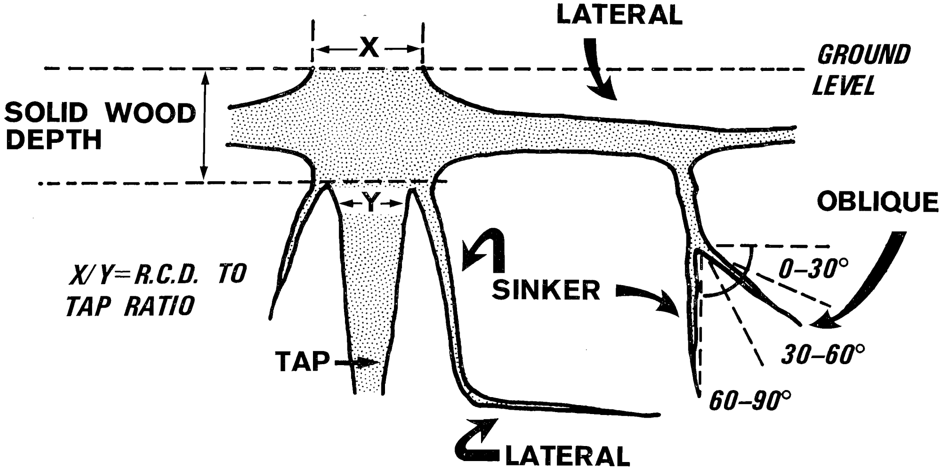


FIG. 7—Root classification.

*Dimensions*

Diameters of laterals and obliques were recorded at the core boundary by sector and by horizon. Diameters of sinkers were recorded in the core at the 50- and 100-cm horizons and in the sectors (by sector) at the 25-, 50-, and 100-cm horizons. Other measurements included r.c.d.i.b., the diameter of the tap root (if present) at the point it joined the solid wood stump, the depth of the solid wood stump (stump depth), and the total depth of roots over 1 cm (effective rooting depth or ERD). The ERD was usually clearly defined by an abrupt and often malformed end to the sinkers.

*Oven-dry Weights*

For each tree the weight of the stump and weights of sinkers, obliques, and laterals were recorded for the 35 zones. Oven-dry subsamples taken from each depth stratum were used to convert the weight data to oven-dry weights.

*Analysis*

Sets of data were compared by analysis of variance, Student's t test, and covariance analysis using volume index (VI) as the covariate.

$$VI = (H) \times \text{d.b.h.o.b.} \times \text{r.c.d.i.b.}$$

## *Results*

*Tap Roots*

The proportion of trees with tap roots in each treatment, and the tap root to r.c.d. ratio are shown in Table 5.

Observations fell into three classes. The regeneration had large-diameter tap roots where soil penetration allowed. Trees in the unripped treatment (planted with 1/0 stock) also had a tendency to form tap roots although they were slightly smaller. Trees in the other treatments (machine-planted with 2/0 stock) had little tendency to form tap roots, and those that did formed only small ones. This may well reflect the repeated wrenching the 2/0 stock would have received in the nursery.

TABLE 5—Tap roots, and tap root to root-collar diameter ratio

| | Treatment | | | | | |
|---|---|---|---|---|---|---|
| | Regen | No rip | S | D | S × D | D × D |
| No. of trees | 12 | 10 | 10 | 10 | 9 | 10 |
| No. with tap root | 10 | 6 | 1 | 1 | 3 | 3 |
| Tap root diam. : r.c.d. | 0.75 | 0.68 | 0.40 | 0.63 | 0.47 | 0.48 |
| (s.d.) | (0.10) | (0.14) | | | (0.47) | (0.09) |

### *Stump Depth*

The mean stump depths for each treatment, together with a comparison of these means by analysis of variance, are as follows:

| *Treatment* | Regen. | No rip | S | D | S × D | D × D |
|---|---|---|---|---|---|---|
| *Mean stump depth (cm)* | 25 x | 28 xz | 29 z | 29 z | 33 y | 33 y |

In this analysis of variance, means identified by z are not significantly different from each other but are significantly different from other means at the 5% level.

Naturally regenerated trees tended to have shallow stumps, although the cut-off point between stump and tap root was not always clear.

Machine-planting with large tree stock on ripped ground often results in deep planting and this may have initiated the deep stump formation in the cross rips.

### *Vertical and Radial Development of Roots*

The mean ERD per treatment, together with a comparison of these means by analysis of variance, are as follows:

| *Treatment* | Regen. | No rip | S | D | S × D | D × D |
|---|---|---|---|---|---|---|
| *Mean ERD (cm)* | 70 x | 67 x | 64 x | 108 y | 122 z | 115 yz |

The ERD of treatments that did not involve deep ripping was determined by the natural soil condition. The ERD of deep-rip treatments was determined by the shatter zone of the deep rip.

Table 6 summarises the oven-dry weights of lateral, oblique, and sinker roots in each depth stratum. Data are not actual but are adjusted by the covariate VI.

TABLE 6—Mean oven-dry weights (g) per tree by depth strata, with a comparison of means by covariate analysis

| Root type | Depth strata (cm) | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | Regen | No rip | S | D | S × D | D × D |
| Laterals (sectors) | 0-25 | 5 299 | 4 055 | 3 467 | 3 538 | 3 629 | 3 756 |
| | | x | y | y | y | y | y |
| | 25-50 | 563 | 609 | 475 | 848 | 1 097 | 625 |
| | | x | xy | x | xy | y | xy |
| | 50-100 | 186 | 32 | 338 | 132 | 18 | 102 |
| | | NS | NS | NS | NS | NS | NS |
| | Below 100 | —2 | 9 | 0 | 73 | —4 | 71 |
| | | x | x | x | y | x | y |
| | Total | 6 046 | 4 705 | 4 208 | 4 590 | 4 740 | 4 554 |
| | | x | xy | y | xy | xy | y |
| Obliques (sectors) | 0-25 | 7 | 17 | 11 | 5 | 2 | 0 |
| | | NS | NS | NS | NS | NS | NS |
| | 25-50 | 243 | 142 | 51 | 53 | 37 | 56 |
| | | x | xy | y | y | y | y |
| | 50-100 | 38 | 25 | 42 | 85 | 22 | 125 |
| | | NS | NS | NS | NS | NS | NS |
| | Below 100 | —1 | 3 | 0 | 0 | —3 | 16 |
| | | xy | xy | xy | xy | x | y |
| | Total | 287 | 187 | 104 | 143 | 58 | 197 |
| | | NS | NS | NS | NS | NS | NS |
| Stump | 0-50 | 7 001 | 7 626 | 8 785 | 8 727 | 12 018 | 9 759 |
| Sinkers (core) | 0-50 (below stump) | 1 609 | 2 042 | 1 372 | 1 167 | 883 | 1 138 |
| | | xz | z | xyz | xy | y | xy |
| | 50-100 | 605 | 482 | 719 | 1 282 | 900 | 1 124 |
| | | xy | x | xy | y | xy | xy |
| | Below 100 | 1 | —3 | 0 | 67 | 73 | 40 |
| | | x | x | x | y | y | y |
| | Total | 2 214 | 2 522 | 2 091 | 2 516 | 1 856 | 2 303 |
| | | NS | NS | NS | NS | NS | NS |
| Sinkers (sectors) | 0-25 | 55 | 20 | 24 | 45 | 60 | 13 |
| | | NS | NS | NS | NS | NS | NS |
| | 25-50 | 259 | 155 | 137 | 185 | 395 | 254 |
| | | xy | y | y | y | x | xy |
| | 50-100 | 183 | 85 | 66 | 172 | 418 | 573 |
| | | x | x | x | x | xy | y |
| | Below 100 | 2 | 10 | 0 | 27 | 105 | 70 |
| | | x | xy | x | xy | y | xy |
| | Total | 499 | 270 | 227 | 429 | 978 | 910 |
| | | xy | x | x | x | z | yz |
| | | NS | NS | NS | NS | NS | NS |

TABLE 6—continued

| Root type | Depth strata (cm) | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | Regen | No rip | S | D | S × D | D × D |
| Sinker (total) | 0-50 | 1 923 | 2 217 | 1 533 | 1 397 | 1 338 | 1 406 |
| | | xy | y | xy | x | x | x |
| | 50-100 | 788 | 568 | 785 | 1 454 | 1 318 | 1 697 |
| | | xy | x | xz | yz | yz | y |
| | Below 100 | 2 | 6 | 0 | 93 | 179 | 111 |
| | | x | x | x | xy | y | xy |
| | Total | 2 713 | 2 791 | 2 318 | 2 944 | 2 835 | 3 214 |
| Root Total | 0-25 (excludes core) | 5 362 | 4 091 | NS | NS | NS | NS |
| | | | x | 3 503 | 3 588 | 3 690 | 3 769 |
| | 25-50 | 2 673 | 2 949 | x | x | x | x |
| | (includes core sinkers 0-50) | xy | y | 2 034 | 2 253 | 2 412 | 2 074 |
| | | | | x | xy | xy | x |
| | 50-100 | 1 012 | 625 | 1 165 | 1 671 | 1 358 | 1 924 |
| | | xy | x | xy | y | xy | y |
| | Below 100 | 0 | 18 | 0 | 166 | 173 | 197 |
| | | x | x | x | y | y | y |
| | Total | 9 047 | 7 683 | 6 702 | 7 678 | 7 633 | 7 964 |
| | | y | xy | x | xy | xy | xy |
| Root Total plus Stump | | 16 042 | 15 309 | 15 487 | 16 405 | 19 651 | 17 723 |
| | | x | x | x | x | y | xy |

Table 7 summarises the cross-sectional area data of lateral and oblique roots by depth strata, and of sinkers by depth strata and core or sector classification. Data are the sums of diameters-of-roots-squared, and are adjusted by the covariate VI. Lateral and oblique roots were recorded at the core boundary, and sinkers where they crossed the 25-, 50-, and 100-cm horizons.

(1) *Laterals:* Laterals were the most important root component by weight and accounted for approximately two-thirds of the total root weight. Natural regeneration had the largest total weight of laterals. Other treatments had similar amounts. There were only slight between-treatment differences in the vertical distribution of laterals. The six treatments had a range of 77-88% of the total lateral weight in the 0-25 cm surface stratum. There was a slight redistribution of roots to the 25-50 cm stratum in the D and S × D treatments. In all treatments, only a small percentage of the lateral weight was below 50 cm. The high figure in the 50-100 cm stratum of the S treatment resulted from the inclusion of one atypical tree.

(2) *Obliques:* Obliques were an unimportant root component by weight and cross-sectional area, comprising only 1-3% of the total root mass. Regeneration and, to a lesser extent, the unripped treatment trees had significantly higher oblique root weights in the 25-50 cm stratum. Most of these additional obliques in the unripped treatment had grown down from laterals and missed the diameter assessment at the core boundary.

TABLE 7—The mean sum of the diameter squared of roots ($cm^2$) by zone per tree by treatment, with a comparison of means by covariate analysis

| Root type | Depth strata (cm) | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | Regen | No rip | S | D | S × D | D × D |
| Laterals | 0-25 | 291 | 282 | 229 | 234 | 258 | 239 |
| | | NS | NS | NS | NS | NS | NS |
| | 25-50 | 33 | 44 | 32 | 59 | 71 | 58 |
| | | xy | xy | x | xy | y | xy |
| | 50-100 | 21 | 5 | 20 | 7 | 3 | 12 |
| | | NS | NS | NS | NS | NS | NS |
| | Below 100 | 0 | 0 | 0 | 4 | 0 | 3 |
| | | NS | NS | NS | NS | NS | NS |
| | Total | 345 | 331 | 281 | 304 | 332 | 312 |
| | | NS | NS | NS | NS | NS | NS |
| Obliques | 0-25 | 0 | 3 | 0 | 0 | 0 | 2 |
| | | NS | NS | NS | NS | NS | NS |
| | 25-50 | 6 | 8 | 7 | 2 | 8 | 5 |
| | | NS | NS | NS | NS | NS | NS |
| | 50-100 | 0 | 1 | 2 | 4 | 1 | 0 |
| | | NS | NS | NS | NS | NS | NS |
| | Below 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | NS | NS | NS | NS | NS | NS |
| | Total | 6 | 12 | 9 | 6 | 9 | 7 |
| | | NS | NS | NS | NS | NS | NS |
| Sinkers (core) | 50 | 68 | 53 | 82 | 87 | 66 | 86 |
| | | NS | NS | NS | NS | NS | NS |
| | 100 | 0 | 0 | 0 | 8 | 8 | 9 |
| | | x | xy | xz | xyz | yz | y |
| (sectors) | 25 | 24 | 10 | 14 | 12 | 32 | 19 |
| | | xy | y | y | y | x | xy |
| | 50 | 13 | 12 | 6 | 14 | 40 | 45 |
| | | x | x | x | x | y | y |
| | 100 | 0 | 1 | 0 | 2 | 4 | 11 |
| | | x | x | x | x | x | y |
| Total (core and sector) | 50 | 81 | 65 | 88 | 101 | 106 | 131 |
| | | xy | x | xy | xy | xy | y |
| | 100 | 0 | 1 | 0 | 10 | 12 | 20 |
| | | x | x | x | xy | yz | z |

(3) *Sinkers:* Sinkers accounted for about one-third of the total root weight. All treatments had similar total weight of sinkers but significantly different distributions.

(i) Radial distribution of sinkers. The core to sector ratio of total sinker weight in the S and unripped treatments was 1 : 10. In the regeneration and D treatments the ratio was approximately 1 : 5, and in both cross-ripped treatments the ratio was about 1 : 3. With an increase in ground disturbance from ripping there has been outward radial redistribution in the weight of sinkers. The regeneration showed a better sinker penetration ability away from the core than other treatments without deep ripping.

(ii) Vertical distribution of sinkers. Sinkers accounted for only a small proportion of the root weight in the 0-25 cm stratum but below 25 cm they were the major root component. In the unripped treatment the weight of sinkers above and below 50 cm was in the ratio of 4 : 1. The ratio was about 2 : 1 for S and regeneration, and 1 : 1 for all the deep-ripped treatments. With an increase in ground disturbance there has been a significant redistribution of sinker weight to lower ground depth.

Cross-sectional area data support the weight data.

*Total Root Data*

Regeneration, without stump, had a significantly greater weight of root material than the planted treatments. Most of this additional root material was in laterals in the 0-25 cm surface stratum. The S treatment produced significantly less total root material than other treatments.

Trees in unripped and deep-ripped treatments had similar total root material but dissimilar distributions.

The very heavy stumps from the cross-ripped treatments gave these trees the greatest underground wood mass.

*Stump Wood Grain Properties*

In the winching exercise, in treatments without deep ripping, the intact root plate tended to lift and the tree then uprooted. The tendency in the deep-ripped treatments was for the root system to stay anchored and the stem to fail or roots to fracture.

A structurally weak point in planted trees proved to be the base of the stump where sinkers joined. Fractures in this zone were observed in stumps as follows:

| *Treatment* | Regen. | No rip | S | D | S × D | D × D |
|---|---|---|---|---|---|---|
| *No. of trees* | 12 | 10 | 10 | 10 | 9 | 10 |
| *No. with fractures in base of stump* | 1 | 1 | 2 | 4 | 4 | 4 |

Several stumps were sawn through to allow examination of the wood grain. Three examples are shown in Fig. 8. The stump from the natural regeneration treatment has straight unimpeded wood grain continuing down the stem and deep into the ground. The stumps from the cross rip treatments, originating from planted stock, have straight grain ending abruptly in a mass of grain distortions. Five planted stumps were sawn and all had similar patterns. The stump from the cross shallow × deep rip treatment also shows the fractures associated with these grain distortions.

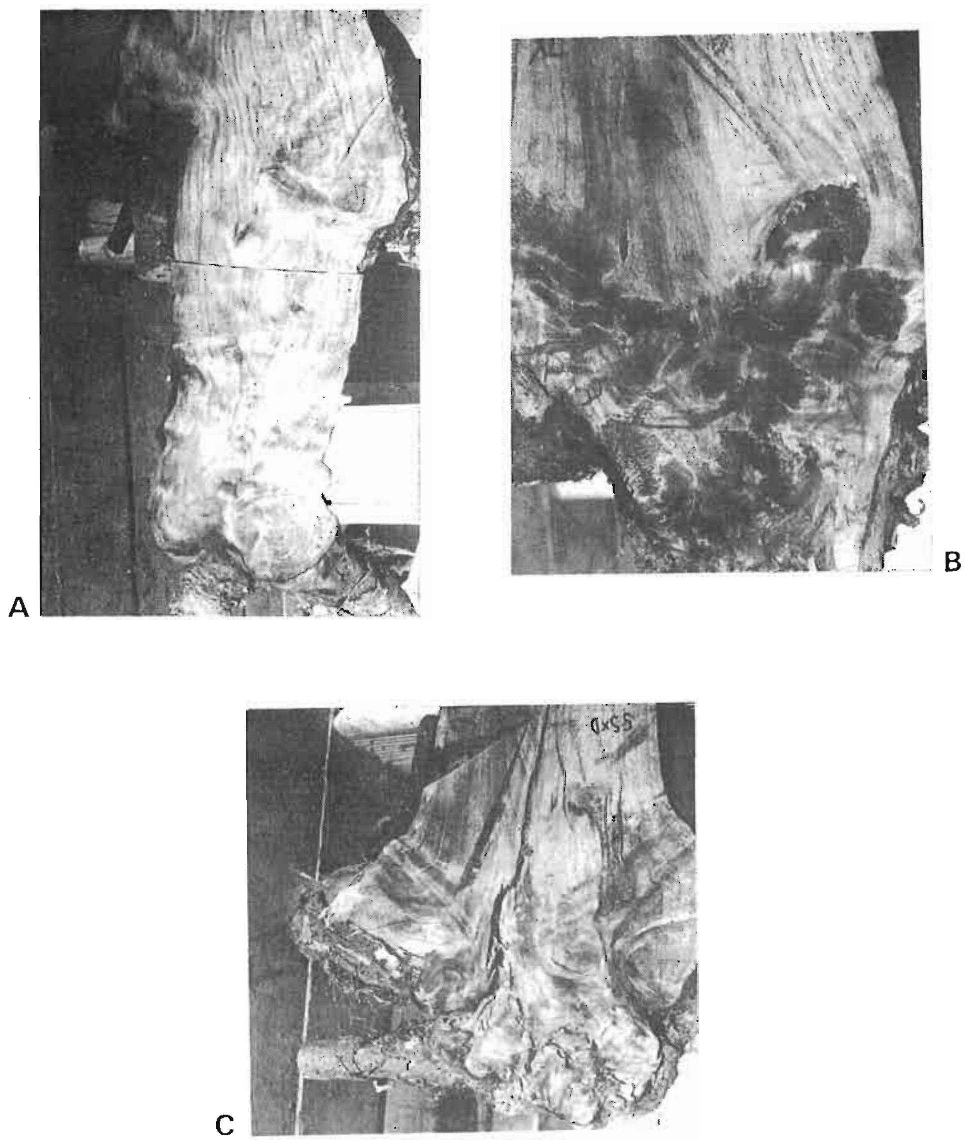


FIG. 8 — Vertical section through stumps from **A** — regeneration, **B** — cross deep × deep rip treatment, **C** — cross shallow × deep rip treatment.
In each photograph the top boundary represents ground level.

*Root Alignment with Rips*

To examine whether there was root alignment with rips, weight and cross-section data were grouped by ripped/unripped sectors and examined by the Student's t test for paired plots. Results are shown in Table 8. The weight analysis compares the weight of roots at all depths for sectors with rips with the data for the corresponding unripped

TABLE 8—Data are per tree and are the sum of the grouped sectors. The probability levels at which means are significantly different are given to 10%

| | Root type | Sectors | Sectors compared S 1 & 5 with 3 & 7 | D 1 & 5 with 3 & 7 | S × D 1,3,5,7 with 2,4,6,8 | D × D 1,3,5,7 with 2,4,6,8 |
|---|---|---|---|---|---|---|
| Weights | Lats & Obliq. | Ripped | 1573 | 1678 | 2710 | 2696 |
| | | Unripped | 784 | 797 | 2463 | 2022 |
| | | | 10% | 5% | NS | 10% |
| | Sinkers | Ripped | 134 | 144 | 762 | 397 |
| | | Unripped | 37 | 62 | 275 | 492 |
| | | | NS | NS | 10% | NS |
| Area ($cm^2$) | Lats & Obliq. | Ripped | 85 | 93 | 176 | 190 |
| | | Unripped | 65 | 50 | 172 | 128 |
| | | | NS | 5% | NS | 10% |

sectors. The cross-sectional area analysis compares data for laterals and obliques at the core boundary for the same sectors.

Laterals and obliques had a tendency to follow rip zones. The sinker mean root weight data also suggest a similar tendency. This was supported by a visual examination of the excavated root systems.

Data show far more alignment in the single rip treatments where the trees were more accurately planted in the centre of the rip and hence the sectors in the data collection more closely coincide with the actual shattered and non-shattered zones. Root alignment could be a consequence of enhanced root penetration through the loose ripped soil with some contribution from the characteristic sweeping of roots in the machine planting operation. The latter factor would have less bearing in sinker formation.

*Root Development in Response to the North-west Wind*

To examine whether north-westerly winds caused any asymmetrical root development, the upwind sectors (8, 1, and 2) were compared with the downwind sectors (4, 5, and 6) of each tree in the whole sample and within treatments by the paired plot Student's t test. Results are shown in Table 9. Weight data are average per tree data for the sum of the three sectors. Area data are the corresponding data for laterals and obliques at the core boundary.

The means that vary significantly suggest an atypical root development with a heavier sinker and lateral development on the windward side. This trend is not always consistent and is reversed in the treatment with maximum ground disturbance (D × D).

## DISCUSSION

### *Root Anchorage*

The study showed that the trees on unripped ground were close to maximum root anchorage before structural failure. More energy input in winching the trees on deep rips resulted in stem and base of stump failure.

TABLE 9—Comparing upwind and downwind sectors by weight and cross-sectional area. The probability levels at which means are significantly different are given to 10%

| | Root Type | Sectors | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Regen | No rip | S | D | S × D | D × D | Total |
| Weight (g) | Lats & Obliq. | Upwind | 2512 | 1880 | 1696 | 1724 | 2106 | 1374 | 1899 |
| | | Downwind | 2182 | 2066 | 1131 | 1364 | 1547 | 1953 | 1726 |
| | | | NS | NS | 5% | NS | NS | NS | NS |
| | Sinkers | Upwind | 260 | 181 | 46 | 229 | 441 | 201 | 224 |
| | | Downwind | 163 | 7 | 61 | 11 | 372 | 469 | 177 |
| | | | NS | 1% | NS | 5% | NS | NS | NS |
| Area ($cm^2$) | Lats & Obliq. | Upwind | 138 | 132 | 104 | 111 | 156 | 80 | 122 |
| | | Downwind | 137 | 145 | 102 | 105 | 104 | 124 | 120 |
| | | | NS | NS | NS | NS | 5% | NS | NS |

The study did not determine whether trees on deep rips under actual windthrow conditions would fail in the same manner as in the winching exercise. It would seem likely that the mode of failure would be similar since roots were so well anchored in deep rips as to show little tendency to uproot and only a small increase in bending moment caused other structural failure.

Deep ripping resulted in increases of up to double the vertical root space so its effects are likely to remain as the tree matures.

Regeneration, with large straight-grained tap roots had potentially the strongest root system, anchorage behaviour depending on the available rooting space.

The characteristic mode of failure in past windthrows on the Canterbury Plains has been uprooting, and fallen trees have tended to live indefinitely, recovery logging usually spanning several years. Where stems fail, degrade is rapid and recovery may necessarily have to be completed in a matter of months.

If future windthrow on the Plains gives rise mainly to uprooting and is confined to the oldest of adequately distributed age classes, then the handling of the damaged material could be within the region's normal capacity. Processed wood may be stored and long-term supply may not be seriously affected. If the proportion of stem failure were high then the recovery requirements could be huge and the situation one of chaos.

The sample trees on other than deep-ripped ground were already near to maximum anchorage before structural failure, the next weakest point. Deep ripping on this site, because it improves root anchorage, is therefore a potentially dangerous practice — and one that cannot be corrected once done. However, it could have application for the first 100 m of stand immediately downwind from exposed windward edges as this zone is the most prone to windthrow (Somerville, in prep.). Deep ripping in this high-risk zone may offer a stability advantage to the stand as a whole whilst not increasing the likelihood of stem failure throughout the interior of the stand.

### *Root Morphology*

The amount of wood material below the ground remains relatively unaffected by treatment, but the vertical distribution and form of the roots is very dependent on treatment. The morphology and hence the anchorage behaviour of root systems on this site are very much in the forest manager's hands.

Natural regeneration offers certain structural advantages over nursery stock as it forms large-diameter straight-grained tap roots. With ripping these tap roots would penetrate deeply and result in very strong, well-anchored root systems. Such root systems are also possible with direct seeding, and probably with nursery stock that has had appropriate tending and careful planting.

The surface lateral root system which comprised the main body of roots remained essentially unchanged by treatment. Increasing the vertical rooting space redistributed root mass downwards, and downwards and outwards, mainly in the form of sinkers. These sinkers increased the root anchorage of trees on deep rips.

## ACKNOWLEDGMENT

The assistance of G. Filer in the planning and preparation of this study is gratefully acknowledged.

## REFERENCES

SOMERVILLE, A. R.: Wind stability: silviculture and forest layout (in prep.).

WILSON, H. H. 1976: The effect of the gale of August 1975 on forests in Canterbury. **N.Z. J. For. 21(1):** 133-40.