

TOPPLING IN YOUNG PINES: TEMPORAL CHANGES IN ROOT SYSTEM CHARACTERISTICS OF BARE-ROOT SEEDLINGS AND CUTTINGS

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ABSTRACT

Bare-root seedlings and bare-root cuttings of *Pinus radiata* D. Don at three ages (11, 27, and 36 months) were excavated by hand from a nursery and two trial sites in the North Island, New Zealand. A total of 48 trees were sampled, 24 from each plant type. Root system characteristics were compared by investigating differences in above- and below-ground biomass, root length, root size, and root biomass distribution. It was found that by 36 months a greater portion of wind-induced biomass had been allocated to the near-stem lateral roots of bare-root cuttings than bare-root seedlings. The presence of this indicated growth over and above what could be expected solely from age, and was likely to be related to a wind-induced adaptive growth response. The development of juvenile-tree stability can be attributed primarily to the increasing rigidity of those near-stem areas of the root system subjected to higher concentrations of wind-induced stress. As only a portion of the root system, i.e., the near-stem roots, contributes to tree stability, the use of root:shoot ratio as a primary indicator of tree wind-stability ranking could be suspect.

Keywords: biomass allocation; root biomass; root:shoot ratio; root stiffness; toppling; wind stability; wind-throw; *Pinus radiata*.

INTRODUCTION

Wind instability can be a serious problem with *Pinus radiata* stands. Young pines can be unstable for up to 5 years after planting, particularly on wet sites, or if subjected to strong wind events accompanied by high-intensity or prolonged rainfall (Watson & Tombleson 2002). This early instability, known as toppling, was defined by Lines (1980) as a wind-induced lean caused when a tree is rotated below ground level about a point located along the stem axis. A subsequent empirical definition (Mason 1985) described a tree as toppled if it acquired a lean greater than 15° from vertical. This definition was based on the

observation that a permanent lean of 15° in juvenile *P. radiata* was likely to result in some degree of stem distortion at maturity.

The consequences of toppling to the New Zealand forest industry are wide ranging and, surprisingly, by and large unevaluated. The follow-on effects of toppling in young stands are a decrease in the choice of final-crop trees and an increase in the possibility of future wind-throw of previously toppled trees due to weakened root systems. As toppled trees mature, butt sweep and subsequent formation of compression wood, particularly in the high-value lower stem, can have a severe impact on clearwood production and hence final-crop value (Forest Research Institute 1987). Post-harvesting, the effects of toppling can downgrade the higher-value butt logs and consequently lower the production of high-quality veneer and sawn timbers. Financial losses due to increased appraisal, transport, handling, and sawmilling process-times are costs not often acknowledged. Compression wood is in many aspects the most insidious of defects to encounter. It not only reduces strength and causes distortion in apparently "clear" timber, but being of shorter fibre and containing less cellulose, tends to require more chemicals in processing and yield a lower quality and quantity of pulpwood (Harris 1977).

In this study, we compared the root systems of 11-, 27-, and 36-month-old *P. radiata* bare-root seedlings and bare-root cuttings to investigate how temporal changes in above- and below-ground biomass, root distribution, and allocation may contribute to the development of wind stability in juvenile trees.

METHODS

Site Description

Pinus radiata bare-root seedlings and cuttings of three ages (11, 27, and 36 months) were excavated by hand from three sites in the North Island, New Zealand:

- (1) The 11-month-old trees were sampled from the Forest Research nursery, Rotorua ($38^\circ 09' S$, $176^\circ 16' E$).
- (2) The 27-month-old trees were excavated from a Bay of Plenty toppling trial, planted on a fertile ex-farm site situated at approximately 80 m elevation on rolling hill country above Welcome Bay, about 8 km south-east of Tauranga ($37^\circ 44' S$, $176^\circ 13' E$). The trial faced north-west (315°) on a slope of around 10° .
- (3) The 36-month-old trees were dug from a Taranaki planting trial, located at about 120 m elevation on an exposed, fertile, farm site on the western frontal hill country of the Waitui District, roughly 20 km east of New Plymouth ($39^\circ 06' S$, $174^\circ 18' E$). The site faced approximately north-east (53°) on a 15° slope.

The climate at Welcome Bay and at Waitui is temperate marine, with moderately warm summers and cool wet winters. Each site was subjected to coastal up-valley prevailing winds that travelled across slope from the north-east and north-west respectively. Both sites occasionally experienced strong southerly winds.

The Welcome Bay toppling trial was underlain by hill soils of the Te Puke series. The soils, mainly Kaharoa and Waihi ash over Taupo ash, are represented by yellowish brown sandy to silt loams changing to silt-clay loam and then clay loam with depth (Rijkse & Cotching 1995). The Waitui planting trial was underlain by Stratford coarse sandy loam,

a member of the Stratford volcanic ash suite of soils. In general, the soils are a dark brown coarse sandy loam over a dark yellowish brown to dark brown friable silt loam changing to a more compacted, yellowish brown, greasy silt loam with depth (Aitkens *et al.* 1978). The characteristics of both soils appeared to present no restriction to root growth or root system development.

Sampling

Two plant types were investigated: bare-root seedlings and bare-root cuttings. The growth and form ratings and, where available, seedlot collection numbers (Forest Research Institute 1987) of the seedlings were GF19:97/4B, GF19:98/464, and GF19 and the cuttings were GF26:98/816, GF27:92/195, and GF23 for the 11-, 27-, and 36-month trees, respectively. A total of 48 trees were sampled. From each plant type 12, six, and six randomly selected trees were sampled from the 11-, 27-, and 36-month age-classes, respectively. Tree age was taken to be zero at their nursery establishment date.

For all trees, the following above-ground parameters were measured: height, diameter at breast height (dbh), and/or root collar diameter (RCD). The trees were partitioned into stem, branch, and foliage components and the oven-dry biomass weight was determined.

The 27- and 36-month root systems at Welcome Bay and Waitui were excavated and sampled as described by Watson & Tombleson (2002). Briefly, a trench 1.0–1.5 m deep was dug around each tree at a radius of 1.5 m from the base of the stem and the resulting root-soil block was excavated using hand tools. As a surrogate for root architecture determination, each tree root system was divided into 45°-sectors orientated to true north, then partitioned at 0.5-m distances from the stump and 0.5-m depths below ground level. Three root types were considered: lateral roots (inclined <45° to ground surface), sinker roots (originating from the underside of lateral roots, and those roots inclined >45° to ground surface), and tap roots (originating from the root bole or the stump, and growing directly beneath it). For the purpose of this study the root bole was defined as that portion of the tree between ground-level and the below-ground base of the stem. In each sector, root types were collected from each 0.5 × 0.5-m block, partitioned into 5-mm-diameter classes, weighed, and those roots >2 mm in diameter were measured for length. Field root samples from each diameter class were dried to a constant weight at 70°C in a forced-air drying oven to obtain the percentage moisture loss, which was then used to calculate the dry root biomass.

To conform to current planting practice, the roots of the 11-month-old nursery trees were trimmed to a length of 10 cm (measured from the root collar) prior to evaluation. The trees were then partitioned into their principal below-ground components and appraised in a similar fashion to the older trees.

For each site, two-sample t-tests, part of the statistical package GENSTAT (GENSTAT 2002), were used to test for differences between the two plant types. Where the variances of the two samples were not equal, a corrected t-test was performed that used a separate estimate of the variances, not a pooled estimate (*see* Zar 1999). The nature of the contract under which this research was done did not allow time for the establishment of a purpose-planted field trial. It is appreciated that as each age group of trees was sampled from a different site, it is difficult to separate out the possible effects of site difference on tree growth characteristics. To counter this, an effort was made in choosing Welcome Bay and

Waitui to ensure some degree of site uniformity, in so far as both were fertile ex-farm sites with northerly aspects, and similar latitude, altitude, climate regime, soil characteristics, exposure, and slope.

RESULTS

Above-ground Tree Components

Tree size parameters

As there was no significant difference in tree height between plant types, at least for the period represented by the study, it could be assumed that the heights of both plant types increased at a similar rate (Fig. 1). At age 11 months, the root collar diameter (RCD) of the seedlings was significantly less than that of the cuttings. At 27 months there was no significant difference, and by 36 months the difference had reversed. This suggests that the RCD of bare-root seedlings increased at a greater rate than that of bare-root cuttings.

Biomass

There was no significant difference in mean branch weight between the two plant types during the 3 years of tree growth considered in the study. However, the data indicate that both stem and foliage biomass of bare-root seedlings increased at a faster rate than those of bare-root cuttings (Fig. 2).

Below-ground Tree Components

Biomass

At 11 months, bare-root cuttings showed a significantly greater mean lateral root biomass than bare-root seedlings. However, this difference was not apparent in the 27- and 36-month-old trees (Fig. 3). There was no difference in mean tap root and sinker root biomass between the seedlings and cuttings during the 36-month period of investigation. This indicates similar rates of increase in biomass for these components for both plant types. The root bole biomass of the cuttings was significantly greater than that of the seedlings at 11 months. By 36 months this difference had reversed, indicating that the rate of increase in root bole biomass was greater for bare-root seedlings than for bare-root cuttings.

Root length

At age 11 months, the mean total lateral root length of bare-root seedlings was significantly less than that of bare-root cuttings. At 27 months there was no difference, and by 36 months the difference had reversed (Fig. 4). Until 27 months, the mean total tap root length of bare-root seedlings was similar to that of bare-root cuttings, but by 36 months the tap root length of the seedlings exceeded that of the cuttings. This indicates that, overall, both the lateral root and tap root lengths of the seedlings increased at a greater rate than those of the cuttings.

Root:shoot ratio

A comparison of the mean root:shoot ratios showed no significant difference ($p>0.05$) between plant types for the three sites represented in this study. For the 11-month-old trees,

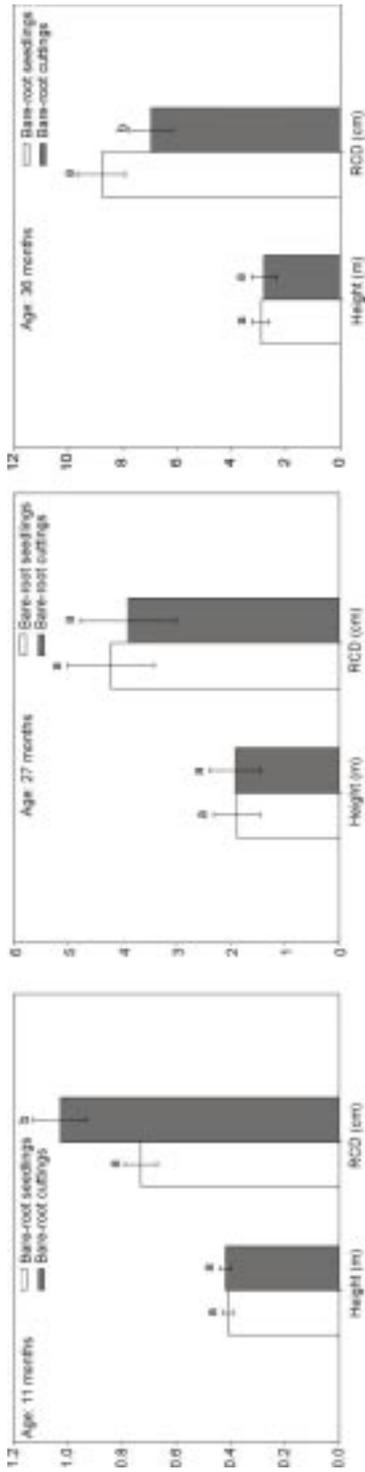


FIG. 1—Means of tree size parameters of *Pinus radiata* bare-root seedlings and bare-root cuttings. Standard errors of means with the same letter are not significantly different at the 5% level.

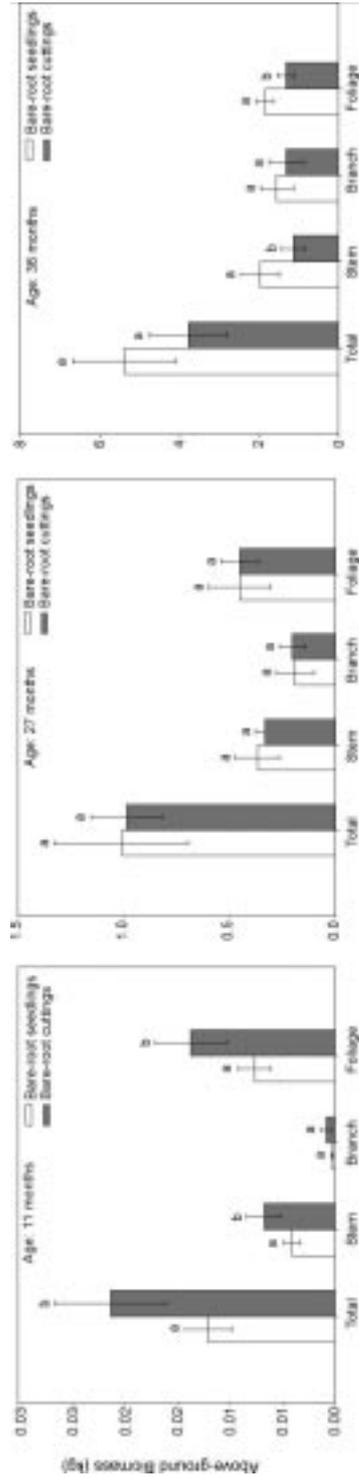


FIG. 2—Means of above-ground biomass parameters (total, stem, branch, and foliage) of *P. radiata* bare-root seedlings and bare-root cuttings. Standard errors of means with the same letter are not significantly different at the 5% level.

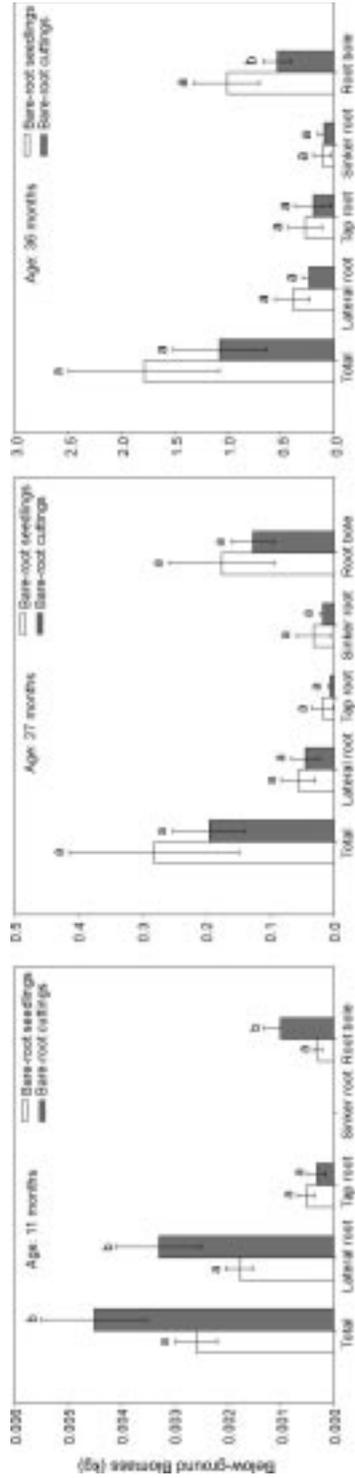


FIG. 3—Means of below-ground biomass parameters (total, lateral, tap and sinker roots, and root bole) of *P. radiata* bare-root seedlings and bare-root cuttings. Standard errors of means with the same letter are not significantly different at the 5% level.

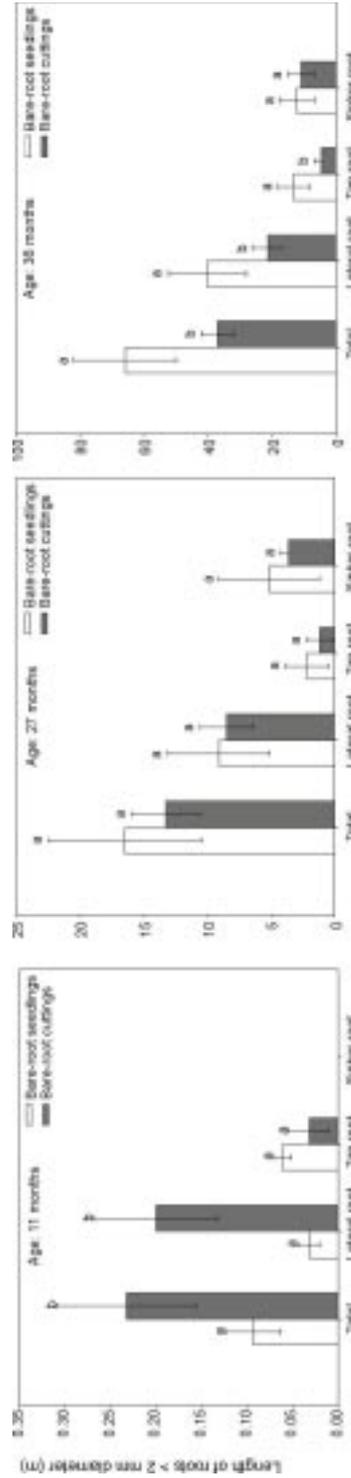


FIG. 4—Root length means of roots >2 mm diameter (total, lateral, tap, and sinker roots) of *P. radiata* bare-root seedlings and bare-root cuttings. Standard errors of means with the same letter are not significantly different at the 5% level.

there was a significant difference ($p < 0.05$) within plant-types when the root:shoot ratios were compared before and after trimming.

DISCUSSION

International research, mainly on Sitka spruce (*Picea sitchensis* (Bong.) Carr.), suggests that wind-induced stresses tend to concentrate at the base of a tree and are transferred, via the near-stem roots, to the surrounding soil. To help dissipate localised and potentially damaging concentrations of stress, biomass is allocated from other parts of the tree to those roots under greatest load (Coutts *et al.* 1999; Nicoll *et al.* 1995; Nicoll & Ray 1996). As a consequence, the lateral roots immediately adjacent to the stem increase in diameter (Coutts *et al.* 1999) in what Wilson (1975) described as the “zone of rapid taper”. The proximity of the near-stem roots to the stem varies according to tree age, wind exposure, and the direction of the predominant wind (Coutts *et al.* 1999). In mature Sitka spruce the zone of “wind-induced thickening” can extend up to 1 m from the stem. It could be similar in *P. radiata*. An increase in root diameter will bring about a decrease in root flexibility and thereby an increase in the rigidity of those areas of the root system subjected to high concentrations of wind-induced stress. This results in a decrease in tree susceptibility to wind movement and subsequently an improvement in tree stability.

With time, the near-stem lateral roots of young trees thicken to become supporting structural roots. In exposed situations, a secondary thickening will occur, whereby the size and shape of the root cross-section will be altered in response to wind-induced root movement (Wood 1995). As the bending rigidity of a root is directly proportional to the fourth power of its diameter (Ennos & Pelerin 2000), even a small diameter increase will generate a significant increase in root rigidity. Subsequently, as the proportion of wind-induced biomass allocated to the near-stem lateral roots is increased, there will be a notable increase in root stiffness and hence root anchorage (Blackwell *et al.* 1990; Ray & Nicoll 1998; Watson & Tombleson 2002).

The rate of increase in total root length of the lateral and tap roots of bare-root cuttings is less than that of bare-root seedlings (Fig. 4), but the rates of increase in lateral and tap root biomass of both plant-types are similar (Fig. 3). This indicates that the roots, and in particular the near-stem roots, of bare-root cuttings are, in general, thicker and therefore of greater rigidity than those of bare-root seedlings. This finding is supported by the observation that root distortion at planting is less likely in bare-root cuttings than bare-root seedlings because of their “more solid and rigid root systems” (Forest Research Institute 1987, 1991). This initial advantage in root rigidity would help to account for the greater resistance to toppling observed in bare-root cuttings.

By 36-months:

- (a) Bare-root seedlings had a significantly greater root collar diameter than bare-root cuttings (Fig. 1). An increase in RCD denotes a stiffer stem. This would increase the amount of energy required to bend the stem, which in turn would leave less wind-related energy available to induce diameter increase and hence root stiffness in the near-stem roots.
- (b) Bare-root seedlings had significantly more foliage than bare-root cuttings (Fig. 2). More foliage is often associated with greater wind drag and hence increased wind instability.

Collectively (a) and (b) may increase the susceptibility of bare-root seedlings to toppling.

Initially, attempts were made to directly compare the two plant-types across age-classes, but as the data differed between data sets by several orders of magnitude, we came to the conclusion that the only way to compare “apples with apples” was to normalise the data. Hence, when the biomass allocated to the near-stem (i.e., the larger) lateral roots was normalised and expressed as a percentage of total root biomass, a comparison of the temporal biomass allocation changes that occurred within and between plant types was possible. From this type of analysis some indication of their comparative degree of wind stability was obtained (Fig. 5).

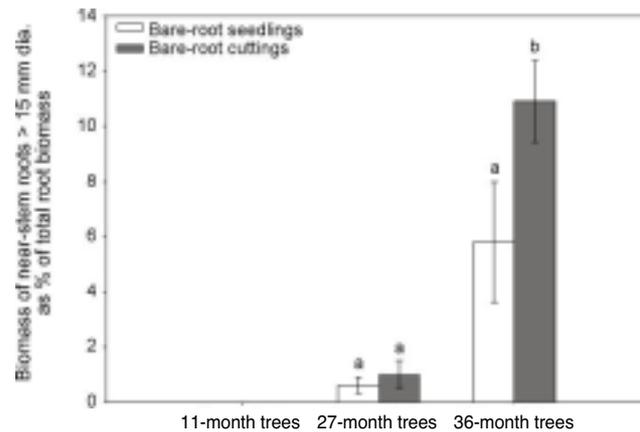


FIG. 5—Distribution of biomass allocation of lateral roots >15 mm diameter in relation to plant type. Standard errors of means with the same letter are not significantly different at the 5% level.

By 27 months, both plant types had allocated only a minor percentage of their total root biomass to their near-stem lateral roots. The non-significant percentage difference suggests that the development of the near-stem roots of both plant types was for the most part growth-induced. At 36 months, as would be expected, a greater portion of biomass had been allocated to the near-stem roots of both plant types. However, a significantly greater percentage of biomass had been allocated to the near-stem roots of bare-root cuttings than of bare-root seedlings (Fig. 5). The presence of this increased biomass percentage indicates growth over and above what could be expected solely from age, and is very likely to be related to a wind-induced adaptive growth response. The extra percentage of biomass of the near-stem roots of bare-root cuttings indicates a greater increase in the rigidity of the near-stem roots, which in turn would provide a greater increase in root anchorage and hence wind stability. Note that in Fig. 5 the 15-mm diameter was selected simply because 15 mm was the lower end of the largest root diameter-class common to both the 27- and 36-month-old trees, and not for any functional criteria.

The data from this study indicated that there was no significant difference in root:shoot ratio between plant-types, whereas elsewhere in the text it has been suggested that bare-root cuttings have greater wind stability than bare-root seedlings. The following explanation is presented for this apparent inconsistency: because wind-induced stresses are dissipated

along the length of the root as they are transferred to the surrounding soil (Stokes 2000), roots or those parts of roots beyond the “zone of rapid taper” play little or no part in tree wind-stability (Coutts *et al.* 1999; Nicoll & Dun 2000). As only a portion of the root system, i.e., the near-stem roots, contributes to tree stability (*see* Fig. 5), the use of a ratio that includes the total root biomass as a primary indicator of tree stability is at best suspect. All of the above-ground biomass contributes to tree instability, but not all below-ground biomass contributes to tree anchorage, i.e., the resistive moment is provided by only a portion of the total root mass. Consequently, the use of differences in root:shoot ratio to indicate tree wind-stability ranking is not realistic. The authors have yet to sight a peer-reviewed manuscript that shows an objective association between root:shoot ratio and wind-stability ranking. This may be because such a link either has yet to be shown, or does not exist.

CONCLUSION

The temporal development of juvenile-tree stability can be attributed primarily to the increasing rigidity of those near-stem areas of the root system subjected to higher concentrations of wind-induced stress.

A wind-induced increase in diameter growth and the subsequent greater percentage of structural biomass allocated to the near-stem lateral roots can be considered as an indicator of emerging tree stability.

To develop plant types for greater resistance to toppling, this study suggests that root stiffness, i.e., less root flexibility, should be a consideration in any selection or breeding programme.

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