STRUCTURAL ROOT MORPHOLOGY AND BIOMASS OF THREE AGE-CLASSES OF *PINUS RADIATA*

ALEX WATSON and COLIN O'LOUGHLIN
Ministry of Forestry, Forest Research Institute,
P.O. Box 31-011, Christchurch, New Zealand

(Received for publication 1 December 1988; revision 13 June 1989)

ABSTRACT

The root systems of 13 *Pinus radiata* D. Don. trees from three age-classes in Mangatu Forest were hydraulically excavated. Each system was drawn in plan and elevation, then dissected and sorted into six diameter-classes for weight and length measurements to obtain information on changes in root biomass and root extension with time. Lateral roots had a maximum length of 4.7, 6.4, and 10.4 m at ages 8, 16, and 25 years respectively. Vertical roots grew to depths of 2.1, 2.6, and 3.1 m for the three age-classes respectively. At 8 years the root bole contained 40% of the total root weight. This increased to approximately 50% after 16 years. Stand biomass of roots was 9, 67, and 151 tonnes/ha at a stocking rate of 253 stems/ha for the three age-classes respectively. Total root weight (kg) was regressed on diameter at breast height (cm) to give the relationship: $\log_e$(total root weight) = 2.24 $\log_e$(dbh) - 2.68 (r^2 = 0.99), which can be used to estimate the below-ground biomass from dbh.

Keywords: root systems; biomass; morphology; slope stability; *Pinus radiata*

INTRODUCTION

The mechanical reinforcement given by tree root systems to erosion-prone hill soils has been the subject of much research over the last 25 years (Bishop & Stevens 1964; O'Loughlin 1974; Ziemer & Swanston 1977; Wu *et al.* 1979; Ziemer 1981; Tsukomoto & Kusakabe 1984; O'Loughlin & Zhang 1986). There has also been an increase in research on root biomass and morphology over recent years. This research has tended to look at the morphology/biomass of trees of similar age and same species or has compared the morphology/biomass of different species (Will 1966; Squires *et al.* 1978; Deans 1981; Henderson *et al.* 1983; Strong & La Roi 1983; Eis 1987), but less research has been carried out on how root morphology/biomass of a single species changes over two or more decades (McMinn 1963; Fayle 1975; Coutts 1983).

After logging, *Pinus radiata* root systems lose half their tensile root strength within 15 months and the balance within 3 years (O'Loughlin & Watson 1979). A replacement crop establishes a root system of sufficient strength by year 8 to contribute significantly to soil stability, and by year 30 *P. radiata* has probably attained its maximum root spread and soil reinforcement capacity (O'Loughlin 1985).

The purpose of this study was to investigate changes in morphology and biomass of the structural root system from the time a *P. radiata* crop begins to reinforce the soil (at 8 years) to the time assumed maximum capacity for soil reinforcement is reached (25 years). Most studies of root systems deal with roots ranging from < 2 mm to about 50 mm in diameter (e.g., Jackson & Chittenden 1981; Strong & La Roi 1983), but trees of the ages studied here had roots that were nearly an order of magnitude larger than this. Roots less than 0.2 cm in diameter on trees of such ages were not considered to be major structural contributors to slope stability, and were not included in diameter-class-based assessments. They were, however, included in biomass estimates.

STUDY SITES

Root systems were hydraulically excavated from trees in three stands aged 8, 16, and 25 years at Mangatu Forest, east of the Raukumara Range in the headwaters of the Waipaoa and Mangatu Rivers (Fig. 1). Mangatu Forest is underlain by severely crushed, sheared, and distorted sandstones, mudstones, and shales, giving rise to a variable topography (Black 1980). The terrain varies from steep dissected slopes (25–40°) on hard, fine-grained sandstone to gentle (12–15°) slopes on clay-rich shales. Terrain on clay-rich shales is generally more erodible (Pearce *et al.* 1987).

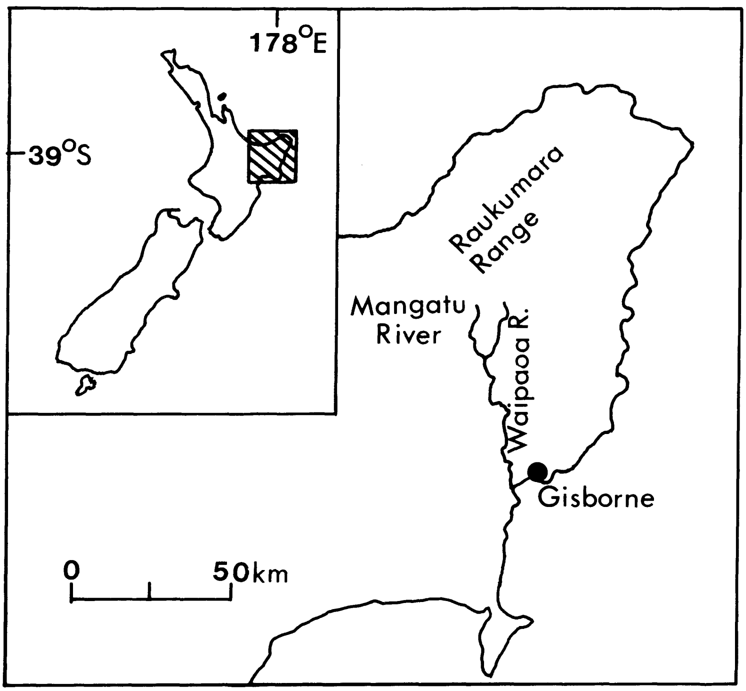

FIG. 1 — Location map of study area.

Mean annual rainfall at lower elevations (Mangatu Forest, Station No. D87284, altitude 182 m) is approximately 1320 mm, increasing to 2100 mm at higher elevations (Mt Arowhana, Station No. D87181, altitude 732 m) (New Zealand Meteorological Service 1984).

The three study sites were determined mainly by the proximity of stands of the required age to a reliable source of water. Trees representative of each stand were chosen on terrain suitable for hydraulic excavation.

Eight-year-old Stand

This stand was planted in 1978 at an altitude of 700 m in the headwaters of the Tikihore Stream. The site faced south-west (210°) with an average slope of 26°. The five sampled trees had an average height of 9.5 m with a mean stump diameter of 21 cm (0.2 m above ground-level) (Table 1). The stand had been pruned and thinned to a final stocking rate of 236 stems/ha in 1985.

TABLE 1–Age and size of sampled trees and dimensions of their root systems

Tree No.	Age (yr)	Stump diameter (cm)	Maximum lateral length (m)	Maximum vertical depth (m)
1	8	17	2.80	1.45
2	8	20	3.20	1.70
3	8	20	3.60	1.78
4	8	23	3.30	2.07
5	8	23	4.70	2.05
Mean		21	3.50	1.81
1	16	30	3.70	2.10
2	16	32	3.60	2.16
3	16	39	4.10	2.30
4	16	39	6.40	2.64
5	16	45	3.40	2.60
Mean		37	4.20	2.36
1	25	55	7.00	2.75
2	25	60	10.40	3.10
3	25	65	9.80	2.95
Mean		60	9.10	2.93

Typical soil profile

0–5 cm	Black topsoil containing small fragments of charcoal and minor amounts of Taupo pumice.
5–10 cm	Grey-white Taupo pumice.
10–20 cm	Red-brown, light, friable ash-rich (Waimihia ash) silt loam with large weathered pumice up to 10 cm diameter.
20–70 cm	Yellow-brown Waiohau ash.
70 cm +	Grey-green, clay loam containing numerous angular clasts of mudstone and siltstone up to 30 cm diameter. Soil had a mottled appearance. Clasts of harder lithologies were weathered. Resembled a typical slope colluvium.

For an explanation of the volcanic airfall deposits see Gage & Black (1979).

Sixteen-year-old Stand

This stand was on the true right upper slopes of the Matekonekone Stream, a tributary of the Waipaoa River, at an altitude of 580 m. This area was planted in 1969 and was thinned in 1977 to a final stocking rate of 865 stems/ha. The site has a northerly aspect (335°) and an average slope of 22°. The five sampled trees had a mean height of 21.1 m and an average stump diameter of 37 cm (Table 1).

Typical soil profile

0–2 cm	Humus and pine litter.
2–10 cm	Light-brown silt loam containing small fragments of charcoal and small angular stone chips up to 1 cm diameter.
10–50 cm +	Grey-green mottled clay loam containing numerous small stone chips and large blocks up to 30 cm diameter. The stone fragments were very weathered. Resembled a typical slope colluvium.

Twenty-five-year-old Stand

This stand was growing in the lower reaches of Homestead Creek, at an altitude of 240 m. It had a final stocking rate of 270 stems/ha. The stand was planted in 1960 during the initial stages of the reforestation of the upper Waipaoa catchment. The excavation site faced due north (20°) with a mean slope of 15°. The three sampled trees had an average height of 30.4 m and a mean stump diameter of 60 cm (Table 1).

Typical soil profile

0–8 cm	Dark-brown friable topsoil and forest litter.
8–20 cm	Mixed dark-grey organically enriched silt loam. Good crumb structure, many roots, few pebbles.
20–35 cm	Light grey-brown clay with weak structure, some organic staining. Many stones.
35–60 cm	Light grey-brown plastic clay-clay loam, yellow-brown mottles. Some stones.
60–80 cm	Stiff clay, some iron staining and mottling.
80–120 cm +	Stiff light-grey clay, occasional mottles. Increasing stoniness.

METHODS

Excavation Technique

The root systems of all three age-classes of trees were hydraulically excavated. The technique required a ground slope of at least 15° and a cleared downslope area to allow easy flow of the sluiced material from the excavation site. Two types of nozzle were used—a 5-mm diameter nozzle which supplied a narrow high-pressure jet of water, and an adjustable nozzle which gave a broad spray pattern to remove soil from the finer roots. Water was available from 220 000-litre capacity rubber-lined fire ponds for the 8- and 16-year-old stumps, but water had to be transported to the 25-year-old trees in 4500-litre neoprene bladders. One or two fire pumps (capacity 360 litres/min) were used to provide pressure. The number of pumps used depended on the distance between the water source and the excavation site.

Tree height and stump diameters were measured after the trees were felled, and the site was manually cleared of slash and ground cover. Sluicing began far enough downhill from the stump to ensure that the excavation under the root bole exposed the deeper vertical roots. As the cut face progressed upslope, the excavated structural roots and root bole were propped in their original position until their morphology had been drawn and described. Hydraulic sluicing was a practical way of moving large quantities of soil in a relatively short time with very little damage to the root system. Sluicing proved suitable even for soils with a high clay fraction, as long as they were friable and had a low moisture content. Excavation became more difficult and time-consuming as clay-rich material approached saturation.

A recovery efficiency of 80% was estimated for roots ≤0.2 cm diameter and 100% for roots ≥0.3 cm. The longer roots, laterals, and verticals that extended beyond and below the excavation sites were excavated using spades and hand trowels until their diameters were less than 0.2 cm.

Measurement Technique

Builders' scaffolding was used to construct a platform above each excavated root system. Directly underneath the platform, but above the root system, a 50 × 50-cm nylon cord grid was suspended to divide the root system up into manageable sections, enabling the plan view of the root morphology to be drawn in detail. The vertical elevations were drawn using a similar 50 × 50-cm grid attached vertically to the front of the scaffolding. Each root system was cut up and sorted into the following diameter classes:

- Very small structural roots — 0.2–1 cm diameter
- Small structural roots — 1–2 cm diameter
- Medium structural roots — 2–5 cm diameter
- Large structural roots — 5–10 cm diameter
- Coarse structural roots — >10 cm diameter
- Central root bole at base of stem

Distance and cost prohibited the transportation of the roots to a laboratory for oven-dried weight determination. Each root system was allowed to air dry for up to 6 months before being weighed and measured for length.

RESULTS

Morphology

Eight-year-old trees

At 8 years old the lateral roots were confined mainly to the upper 40 cm of soil. In four of the five trees excavated they tended to grow predominantly across slope. The longest lateral root was 4.7 m (Table 1). The roots that extended furthest from the tree stump were generally those growing within 10 cm of the ground surface, and they tended to follow the lower rooting zone of the grass cover. The main lateral roots tapered rapidly and were usually less than 1 cm diameter at a distance of 1 m from the stump (Fig. 2). Thereafter the loss of diameter tended to be uniform for the remainder of their length, with few laterals (<10%) showing any sign of branching.

Vertical roots all originated from directly below the stump (Fig. 2). The deepest root excavated extended to 2.07 m below ground-level (Table 1). Generally, the root systems showed strong vertical development down to 1.0–1.5 m. Below that level the

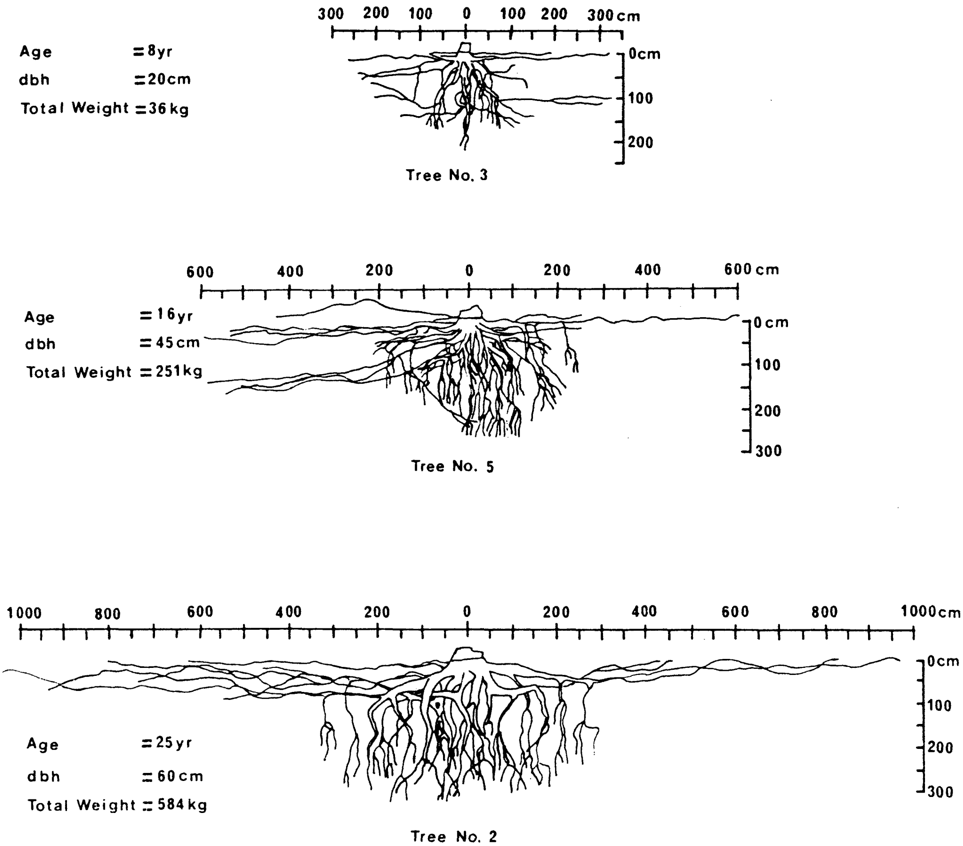

FIG. 2 — Side elevations of the three age-classes of *P. radiata,* showing the changes in root morphology up to Year 25.

frequency of branching increased as the stone content of the soil increased. Once vertical roots branched, they seldom penetrated more than another 20 cm into the soil.

Sixteen-year-old trees

In plan view, the roots of the five sampled 16-year-old trees extended asymmetrically from the stump, in a direction apparently dictated by competition from the longer roots of the neighbouring trees. All lateral roots were confined to the upper 1 m of the soil profile, and up to 75% occurred in the 0–50 cm zone. The roots that extended furthest from the tree stump were generally those growing within 10 cm of the ground surface. The longest lateral root extension was 6.4 m (Table 1). All major branching occurred within a 1.5-m radius of the stump, and roots tended to taper rapidly beyond that distance (Fig. 2). Deeper laterals often branched closer to the stump than shallower laterals and often terminated in a proliferation of fine roots. This was caused mainly by the increase in stoniness with depth.

Vertical root growth was dominated by strong sinker root development directly below the stump. The deepest root excavated was 2.64 m long (Table 1). Frequency of branching increased below 1.5–2 m, coinciding with an increase in stone content. By this age a secondary range of well-developed vertical roots had grown from the underside of the main laterals, up to 2 m from the central root bole. These roots penetrated down to 1.75 m (Fig. 2).

Twenty-five-year-old trees

By 25 years the root networks had developed into massive systems dominated by shallow lateral roots (Fig. 3). Roots in the vicinity of the stumps were up to 26 cm diameter, with strong development across and down slope. All laterals grew in the upper 1 m of the profile, and most were within 50 cm of the soil surface. The maximum lateral root extension observed was 10.4 m (Table 1). The longer roots tended to follow the humus-horizon/upper-mineral soil interface.

Vertical roots that originated from the underside of the main laterals within 2.5 m of the stump had grown to a size and depth similar to those growing from under the stump (Fig. 2). The larger vertical roots had penetrated to a maximum depth of 3.10 m (Table 1), but average root penetration was about 2.6 m. A saturated grey clay restricted further growth of the major vertical roots (diameter 7–15 cm), which proliferated into many smaller gnarled roots (diameter 1.5 cm or less) once they penetrated the clay.

FIG. 3 — Exposed root system of a 25-year-old *P. radiata*. Maximum root depth = 3.1 m, total biomass = 0.58 tonnes.

Root Biomass

Relation to tree age

The root bole contained 40% of the total root biomass at 8 years. This had increased to 50% by 16 years and remained reasonably constant for the next 9 years (Table 2). Mean total root biomass increased exponentially between 8 years and 25 years. For all three age-classes, the roots <2 cm diameter on average contributed only about 8% of the total root biomass, but represented 80% of the total root length (Table 3). Medium

TABLE 2–Biomass (kg) of root systems of *Pinus radiata* trees sampled at Mangatu Forest. All root material recovered by sluicing was weighed after air-drying for 6 months, including any roots >0.2 cm. Figures in parentheses represent percentage of totals.

Root diameter class	Tree No. 1	2	3	4	5	Mean
8-year-old root systems						
< 1 cm	1.2 (5)	1.5 (5)	1.5 (4)	1.8 (4)	3.0 (7)	1.8 (5)
1–2 cm	2.0 (8)	2.0 (6)	2.2 (7)	2.0 (4)	3.4 (8)	2.3 (6)
2–5 cm	5.4 (22)	6.2 (20)	6.8 (19)	9.2 (18)	8.7 (19)	7.3 (19)
5–10 cm	2.8 (11)	2.8 (9)	7.2 (20)	13.0 (26)	13.0 (29)	7.8 (21)
>10 cm	3.9 (16)	2.2 (7)	2.6 (7)	10.0 (20)	nil (–)	3.7 (10)
Root bole	9.4 (38)	16.5 (53)	15.5 (43)	14.3 (28)	16.9 (37)	14.5 (39)
Totals	24.7	31.2	35.8	50.3	45.0	37.4
16-year-old root systems						
<1 cm	3.9 (4)	5.8 (6)	7.2 (4)	6.4 (3)	5.4 (2)	5.7 (3)
1–2 cm	2.8 (3)	3.6 (4)	8.4 (4)	6.8 (3)	6.8 (3)	5.7 (3)
2–5 cm	19.3 (18)	13.4 (14)	22.9 (12)	24.7 (11)	30.0 (12)	22.1 (13)
5–10 cm	13.8 (13)	5.0 (5)	33.4 (17)	35.9 (16)	20.0 (12)	23.6 (14)
>10 cm	20.6 (19)	14.0 (14)	24.0 (13)	61.0 (27)	30.3 (12)	30.2 (17)
Root bole	45.0 (43)	56.4 (57)	94.6 (50)	89.9 (40)	148.5 (59)	86.9 (50)
Totals	105.4	98.2	190.5	225.6	251.0	174.1
25-year-old root systems						
<2 cm	33.3 (9)	22.5 (4)	42.9 (6)			
2–5 cm	87.2 (23)	75.9 (13)	123.4 (17)			
5–10 cm	40.0 (10)	71.6 (12)	115.6 (16)			
>10 cm	37.0 (10)	142.2 (24)	109.4 (16)			
Root bole	185.5 (48)	271.4 (47)	321.3 (45)			
Totals	383.0	583.6	712.6			559.7

and coarse (>5 cm diameter) structural roots contributed about 30% of total root biomass, but only 4% of the total root length.

Total root biomass for the stand of 8-year-old trees, with a stand density of 236 stems/ha, was 8.8 tonnes/ha. Root biomass for the 25-year-old trees, with 270 stems/ha, was 151 tonnes/ha. The 16-year-old stand had a stocking rate of 865 stems/ha, 3.0–3.5 times higher than the other stocking rates. Root biomass at age 16 years at this stocking rate was also 151 tonnes/ha. At this stand density it is likely that tree diameter, and hence mean tree root weight, would be lower than that for trees of the same age grown at 253 stems/ha (average of the stocking rates of the 8- and 25-year stands). The growth model program STANDMOD (Manley 1987) was used to predict a mean dbh of 40 cm for a 16-year-old stand grown at 253 stems/ha, using the 8- and 25-year-old trees as the two end points of the growth model. When using Equation 5 (shown below) this was found to be equivalent to an individual total root weight for 16-year trees of 266 kg, which translates to a total root biomass of 67 tonnes/ha. If we assume a stand density of 253 stems/ha, root biomass in the STANDMOD growth model increased at an annual rate of 1–2 tonnes/ha up to 8 years old, then at 7–8 tonnes/ha over the next 8 years, and at a slightly increased annual rate of 9–10 tonnes/ha over the following 9 years.

TABLE 3–Total lengths (m) of *Pinus radiata* roots of different diameter classes sampled at Mangatu Forest. Figures in parentheses represent percentage of totals.

Root diameter class	Tree No. 1	2	3	4	5	Mean
8-year-old root systems						
0.2–1 cm	73.5 (72)	112.0 (75)	129.5 (76)	91.0 (69)	133.0 (78)	107.8 (75)
1–2 cm	15.7 (15)	20.7 (14)	21.5 (12)	19.1 (14)	19.5 (11)	19.3 (13)
2–5 cm	10.8 (11)	13.4 (9)	15.0 (9)	16.9 (12)	11.2 (8)	13.5 (9)
5–10 cm	1.0 (1)	1.2 (1)	3.1 (2)	4.8 (4)	5.9 (3)	3.2 (2)
>10 cm	0.4 (1)	0.3 (1)	0.4 (1)	0.8 (1)	nil (–)	0.4 (1)
Totals	101.4	147.6	169.5	132.6	169.6	144.1
16-year-old root systems						
0.2–1 cm	172.3 (84)	257.5 (80)	297.8 (67)	279.0 (67)	346.3 (69)	270.6 (72)
1–2 cm	9.6 (5)	29.2 (9)	58.9 (13)	49.0 (12)	64.1 (13)	42.2 (11)
2–5 cm	15.7 (7)	28.6 (9)	63.8 (14)	63.0 (15)	69.0 (14)	48.0 (13)
5–10 cm	6.0 (3)	2.5 (1)	19.9 (5)	19.3 (4)	13.1 (3)	12.2 (3)
>10 cm	1.9 (1)	1.9 (1)	5.4 (1)	7.4 (2)	4.6 (1)	4.2 (1)
Totals	105.4	98.2	190.5	225.6	251.0	174.1
25-year-old root systems						
0.2–2 cm	601.8 (73)	483.5 (63)	619.3 (77)			568.2 (71)
2–5 cm	171.9 (21)	179.1 (23)	144.3 (18)			165.1 (20)
5–10 cm	45.2 (5)	77.4 (10)	36.0 (4)			52.9 (7)
>10 cm	5.9 (1)	31.2 (4)	10.0 (1)			15.7 (2)
Totals	824.7	771.1	809.6			801.8

Relation to tree diameter

Some of the study trees were part of a logging trial carried out 3 months before sampling, and were hauled away before their dbh could be measured. Therefore the field measurement used was stump diameter. To enable comparisons with similar biomass data from other study areas, the stump diameter (0.2 m above ground) and dbh (1.4 m above ground) were measured over bark on 10 representative trees for each age-class (Fig. 4). The resulting regression equation was:

$$\text{dbh} = 0.97\ (\text{stump diameter}) - 3.42\ (r^2 = 0.99). \qquad (1)$$

Equation 1 was used to convert stump diameters (Table 1) to the dbh values for the following analysis.

When the estimated overbark dbh (cm) for the 13 individual trees sampled was plotted against the corresponding total root weight (kg) (Fig. 5), the linear equation obtained was:

$$\text{Total root weight} = (13.7 \pm 2.6)\ \text{dbh} - (220 \pm 90)\ (r^2 = 0.93). \qquad (2)$$

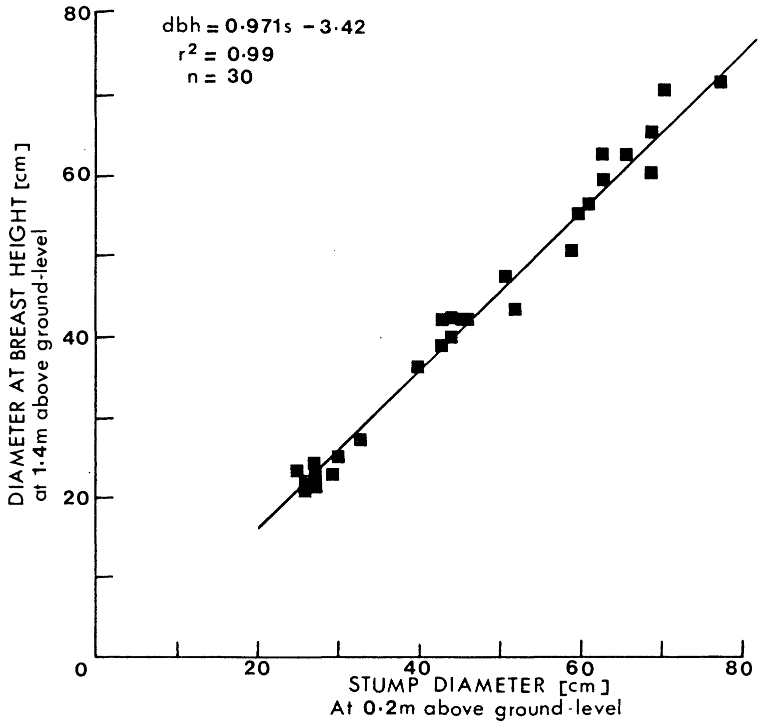

FIG. 4 — Regression of dbh (cm) on stump diameter (cm) for 30 *P. radiata* trees.

DISCUSSION

The relationship found between total root weight and dbh in this study (Equation 2) agreed with that found by Heth & Donald (1978) for South African *Pinus radiata* root biomass from 10 trees with an overbark dbh range of 39.2 cm to 64.5 cm. Their equation was:

$$\text{Total root weight} = 11.9\,\text{dbh} - 267 \quad (r^2 = 0.87). \qquad (3)$$

The intercept and slope values in Equation 3 are within the 95% confidence limits for the corresponding values in Equation 2. Therefore, the two equations can be considered to be not significantly different.

Jackson & Chittenden (1981) combined their own data on *P. radiata* biomass with that of three other researchers—Ovington *et al.* (1967), Dargavel (1970), and Heth & Donald (1978)—to give a total of 247 sampled trees with an overbark dbh range of 3.4 cm to 56.3 cm. The resulting log/log equation was:

$$\log_e(\text{total root weight}) = 2.73 \log_e(\text{dbh}) - 5.01 \quad (r^2 = 0.97). \qquad (4)$$

When the Mangatu root biomass was treated similarly (Fig. 6), the resulting equation was:

$$\log_e(\text{total root weight}) = (2.24 \pm 0.14) \log_e(\text{dbh}) - (2.68 \pm 0.46) \quad (r^2 = 0.99). \qquad (5)$$

When the root biomass data were compared with the data collated by Jackson & Chittenden (1981), it appeared that the Mangatu trees had a consistently higher root

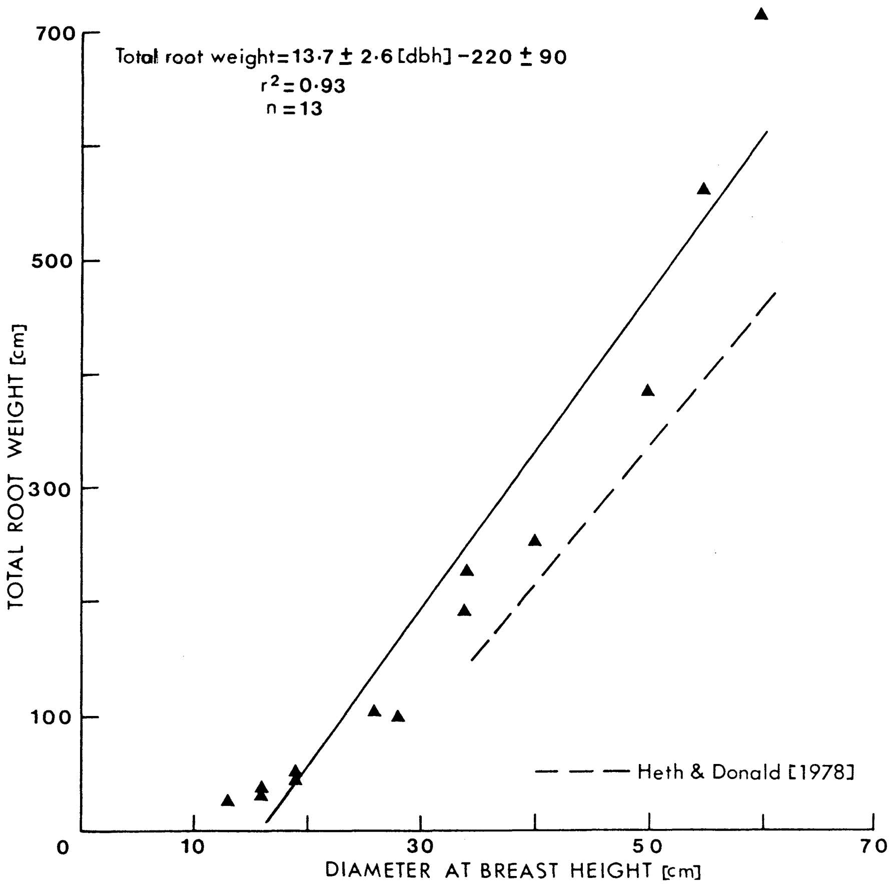

FIG. 5 — Regression of total root weight (kg) on dbh (cm) for 13 *P. radiata* trees.

biomass (Fig. 6). Data for most of the larger trees (>20 cm dbh) that contributed to the upper end of Equation 4 were supplied by Dargavel (1970) and Heth & Donald (1978). Both these researchers extracted the roots by partially digging and then winching the root systems from the ground. The higher root biomass of the Mangatu trees is thought to be due in part to the improved extraction techniques.

The root biomass data (Fig. 5 and 6) confirmed the expected relationship between total root weight and dbh. The possibility of estimating below-ground biomass using an easily obtainable above-ground parameter has been shown previously (Santantonio *et al.* 1977).

The most dominant factors influencing vertical root developement of the trees older than 8 years studied at Mangatu Forest were increase in stoniness with soil depth, poor drainage or fluctuating ground-water table, and poor growing media, i.e., damp de-oxygenated clays. Horizontal root growth and direction of growth may have been limited by competition from neighbouring trees. However, the laterals of trees growing on steeper sites often grew predominantly across slope and downslope.

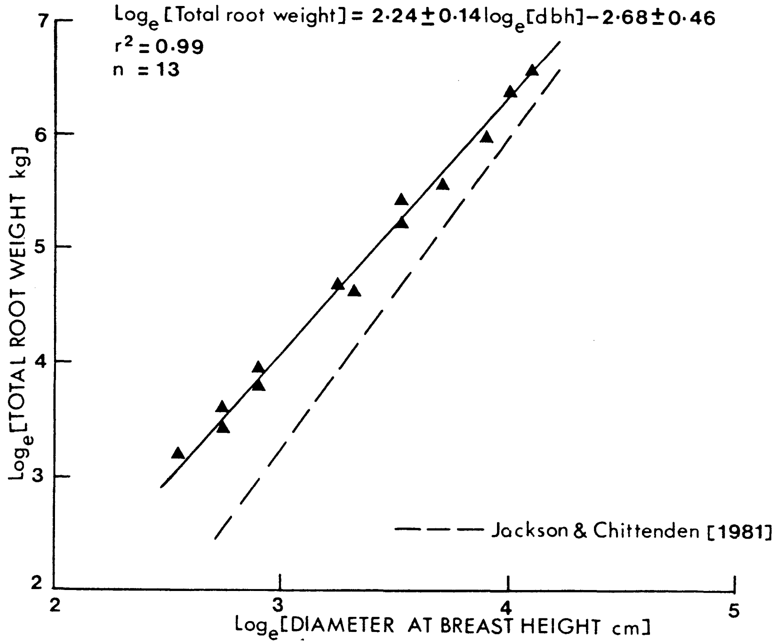

FIG. 6 — Log/log regression of total root weight (kg) on dbh (cm) for 13 *P. radiata* trees.

The detailed mechanism of how tree roots contribute to slope stability is not particularly well understood. The mechanisms depend on tree age, root morphologies, and root density. The latter two are in turn dependent upon the physical nature of the soils, slope, and ground-water conditions. In general terms it has been suggested that three mechanisms predominate (O'Loughlin & Zhang 1986):

(1) Vertical roots which extend across potential failure planes and into stable subsoil can provide a stabilising effect on an unstable upper soil mantle;

(2) Tree root systems provide lateral strengthening of the soil mantle, usually not more than 1 m deep, that contributes to the stability of the underlying substrates;

(3) The structural roots and central root bole provide localised centres of increased reinforcement which tend to act as supporting buttresses.

At age 8 the morphology of *P. radiata* root systems indicates that slope reinforcement most likely occurs via mechanisms (1) and (2) working separately or together. The depths of the 8-year root system (mean maximum depth 1.8 m, Table 1) and the tendency for the structural lateral roots to concentrate in the top 40 cm of the soil profile, suggests that trees of this age could help to maintain stability on slopes susceptible to shallow (<1.5 m) translational landslides. When the trees age, both root extension and root depth gradually increase to 9.1 m and 2.9 m respectively (Table 1) by age 25. As the root systems increase in size it is likely that mechanism (2) becomes more predominant as the density of the larger structural lateral roots increases within the top 50 cm of the soil volume.

As a tree root system develops, the zone of its contribution to the reinforcement and hence the stability of the surrounding soil gradually increases in size. By 16 years a well-formed secondary tier of vertical roots had developed under the main laterals (Fig. 2). By 25 years the zone of influence of these roots had extended 2.5 m horizontally from the stump, and down to depths similar to the original verticals extending beneath the stump. Thus, if a tree root system is viewed as a localised centre of soil reinforcement, mechanism (3), the diameter of the vertical component of the zone of influence is greatly increased as the tree matures.

When variations in regional silviculture patterns are taken into account, *P. radiata* stands in New Zealand are usually thinned at about 8 years of age. The mean maximum lateral root length at 8 years (3.50 m, Table 1) was used to calculate the minimal stocking rate (260 stems/ha) that would still enable the roots to more or less occupy the available soil space at age 8, and also provide a continuing increase to the lateral strength of the soil mantle as the crop matures.

ACKNOWLEDGMENTS

We would like to thank the Officers-in-Charge, Mangatu Forest, N.Z. Forest Service (as it was then) for use of equipment and manpower for this study. We are also appreciative of the efforts of Mike Marden, Donna Rowan, Heather Thomas, Chris Phillips, Jocelyn Ivory, Steve Kitchingman, and John Payne who all helped at one time or another with field work.

REFERENCES

BLACK, R.D. 1980: Upper Cretaceous and Tertiary geology of Mangatu State Forest, Raukumara Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics 23*: 295–312.

BISHOP, D.M.; STEVENS, M.E. 1964: Landslides on logged areas in southeast Alaska. *United States Department of Agriculture Forest Service Paper NOR–1.*

COUTTS, M.P. 1983: Development of structural root systems of Sitka spruce. *Forestry 56*: 1–16.

DARGAVEL, J.B. 1970: Provisional tree weights for radiata pine. *Australian Forestry 34*: 131–40.

DEANS, J.D. 1981: Dynamics of coarse root production in a young plantation of *Picea sitchensis*. *Forestry 54(2)*: 139–55.

EIS, S. 1987: Root systems of older hemlock, cedar, and Douglas fir. *Canadian Journal of Forest Research 17*: 1348–55.

FAYLE, D.C.F. 1975: Extension and longitudinal growth during development of red pine root systems. *Canadian Journal of Forest Research 5*: 109–21.

GAGE, M.; BLACK, R.D. 1979: Slope stability and geological investigations at Mangatu State Forest. *New Zealand Forest Service, Forest Research Institute Technical Paper No. 66.*

HENDERSON, R.; FORD, E.D.; RENSHAW, E.; DEANS, J.D. 1983: Morphology of the structural root system of Sitka spruce. 1: Analysis and quantitative description. *Forestry 56(2)*: 122–35.

HETH, D.; DONALD, D.G.M. 1978: Root biomass of *Pinus radiata* D. Don. *South African Forestry Journal 107*: 60–70.

JACKSON, D.S.; CHITTENDEN, J. 1981: Estimation of dry matter in *Pinus radiata* root systems. 1. Individual trees. *New Zealand Journal of Forestry Science 11*: 164–82.

McMINN, R.G. 1963: Characteristics of Douglas fir root systems. *Canadian Journal of Botany 41*: 105–22.

MANLEY, B.R. 1987: Model system of the Conversion Planning Project Team. Pp. 12–26 *in* Kininmonth, J.A. (Comp.) Proceedings of the Conversion Planning Conference. *Ministry of Forestry, FRI Bulletin No. 128.*

NEW ZEALAND METEOROLOGICAL SERVICE 1984: Rainfall normals for New Zealand 1951–1980. *New Zealand Meteorological Service Miscellaneous Publication No. 185.*

O'LOUGHLIN, C.L. 1974: The effect of timber removal on the stability of forest soils. *Journal of Hydrology (NZ) 13(2)*: 121–34.

——— 1985: Influences of exotic plantation forest on slope stability—Implications for forest management in the Marlborough Sounds. Pp. 313–28 *in* Campbell, I.B. (Ed.) "Proceedings of the Soil Dynamics and Land Use Seminar". New Zealand Society of Soil Science, Lower Hutt.

O'LOUGHLIN, C.L.; WATSON, A.J. 1979: Root wood strength deterioration in radiata pine after clearfelling. *New Zealand Journal of Forestry Science 9(3)*: 284–93.

O'LOUGHLIN, C.L.; ZHANG, X.B. 1986: The influence of fast-growing conifer plantations on shallow landsliding and earthflow movement in New Zealand steeplands. Pp. 217–26 *in* Proceedings of the 18th IUFRO World Congress, Ljublijana, Yugolslavia, Div.1, Vol.1.

OVINGTON, J.D.; FORREST, W.G.; ARMSTRONG, J.S. 1967: Tree biomass estimation. Pp. 4–31 *in* A.A.A.S. Symposium. University of Maine Press, Mass.

PEARCE, A.J.; O'LOUGHLIN, C.L.; JACKSON, R.J.; ZHANG, X.B. 1987: Reforestation: On-site effects on hydrology and erosion, eastern Raukumara Range, New Zealand. Pp. 489–97 *in* Swanson, R.H.; Bernier, P.Y.; Woodard, P.D. (Ed.) "Forest Hydrology and Watershed Management". *IAHS-AISH Publication No. 167.*

SANTANTONIO, D.; HERMANN, R.K.; OVERTON, W.S. 1977: Root biomass studies in forest ecosystems. *Pedobiologia 17*: 1–31.

SQUIRES, R.O.; MARKS, G.C.; CRAIG, F.G. 1978: Root development in a *Pinus radiata* D. Don plantation in relation to site index, fertilising, and soil bulk density. *Australian Forest Research 8*: 103–14.

STRONG, W.L.; LA ROI, G.H. 1983: Root system morphology of common boreal forest trees in Alberta, Canada. *Canadian Journal of Forest Research 13*: 1164–73.

TSUKOMOTO, Y.; KUSAKABE, O. 1984: Vegetative influences on debris slide occurrences on tree slopes in Japan. Pp. 63–72 *in* O'Loughlin, C.L.; Pearce A.J. (Ed.) Proceedings of IUFRO Symposium on "Effects of Forest Land-use on Erosion and Slope Stability". Honolulu, Hawaii.

WILL, G.M. 1966: Root growth and dry matter production of a high producing stand of *Pinus radiata*. *New Zealand Forestry Notes No. 44.*

WU, T.H.; McKINNELL, W.R.; SWANSTON, D.N. 1979: Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian Journal of Geotechnical Research 16(1)*: 19–33.

ZIEMER, R.R. 1981: Roots and the stability of forested slopes. Pp. 343–61 *in* Davis, T.R.H.; Pearce, A.J. (Ed.) "Erosion and Sediment Transport in Pacific Rim Steeplands". *IAHS Publication No. 132.*

ZIEMER, R.R.; SWANSTON, D.N. 1977: Root strength changes after logging in southeast Alaska. *United States Department of Agriculture Forest Service Research Note PNW-306.*