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ROOT/SHOOT RATIOS FOR DERIVING BELOW-GROUND BIOMASS OF *PINUS RADIATA* STANDS

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ABSTRACT

The biomass of *Pinus radiata* (D. Don) root and shoot systems was measured in a number of studies to determine the effect of stand age and environmental factors on the root/shoot ratio. These and other published studies were carefully assessed to determine firstly those which provide unbiased data for estimating below-ground biomass from shoot data and, secondly, the precision of the root/shoot ratios. Because previous studies were designed for a number of different purposes they were assessed in relation to the methodological requirements that we considered had to be met in order to provide accurate root/shoot biomass information.

New data from an effluent irrigation trial at Whakarewarewa Forest near Rotorua, designed to assess the impact of water and nutrient additions on tree growth at stand age 5 years, showed that both the above- and below-ground biomass approximately doubled relative to untreated controls. Consequently, the root/shoot ratio was not significantly affected by effluent type or irrigation rate, and averaged 0.17 across all treatments. At Rangiora near Christchurch, similar results were obtained at an agroforestry trial to assess the impact of moisture and nitrogen supply on tree growth at stand age 5 years, where the mean root/shoot ratio averaged 0.21. These values were similar to the mean ratio (0.20) in a 42-year-old *P. radiata* stand at Woodhill Forest. Studies of nursery seedlings ready for planting gave lower root/shoot ratios of approximately 0.15, though the root systems had been trimmed in the nursery.

Analysis of published data suggested a wide range in root/shoot ratios in *P. radiata*, ranging between 0.12 and 0.58 across all studies. However, we observed a number of limitations in some studies which we believe precluded their use for root biomass estimation and prediction purposes. The root/shoot ratio in studies that met the accuracy requirements necessary for our purpose ranged between 0.13 and 0.24, and in typical *P. radiata* stands the root/shoot ratio averaged 0.19 (95% CI = 0.023) over all ages and sites. The majority of the root system of trees, other than seedlings, was composed of coarse roots

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and the root stock, and these were largely extracted in studies we considered as suitable. Root biomass procedures generally resulted in the loss of fine roots in most studies, and a slightly increased root/shoot ratio of 0.2 is therefore recommended for carbon estimation in *P. radiata* stands across all stand ages and sites. This value is consistent with findings reported for various other coniferous species.

Keywords: root/shoot ratio; root biomass; shoot biomass; biomass expansion factors; carbon sequestration.

INTRODUCTION

The biomass of root systems is difficult and expensive to measure accurately in forest trees, and few biomass studies of *P. radiata* include the roots (Madgwick 1994). In addition, sampling protocols differ among studies, with the root excavation methods employed often dictated by site conditions — for example, the type of soil, the presence of hardpans, the rock content, and the type of equipment available. Root systems can extend both laterally and vertically to a considerable distance, and roots of different trees are usually interlaced. Not surprisingly, studies differ in terms of the sampling methods used (based on unit area or individual tree), the root size fractions measured, and the soil depths assessed. Comprehensive studies aim to extract the majority of the root system, which excludes the above-ground stump (Will 1966; Heth & Donald 1978; Watson & O'Loughlin 1990; Mund *et al*. 2002). Structural roots are composed of the root stock (also referred to as the root crown by Snowden *et al*. 2000, or root bole by Phillips & Watson 1994), taproot, lateral roots, and sinker (vertical roots that emanate from lateral roots). Lateral roots taper into small roots approximately 1 cm in diameter within a few metres of the base of the tree, and can run for 10 m or more in friable soils with little additional taper. Vertical roots can extend to depths of 5 m or more.

Root weight of individual trees can be estimated from stem diameter, which is the approach recently recommended by Drexhage & Colin (2001), or from the root/shoot ratio. The use of regression equations based on stem diameter has been questioned, because shoot weight is known to vary with both stem diameter and height, whereas diameter-based estimates of root weight would be the same irrespective of tree height. Madgwick (1994) concluded, from comparisons of regressions for estimating root and stem weight from diameter at breast height (dbh), that the derived root/stem ratios did not agree with published data. The IPCC (2003) has proposed that root/shoot ratios are an acceptable method of estimating root biomass when reporting carbon stocks and changes in forest land and land converted to forest, which is the approach we have adopted for estimating root weight in this paper.

Madgwick (1991b) used simulated sampling to examine the effects of estimation method and sample size on the coefficient of variation of estimated stand component weights. The set of sample trees selected for biomass measurements was found to be an important consideration, with aberrant stand estimates possible when the sample size was small (one to three trees). Madgwick's analysis showed that there was a rapid convergence of sample-tree-based estimates towards the expected stand value as sample size increased above five trees, and that a sample of 12–17 trees yielded estimates within 5% of the stand biomass. A sample size of less than five trees was insufficient to characterise a stand.

Methods for investigating root biomass in intensively managed plantation forests also need to consider variation among stands, which can differ in tree age, site conditions, and silviculture. Root/shoot ratios in seedlings typically average around 0.2 in fertile soils, increasing to 0.4 in infertile soils or after conditioning treatments (undercutting/wrenching) undertaken in the nursery (Nambiar 1980; Rook 1971; Payn 1991). The impact of soil fertility and other site factors on root/shoot ratios can be expected to be most evident at the seedling stage, as indeed was found. However, root/shoot ratios in *P. radiata* were reported to vary between 0.08 and 0.58 in older trees (Will 1966; Ritchie 1977; Gadgil 1979; Phillips & Watson 1994) which was unexpected. Much more consistent root/shoot ratios (range 0.2–0.3) were reported along a chronosequence of *Picea abies* (L.) H.Karst. (Norway spruce) stands aged 16–142 years old (Mund *et al.* 2002), and in 67 woodlands of *Pinus densiflora* Siebold & Zucc. in eastern Japan where ratios ranged between 0.19 and 0.22 (mean of 0.20) in stands 13–46 years old (Satoo 1967). Root/shoot ratios reportedly averaged 0.2 in *P. taeda* L. (loblolly pine) stands between 15 and 25 years old (Van Lear & Kapeluck 1995). In Australian softwood (mainly *P. radiata*) plantations with an average age of 20 years, root/shoot ratios reportedly ranged between 0.04 (which seems unlikely) and 0.23 with a mean of 0.17 (Snowden *et al*. 2000). Vogt *et al.* (1996) reviewed root dynamics in 38 above-ground and 34 below-ground studies from evergreen temperate forests (various species), giving unweighted mean root/shoot ratios across six soil orders which varied between 0.15 and 0.38 (the latter with unusually high fine root biomass) with a median of 0.19. Methodological issues associated with measuring root biomass are expected to have a bearing on the consistency of these results, and root studies therefore need to be carefully evaluated before results are incorporated into biomass estimation and prediction systems.

The objectives of our study were to:

(1) Examine the effects of experimentally varying moisture and nutrient supply on *P. radiata* biomass components, including foliage, branches, stems, and roots.

(2) Evaluate these and previously published *P. radiata* biomass studies as a basis for developing root/shoot ratios suitable for estimating root biomass in *P. radiata* stands in New Zealand.

MATERIAL AND METHODS

New biomass data for *P. radiata* are presented for deriving root/shoot ratios. Study sites cover a wide range in stand age, and include a range of fertiliser and irrigation treatments, to assist in determining the effects of environmental factors on the root/shoot ratio.

Seedlings from Ensis Nursery in Rotorua

The 1-year-old nursery stock included four seedlots.

(1) Museum — which originated from unimproved open-pollinated parents of GF0 on the growth and form (GF) rating scale (Vincent 1987);

(2) Puruki — which originated from moderately improved open-pollinated GF7 parents;

(3) GF30 — highly improved control-pollinated parents of GF30; and

(4) High density — which originated from high wood density control-pollinated parents.

Seed was sown in nursery beds in September 1996, root systems were undercut/side cut (between rows) and wrenched, and lifted for planting in July (Beets *et al*. 2004). A total of 30 seedlings per seedlot were severed at ground level and seedling height was measured. The shoot and root systems of each seedlot were bulked by component, dried to constant weight at 65°C, and root/shoot ratio was calculated. The nursery soil parent material originated from volcanic ash showers; it was mapped as Ngakuru sandy loam (Rijkse 1979) and classified in the New Zealand Soil Classification System as Vitric Orthic Allophanic Soils (Hewitt 1998). The soils were well drained and received an annual rainfall of 1600 mm.

Woodhill Intensive Harvesting Trial

A sample of young trees in a second-rotation intensive harvesting trial established in Woodhill Forest in July 1986 were destructively harvested in December 1987, 18 months after planting. Soils were Pinaki sands and classified in the New Zealand Soil Classification System as Typic Sandy Recent Soils (Hewitt 1998), deep free-draining soils with low nitrogen status. Normal rainfall averaged 1300 mm. Trial establishment methods and a detailed description of the site have been given by Smith *et al*. (1994). The split plot trial design included the following main treatments:

- Above-ground tree harvested with forest floor removed (FF),
- Above-ground tree harvested with forest floor remaining (WT),
- Conventional above-ground stem harvested with normal residue and forest floor remaining (SO),

- Conventional above-ground stem harvested with double residue and forest floor remaining (DS).

The subplots were either with nitrogen fertiliser (F) or without (NF). These plots received full weed control using Glyphosate. In addition “normal management” plots (SO with no weed control) were included to compare sites with (WR) or without (NWR) windrowing of the residues from the previous tree crop. There were three replicate plots per treatment. Two trees per plot (six per treatment) were cut off at ground level; the roots were manually extracted using a combination of digging and lifting, and trimmed to a small-end diameter of 0.5 cm. Samples were oven dried to constant weight at 65°C, and shoot and root systems were weighed on an individual-tree basis.

Rangiora Agroforestry Trial

Pinus radiata shoot and root system biomass was measured in a 5-year-old agroforestry trial at Rangiora on a medium- to free-draining soil developed on fine alluvial sediments (Clinton & Mead 1994). The trial incorporated three levels of pasture management, including grazed pasture (GP), ungrazed rank pasture (UP), and pasture-free (WC), with and without nitrogen fertiliser, with four replicate plots per treatment. A total of 330 kg N/ha was applied over 11 months to the plus-fertiliser plots. Rainfall averaged approximately 700 mm/year. Moisture stress due to weed competition was expected at this site. A total of 24 trees (one tree per plot) were felled, and tree height, diameter at breast height 1.4 m (dbh), and above-ground dry weight were measured. Root oven-dry weight was estimated using a combination of individual tree and unit area methods. Roots in four randomly located soil pits dug to 20 cm depth within a radius of 1.9 m from each central biomass tree were sampled by a combination of washing and sieving, and were separated into fine (<1 mm diameter) and coarse (>1 mm) fractions. Then all roots >1 mm diameter in the top 10 cm of the soil were excavated, including those extending beyond the 1.9-m radius. Finally, roots still attached to the stump were removed by digging a 1.5 × 1.5-m pit to a depth of 2 m (Clinton & Mead 1994). The root data were previously reported by Phillips & Watson (1994).

Whakarewarewa Forest Effluent Irrigation Trial near Rotorua

The biomass of clonal *P. radiata* trees in an irrigation trial installed at Whakarewarewa Forest (planted in 1999) was assessed 5 years after tree planting. The stand was established at an initial stocking of 2336 stems/ha. Biomass measurements were undertaken in 15 plots. The 15 plots each had a rooting area of 5 × 5 m which was lined with root-impervious plastic sheeting to prevent lateral flow of water, and they were underlain with a root-impervious geo-textile filter cloth at 1.3 m depth. The plots were filled with coastal sand and overlain with a mixture of peat/topsoil to provide nutrients for initial tree growth. Two-year-old rooted cuttings were planted at a 1.25-m-square spacing. Each plot contained the same set of nine *P. radiata* genotypes, and was kept weed-free. Experimental treatments included effluent irrigation with 0 (None), 30, and 60 mm/week, using two types of effluent (biological nitrogen reduction — BNR, and mixed BNR/primary effluent — Mix) which were applied to three replicate plots per treatment. Normal rainfall in Rotorua averages nearly 1500 mm annually (NZ Met Service 1983). Current needle samples from secondary branches in the upper third of the crown of each tree were bulked by plot, and foliar nitrogen concentration was determined by thermal combustion (Leco CNS-2000, LECO Corp., St Joseph, Michigan, USA). The biomass study was undertaken in April 2004. Unit area harvesting methods were used because the root systems were intertwined, with many roots running around the perimeter of the plot.

The nine trees per plot were felled at approximately 10 cm stump height, divided into live crown, dead crown, and stem categories, and the fresh weight of each category was determined on a plot basis. A representative set of sample branches (one-tenth) was selected after all branches were sorted into diameter classes. Stem disc samples were taken at 1-m intervals along the stem. The fresh weight of sample branches and stem discs was measured in the field. Samples were oven dried in forced-ventilation ovens at 65°C, foliage was stripped from branches, and the weight of all components was recorded after they had attained constant weight.

Root systems were extracted in three phases:

Phase 1: The nine root systems per plot were individually lifted using an excavator, after the sand around each stump had been gradually loosened. The roots were thoroughly washed free of sand. The stumps were cut off at ground level, and the root systems were divided into three categories — the root stock, roots >1 cm, and roots <1 cm diameter.

Phase 2: Roots that broke off during root stock extraction were dug manually from the central part of the plot, washed free of sand, weighed fresh, and divided into roots >1 cm and <1 cm in diameter. Verical roots kinked and grew hotizontally when they contacted the geo-textile cloth at 1.3 m depth.

Phase 3: Roots running around the perimeter of the plot were lifted by hand after a trench had been dug approximately 0.5 m deep inside the edge of the plot and the sand had been collapsed into the trench to expose the interlaced roots. These perimeter roots were washed, weighed fresh, and divided into >1 cm and <1 cm diameter classes.

Roots extracted during the three phases were combined by size category for each plot, and the total fresh weight was determined. A disc cut from the top of each root stock, and approximately a one-quarter sample of each root category were weighed fresh, and oven dried to constant weight at 65°C. Tree dry mass was calculated from sample oven-dry/fresh weight ratios. For biomass calculation purposes, the above-ground stump section was combined with the rest of the stem. The amount of root mass recovered was expected to exceed 98%, with only small fragments remaining in the sand after root extraction. Plot area was effectively 38.5 m^2, taking into account the mean distance to plot buffer trees.

Mature Trees in Woodhill Forest

A mature 42-year-old first-rotation stand of *P. radiata* on a coastal dune in Woodhill Forest growing at a final stocking of 270 stems/ha was harvested in Nov/Dec 1985. Seven trees were selected for biomass determination, to provide biomass and nutrient pool data for the Woodhill intensive harvesting trial described above, and later installed within this stand. Stand biomass summary data have been published previously (Dyck *et al*. 1988); however, the actual biomass procedures were not described, and are reported here in detail to allow proper evaluation of these data. The trees were felled at approximately 20 cm stump height, and above- and below-ground biomass determined on an individual-tree basis. The above-ground biomass procedure included measurement of stem diameter at breast height and at every 3 m (to divide the tree into zones), total height, and height to base of the live crown. The diameters of all branches were measured at 2.5 cm from their upper point of attachment to the stem. Between three and six live undamaged (due to felling) branches were sampled per zone. The foliage and cones were stripped from sample branches, and each component was dried in forced-ventilation ovens to constant weight at 65°C. All dead branches above the pruned height of 6 m were collected and weighed fresh, and approximately a one-tenth sample was weighed fresh and oven dried. Dead branches below the live crown had largely been shed. Stem disc samples (approximately 10 cm in length) were cut at 6-m intervals along the stem, diameter under and over bark was measured with a diameter tape, and disc length was measured using callipers at eight equidistant points around the perimeter of the disc. Wood and bark samples were oven dried. Stem dry wood and bark weight were calculated from the volume of each section of stem and the density of the associated disc samples. Live crown dry mass per zone was calculated from the ratio between the zone total and sample branch cross-sectional areas multiplied by the dry weight of the sample branches (foliage, branch, cones). The root systems of the sample trees were extracted using a large bulldozer in January 1986. The root stock and large roots were removed largely intact, with a combination of lifting and pulling. Large roots that broke off during extraction were located if possible and dug up by hand. When broken roots could not be located, the root ends were tallied by diameter classes. Losses were allowed for by multiplying the tally by the mean weight of a sample of largely intact roots collected by root diameter class from each tree, with sinker roots sampled separately from lateral roots. This approach is similar to the method followed by Whittaker & Woodwell (1968). After root extraction, the stump was cut off at ground level (and added to the stem), the width and depth of the root system were measured, and roots were weighed by diameter class: 0.2–0.5, 0.5–1, 1–2, 2–10, 10–20, >20 cm (inclusive of root stock). All samples were oven dried to constant weight at 65°C.

Assessment of *P. radiata* Root Biomass Data

The following criteria were used to assess the suitability of studies for deriving valid root/shoot ratios for *P. radiata*.

(1) Both above- and below-ground biomass was measured, and data were considered to be sound;

(2) Oven-dry mass was determined, rather than fresh mass or air-dry mass;

(3) Root biomass sampling methodology was sound and provided accurate estimates of the root system total weight;

(4) At least five sample trees were measured to represent the stand;

(5) Study site was typical of the resource being assessed.

Studies were considered acceptable if all five criteria were met. Biomass studies that involved soil core sampling but without excavation of the root stock were not included in our assessment.

Statistical Analysis

The trial designs were fundamentally different, with some incorporating seedling material and others clones. Variation in trials incorporating seedling origin material included both genetic and environmental sources of variation; in clonal trials only environmental variation was involved. Therefore, each trial was analysed separately using the General Linear Model (GLM) procedure of SAS (Windows Version 8, SAS Institute Inc., Cary, NC, USA 1999). The effects of residue retention and nitrogen fertiliser treatments on the shoot weight, root weight, root/shoot ratio, tree height, and stem sectional area at the root collar were tested at the Woodhill intensive harvesting trial. The effects of understorey competition (for water) and nitrogen fertiliser on biomass components, height, dbh, and root/shoot ratio were tested at Rangiora. At Rangiora only one biomass tree was sampled per plot, and therefore treatment effects on root biomass were also tested after allowing for the shoot biomass in order to improve the sensitivity of the test of treatment effects on biomass partitioning above and below ground. Height effects on the root/shoot ratio were also tested at this and other sites. The effects of effluent application, irrigation rate, and effluent type on tree mean height, basal area, component biomass, and root/shoot ratio were tested at the Whakarewarewa Forest effluent irrigation trial.

Excavation of fine roots <1 cm in diameter was more-or-less complete at Whakarewarewa, and therefore the effect of effluent on the fine root fraction (<1 cm/total root system) was tested, including its relationship with foliar nitrogen concentration. Maximum likelihood analysis indicated that logarithm transformation of the data was necessary in some instances. Finally, the effect of stand age on the root/shoot ratio of acceptable studies (over all sites) was tested using the GLM procedure of SAS, and the overall mean and 95% confidence intervals were reported.

RESULTS AND DISCUSSION

Nursery Seedlings

The shoot and root dry weights of nursery-raised seedlings, which were trimmed immediately prior to planting, are given by seedlot in Table 1. The root/shoot ratio averaged 0.15, with no obvious difference among seedlots. The root mass of these nursery seedlings was influenced by recent undercutting, and consequently the root/shoot ratio was below that reported for seedlings (0.20) that were not undercut or wrenched (Rook 1971). Root trimming practices currently aim to facilitate planting while reducing distortion of the root system. Root/shoot ratios appear to readjust within 1 year from planting (based on data of Watson & Tombleson 2004). While the study provided valid model initial conditions (start values), the root/shoot ratios will be artificially low due to root pruning undertaken in the nursery prior to lifting.

TABLE 1–Mean dry weight, root/shoot ratio, and height of 30 bulked *Pinus radiata* seedlings/seedlot at time of lifting from the nursery beds at Rotorua.

Seedlot*	Foliage (g)	Stem (g)	Root (g)	Root/shoot ratio	Height (cm) (± SE)
Museum	3.98	2.07	0.94	0.16	27.6 (0.5)
Puruki	3.97	2.3	0.93	0.15	33.8 (0.6)
GF30	4.28	2.9	1.14	0.16	38.1 (0.8)
High density	3.24	1.81	0.7	0.14	29.9 (0.7)

* Museum = originating from unimproved open-pollinated (GF0) parents
Puruki = from moderately improved open-pollinated GF7 parents
GF30 = from highly improved control-pollinated GF30 parents
High density = from high wood density control-pollinated parents

Woodhill Forest Intensive Harvesting Trial

Shoot and root biomass after 1.5 years' growth are given in Table 2. Since the trees were planted the plus-fertiliser subplots had received 250 kg N/ha as urea. The root/shoot ratio averaged 0.14, both with and without fertiliser. Statistically significant main treatment differences were evident for shoot weight ($p < 0.0001$),

TABLE 2–Shoot and root mean dry weight, seedling height (Ht), and root collar sectional area (SA) of six trees/treatment from a 1.5-year-old second-rotation *P. radiata* stand at Woodhill Forest. Treatments included with (F) or without (NF) nitrogen fertiliser (Fert). *See* Methods section for explanation of treatments.

Residue retention	Fert*	Shoot (g)	Root (g)	Root/shoot ratio	Ht (cm)	SA (cm^2)
FF	NF	452	60	0.13	103	7.5
	F	875	113	0.13	123	12.6
WT	NF	666	113	0.17	121	9.5
	F	733	103	0.14	125	11.9
SO	NF	411	64	0.16	105	6.4
	F	650	82	0.13	119	9.7
DS	NF	487	73	0.15	121	7.7
	F	291	45	0.15	97	4.5
NWR	NF	85	12	0.14	88	1.8
WR	NF	57	8	0.14	86	1.1
p value for residue retention		<0.0001	<0.0001	ns	<0.0001	<0.0001

* No significant fertiliser effects (p level of 5%) were found for any component

root weight (p <0.0001), basal diameter (p <0.0001), and tree height (p < 0.0001), but not for root/shoot ratio (p = 0.24). Trees in normal management plots (without weed control) were significantly smaller than trees in plots with weed control. No relationship was found between the root/shoot ratio and total height of individual trees.

Roots <0.5 cm in diameter were not measured in this study, but were likely to represent a relatively large proportion of the root mass, given the small size of these seedlings which was a limitation of this study. Consequently, the root/shoot ratio (0.14) would have been under-estimated. Differences in seedling size were not important with respect to root/shoot ratios for the >0.5 cm diameter roots. The study met all other evaluation requirements.

Rangiora Agroforestry Trial near Christchurch

The root and shoot system biomass of 19 individual trees in treated plots was measured (Table 3). The data from five small trees with unusually high root/shoot ratios were omitted because there was a high probability of differential ingrowth of roots from surrounding larger trees introducing a bias in the calculation of root biomass on an individual tree basis. Treatment effects on biomass components were not statistically significant. Shoot weight explained 99% of the variation in root mass, with no further variation explained by pasture management or fertiliser treatments. The individual-tree root/shoot ratios ranged between 0.16 and 0.25 at

TABLE 3–Height (Ht), diameter (dbh), and component dry weight (kg/tree) of individual trees in a 5-year-old *P. radiata* stand at Rangiora. The agroforestry trial included grazed pasture (GP), ungrazed rank pasture (RP), and pasture-free (WC) plots as main treatments. Treatments included with (F) or without (NF) nitrogen fertiliser (Fert). *See* Methods section for explanation of understorey treatments.

Treatment*		Component							
Under-storey	Fert	Ht (m)	Dbh (cm)	Stem	Branches	Foliage	Shoot	Root	Root/ shoot ratio
GP	F	5.35	11.6	15.5	16.3	16.6	48.3	10.6	0.22
GP	F	7.16	14.3	19.3	12.2	14.4	46.0	8.7	0.19
GP	F	5.71	12.5	15.7	10.5	15.8	42.0	7.6	0.18
GP	F	4.59	9.5	8.6	9.1	10.1	27.7	6.2	0.22
GP	NF	5.53	12.4	15.7	17.7	15.4	48.8	10.6	0.22
GP	NF	4.31	9.4	8.5	8.8	10.0	27.4	5.6	0.20
RP	F	5.19	11.4	12.0	11.6	13.5	37.1	9.1	0.24
RP	F	5.08	10.0	10.4	11.8	14.9	37.2	8.2	0.22
RP	F	5.05	12.0	12.9	16.7	13.3	42.9	9.9	0.23
RP	NF	5.44	10.5	14.8	17.9	13.3	46.0	9.4	0.20
RP	NF	5.15	10.2	12.1	11.8	8.9	32.8	7.3	0.22
RP	NF	5.17	9.7	9.3	7.1	10.1	26.5	6.1	0.23
WC	F	4.22	8.7	7.8	10.6	11.5	29.8	4.8	0.16
WC	F	4.6	11.2	13.1	14.0	17.1	44.2	7.9	0.18
WC	F	6.33	14.5	21.6	20.7	27.0	69.2	17.0	0.25
WC	F	4.56	7.2	7.3	15.0	12.3	34.6	6.9	0.20
WC	F	3.91	7.9	6.0	6.6	9.6	22.2	4.8	0.22
WC	F	6.42	12.7	17.1	14.9	17.3	49.3	11.0	0.22
WC	F	5.32	10.8	13.6	16.9	17.8	48.3	9.0	0.19

* No significant treatment effects were found.

Rangiora, with an overall mean of 0.21. This range occurred within the pasture-free (WC) treatment, and was therefore due to genetic variation plus sampling error. The root/shoot ratio was not significantly related to tree height. Roots below 20 cm depth that were outside the pit were not measured, but their contribution to the total root biomass was expected to be small. This study met all other evaluation requirements.

Whakarewarewa Forest Irrigation Trial near Rotorua

Tree growth increased significantly after effluent application (Table 4), particularly at the highest application rate. The largest growth response occurred in plots irrigated with a mix of BNR and primary effluent, which contained appreciably more nitrogen than BNR effluent alone. Even though biomass per plot almost doubled in plots irrigated with effluent, the major tree components responded in a similar manner, and consequently the root/shoot ratio (overall average 0.17) was

TABLE 4–Treatment mean height (Ht), basal area (BA), component dry weight (Mg/ha), and foliar nitrogen concentration (Fol N) in a 5-year-old *P. radiata* stand with or without irrigation (I) with two types of effluent (E) at two rates (R). The effluent irrigation trial was located at Whakarewarewa Forest near Rotorua. Each mean is based on three replicates of nine clonal trees (27 trees per treatment). *See* Methods section for explanation of treatments.

E*	R	I	Ht (m)	BA (m^2/ha)	Fol	Brch live	Brch dead	Stem wood	Stem bark	Shoot total	Root stock	Root >1 cm	Root <1 cm	Root total	Root / shoot ratio	Fol N (%)
None	0	No	7.8	13.6	4.8	6.2	0.6	18.0	2.0	31.6	3.4	1.2	0.8	5.4	0.17	1.46
BNR	30	Yes	8.4	17.6	5.4	9.0	1.1	21.8	2.5	39.7	4.4	1.3	1.3	7.0	0.18	1.41
BNR	60	Yes	8.4	21.3	7.6	11.1	0.9	25.1	2.8	47.4	5.4	1.7	1.4	8.5	0.18	1.42
Mix	30	Yes	8.0	18.2	5.8	10.6	0.7	21.8	2.5	41.4	4.5	1.5	1.1	7.1	0.17	1.58
Mix	60	Yes	8.4	23.8	7.9	13.3	1.1	28.9	3.2	54.4	6.2	2.0	1.3	9.5	0.17	1.64
Significance $p<0.05$			ns	I,R	I,R	I,R	ns	I,R	I,R	I,R	I,R	R	I	I,R	ns	I,E

* Effluent types:
BNR = effluent with biological nitrogen reduction
Mix = mixture of BNR and primary effluent

unaffected by any of the treatments. Shoot weight explained 96% of the variation in total root weight, with no further variation explained by the treatments. The proportion of the root system composed of fine roots increased from 0.15, 0.16, and 0.18 for Mix, None, and BNR treatments, respectively, and was negatively related ($p = 0.0038$) to foliar nitrogen concentration.

The annual rainfall at Rotorua was sufficient for normal growth, and so the addition of 30 or 60 mm water/week as effluent was not expected to increase tree growth. Analysis of basal area data for the entire trial, which included separate water and effluent irrigation treatments that were applied to volcanic ash soil (but without the root-impervious geo-textile filter cloth lining the base of the plot), showed no growth response to the water-only treatment (data not shown). The growth response to effluent addition was presumably stimulated by the increase in available nutrients, including nitrogen. The range in foliar nitrogen values (Table 4) is typical of *P. radiata* on normal forest soils in New Zealand and indicates that all treatments received some benefit from the initial application of peaty topsoil to each plot.

The root biomass was composed of 64%, 20%, and 16% root stock, roots >1 cm, and roots <1 cm, respectively. Eighty-five percent of the total root mass was extracted mechanically using the excavator, while 15% (including roots running around the perimeter of the plot) was extracted by hand. The excavator extracted 62% of the roots <1 cm, and manual digging recovered 38%.

Nambiar (1980) found that root/shoot biomass ratios were higher in a glasshouse study of seedlings grown in nitrogen- or phosphorus-deficient nutrient solutions than in those growing in a “complete” nutrient environment. Likewise, root/shoot ratios of annual biomass increment decreased in nutrient-deficient pine and spruce stands treated with fertiliser (Axelsson & Axelsson 1986). Fine root biomass comprises all of the root mass of seedlings, but represents only approximately 16% of the root mass in the 5-year-old stands we studied, which explains why the fraction of roots <1 cm was significantly higher in treatments with low foliar nitrogen at Whakarewarewa, while the total root/shoot biomass ratio was not significantly related to treatment. This study met all the evaluation requirements.

Mature Trees in Woodhill Forest

The characteristics of seven mature 42-year-old *P. radiata* trees were assessed (Table 5). Tree total height ranged between 30 and 40 m, and diameter between 36 and 59 cm. Individual tree root/shoot ratios ranged between 0.15 and 0.27, with an overall mean of 0.20. The mean and range were similar to the Rangiora trial. Shoot mass explained 89% of the variation in root mass. Most of the root mass was associated with roots greater than 10 cm in diameter (68% of the root mass), and roots 1–10 cm and <1 cm diameter comprised 30% and 1%, respectively, of the total root mass.

TABLE 5–Height (Ht), diameter at breast height (dbh), and component dry weight (kg/tree) of individual trees in a 42-year-old *P. radiata* stand in Woodhill Forest stocked with 270 trees/ha. *See* Methods section for definition of components.

Tree	Ht (m)	Dbh (cm)	Fol	Live branch	Dead branch	Stem wood	Stem bark	Cone	Shoot total	Root >20 cm	Root 10–20 cm	Root 1–10 cm	Root 0.5–1 cm	Root 0.2–0.5 cm	Root total	Root/ shoot ratio
1	38.1	59.0	41.0	117	21.5	1790	212.6	7.9	2189	227	83.6	114	2.4	0.7	428	0.20
2	30.9	45.9	29.7	111	19.7	934.9	165.8	12.9	1274	187	55.9	99.0	2.7	1.1	346	0.27
3	32.5	35.8	10.9	25.7	5.4	556.0	84.4	4.0	686	52.2	23.6	42.4	1.4	0.7	120	0.18
4	31.8	36.2	9.92	32.3	8.2	592.9	105.4	27.7	776	42.4	25.5	45.8	1.2	0.4	115	0.15
5	37.7	47.7	27.4	72.0	11.7	1113	207.3	20.1	1451	126	49.8	75.8	2.5	0.4	256	0.18
6	34.4	52.6	23.4	77.7	14.7	1012	172.5	14.4	1315	143	31.5	95.4	2.5	0.8	273	0.21
7	31.6	50.4	31.4	110	17.5	1153	146.9	18.3	1477	215	45.1	68.4	0.75	0.2	330	0.22

The root system weights of the seven biomass trees included an adjustment to account for losses associated with the method of extraction. The tally of broken root ends averaged 41 per tree, with 60% of these being small roots <1 cm, and 40% medium roots 1–10 cm in diameter. Only one root >10 cm in diameter broke off during extraction. The estimated weight of roots that broke off during extraction represented 3.3% of the root total weight, which indicates that losses associated with the method of root system extraction were relatively minor at this site. The study of 42-year-old trees at Woodhill Forest met all the evaluation requirements.

Evaluation of Previously Published Root/shoot Studies

Previously published studies of *P. radiata* root biomass we evaluated are summarised below. These studies included seedlings, young stands in controlled field experiments, and trees in managed forests (Table 6).

Rook (1971) measured the root and shoot biomass of seedlings in nursery beds in Rotorua twice weekly for a period of 3 months. The root/shoot ratio of autumn-sown nursery seedlings averaged approximately 0.2 in uncut seedlings, with little seasonal variation throughout the first year of growth. Biomass measurements involved lifting intact seedlings and measuring the oven-dry weight (dried at 100°C for 48 hours) of the shoot and root systems.

Jackson & Chittenden (1981) measured root and shoot biomass of 97 trees aged between 3 and 8 years. Eighty-five trees were grown in polythene-lined trenches installed in a trial on pumiceous soil at the Forest Research Institute campus, Rotorua. Trench width varied from 25 cm for 3-year-old trees to 100 cm for 6-year-old trees. Trench length allocated per tree was double the trench width. The 8-year-old trees were grown in 1.22-m square containers of 2.72 m^3 capacity. After the trees were felled, the roots in the section of trench midway between adjacent trees were excavated manually, and extracted and weighed by size class. Samples were oven dried to constant weight at 65°C. The root/shoot ratio averaged 0.24, with a range of 0.10 to 0.48. The root/shoot ratio was negatively correlated with tree height, which is an artefact that presumably resulted from differential ingrowth versus outgrowth of roots from the section of trench allocated to each tree. Although the individual tree ratios are not valid, we expect the overall root/shoot ratio for these stands to be valid.

Gautam *et al*. (2003) measured root biomass in 3- and 4-year-old trees growing in a silvo-pastoral trial in Canterbury in the South Island, on a drought-prone site where rainfall averaged 660 mm annually. Roots >0.2 cm diameter were extracted using a tractor with a hydraulic lift, and losses were taken into account by adjusting for the mass of broken roots using regressions based on root diameter. Samples were oven dried at 70°C to constant weight. The soils were underlain with impervious gravel, and root recovery was thought to be largely complete. Shoot

TABLE 6–Assessment of root biomass studies undertaken in *P. radiata* stands of different ages. Studies are listed in decreasing order of suitability (ordered by age) for estimating carbon stocks from root/shoot ratios. Number of trees is n. Stand age zero refers to seedlings.

	Stand age (years)	Mean root/shoot ratio	n	Valid above- & below-ground data	Oven dry wt	Sampling procedures sound	Sample size adequate (≥5)	Typical site
Rook (1971)	0	0.2	90	√	√	√	√	√
Nambiar (1980) (normal fertility)	0	0.20	12	√	√	√	√	√
Gautam *et al*. 2003	3	0.13	12	√	√	√	√	√
Gautam *et al*. 2003	4	0.18	12	√	√	√	√	√
Whakarewarewa (this study)	5	0.17	135	√	√	√	√	√
Jackson & Chittenden (1981)	3–8	0.24	97	√	√	√	√	√
Rangiora (this study)	5	0.21	19	√	√	√	√	√
Ovington *et al*. (1967)	8	0.19	100	√	√	√	√	√
Woodhill 42 years (this study)	42	0.20	7	√	√	√	√	√
The following studies provided root/shoot ratios but for various reasons were excluded from the final analysis								
Seedlots (this study)	0	0.15	120	X	√	√	√	√
Nambiar (1980) (low fertility)	0	0.38	12	√	√	√	√	X
Rook (1971)	0	0.35	270	X	√	√	√	√
Woodhill 1.5 years (this study)	1.5	0.14	60	√	√	X	√	√
Gadgil (1979)	2	0.50	10	√	√	X	√	√
Gadgil (1979)	3	0.46	10	√	√	X	√	√
Gadgil (1979)	4	0.51	10	√	√	X	√	√
Gadgil (1979)	5	0.58	10	√	√	X	√	√
Evans & Nordmeyer (*in* Phillips &Watson 1994)	14	0.37	6	X	√	√	√	√
Will (1966)	18	0.12	8	X	√	X	√	√
Ritchie (1977)	4	0.21	2	X	√	√	X	√
Ritchie (1977)	15	0.28	1	X	√	√	X	√
Ritchie (1977)	26	0.40	1	X	√	√	X	√

biomass procedures were reported by Bandara *et al*. (2004). The overall mean root/shoot ratio was 0.16, increasing from 0.13 at age 3 to 0.18 at age 4. Gautam *et al*. (2003) found a significant “age” effect; however, this seems unlikely given the small sample sizes and narrow age range. The genotype effect reported by Guatam et al. (2003) presumably reflects their use of a single clone in comparison with seedling-origin trees. Watson & Tombleson (2004) found no significant plant type effects on the root/shoot ratio when comparing the wind stability of cuttings versus seedlings, but they did not report the root/shoot ratios. Gautam’s data were considered suitable for inclusion in our study.

Nambiar (1980) measured root/shoot ratios in 10-month-old seedlings from nursery beds with or without fertiliser. Twelve seedlings were excavated from the high- and low-fertility beds by inserting two spades vertically in the soil 10 cm on either side of the rows of seedlings, to a depth of 20 cm. There was no undercutting or wrenching and root samples included tap roots. The foliar nitrogen status of the seedlings without fertiliser was very low (1.1%) and this suggests that the light-textured sand was nitrogen-deficient and not typical of a production nursery or most New Zealand *P. radiata* forests. The data from the seedlings with fertiliser, which had foliar nitrogen levels of 1.7%, were accepted as suitable for our purpose.

Ovington *et al*. (1967) measured 100 trees growing in a single plot (0.081 ha) in an 8-year-old unpruned *P. radiata* plantation near Canberra, Australia. Trees were felled at ground level, and shoot and root system biomass was determined using detailed field procedures involving complete weighing of the trees by component. Roots of individual trees were extracted using a tractor and by digging. Care was taken to ensure all roots >0.5 cm were recovered, but no attempt was made to collect all the roots <0.5 cm in diameter. Samples were oven dried at 85°C. The root/shoot ratio averaged 0.19, which will be an under-estimate because some of the small roots were not measured. However, the loss is expected to be relatively minor given the stand age. For example, roots <1 cm in diameter (i.e., twice as large) comprised only 16% of the total root weight in the 5-year-old stand at Whakarewarewa.

The following five studies we examined and rejected as unsuitable for our final analysis of root/shoot ratios, because of apparent errors, methodological issues, or lack of applicability.

Evans & Nordmeyer measured the above- and below-ground biomass of 14-year-old trees at Nelson (summary data given by Phillips & Watson 1994). While the root data appear sound, the associated above-ground data for the six trees were not logically correlated with dbh, which suggests either measurement or calculation errors in the above-ground data. This study was therefore excluded.

Ritchie (1977) measured the biomass of 4-, 15-, and 26-year-old trees in a coastal sand forest at Waitarere. Neither the individual tree data nor the stand summary data were consistent with the reported root/shoot ratios, and this suggests calculation errors in the published data, which were therefore excluded.

Gadgil's (1979) estimation of the weight of roots <1 cm diameter using 1-m^3 pits (three per stand) in 2- to 5-year-old *P. radiata* stands at Woodhill was very high and variable compared to the weight of <1 cm roots excavated using 0.5-m radius rings placed around the stump of biomass trees. Roots within a 0.5-m radius around the stem gave root/shoot ratios ranging between 0.23 and 0.26. When the <1 cm roots from pits were included, the root/shoot ratios increased to between 0.46 and 0.58. Roots <1 cm comprised 63% of the total root weight at Woodhill (Gadgil 1979, Table 3), which is high compared to Whakarewarewa, and suggests that pit data over-estimated <1 cm root weight. Roots from understorey vegetation may have been inadvertently included in the pit data.

Will (1966) measured root and crown biomass of eight trees on volcanic ash soils at Kaingaroa. The root/shoot ratio was reported to be 0.12; however, stem weight of biomass trees was not measured, but was estimated on a stand basis from stem volume per hectare to which an unrealistically high wood density was applied. We computed the stem volume of his eight biomass trees from their diameter at breast height and total height, and estimated stem weight by assuming a more typical mean whole stem wood density of 350 kg/m^3, consistent with the young tree age of 18 years and high site fertility, which gave a mean root/shoot ratio of 0.16. This is still likely to be an under-estimate because roots estimated using soil pits did not include those below 1 m depth, or roots >1.25 cm in diameter severed during trench construction. The drying temperature used in this study was not reported.

Nambiar (1980) measured the biomass of nitrogen-deficient seedlings grown in a sandy nursery soil without fertiliser. These data were rejected as being atypical of a modern production nursery, as mentioned earlier.

Rook (1971) also reported root/shoot ratios of undercut (removal of about 25% of the root system) and repeatedly wrenched seedlings. Wrenching was intended to retard shoot growth and increase the root/shoot ratios which levelled off between 0.3 and 0.4, depending on the frequency of wrenching. Current nursery practices do not appear to achieve such high ratios.

The root data of Watson & O'Loughlin (1990) and Heth & Donald (1978) are not included in Table 6 because they did not measure above-ground biomass for calculating root/shoot ratios. The air-dry data and regressions developed by Watson & O'Loughlin (1990) have been shown by Madgwick (1991a, 1994) to be not different from the air-dry data and regressions of Heth & Donald (1978). Although air-dry data are not interchangeable with oven-dry data, the air-dry data of Watson & O'Loughlin (1990) were inadvertently included with oven-dry data for developing functions for predicting root weight from stem diameter by Drexhage & Colin (2001), and Snowden (2000).

GENERAL DISCUSSION

Each study is listed in decreasing order of suitability for estimating root carbon stocks from root/shoot ratios, together with a summary of our evaluation results (Table 6). The mean root/shoot ratio is given for each study. The root/shoot ratio of nine studies considered suitable, which included 484 trees from 0 to 42 years old, ranged between 0.13 and 0.24. The overall stand mean ratio for suitable studies was 0.19 (95% CI = 0.023), with no significant stand age effect evident. This compares with a stand mean root/shoot ratio of 0.34 (range 0.12–0.58) for the 520 study trees considered unsuitable.

Stand mean root/shoot ratios in *P. radiata* were very similar across a wide range of stand age classes, which is consistent with findings reported for other conifers. The mean root/shoot ratio in the 42-year-old *P. radiata* stand growing on a nitrogen-deficient dune at Woodhill (0.20) was similar to the ratio obtained in an 8-year-old stand in Australia (0.19), and 5-year-old stands at Whakarewarewa (0.17) and Rangiora (0.21). The latter two sites included a range of nitrogen fertiliser, weed control, and effluent irrigation treatments, none of which influenced the root/shoot ratio. Experimental treatment effects on nitrogen supply were more precisely tested at the Whakarewarewa trial than at the Rangiora trial, which suggests that environmental sources of variation on the root/shoot ratio are small relative to genetic sources of variation observed at Rangiora and Woodhill. No stand age effect was found in 67 woodlands dominated by *P. densiflora* in eastern Japan (Satoo 1967), where the root/shoot ratio of the tree layer was stable (mean 0.20, range 0.19–0.22) in stands ranging in age between 13 and 46 years. More recently Mund *et al*. (2002) reported root/shoot ratios ranging between 0.2 and 0.3 along a chronosequence of Norway spruce stands aged 16–142 years. Stand age influenced only the root size class distribution, with 99% of the roots >1 cm at Woodhill compared to 84% at Whakarewarewa.

As some loss of fine root biomass was inevitable in most studies, a slightly increased root/shoot ratio of 0.20 is recommended as appropriate for *P. radiata* over all sites and stand ages. This recommendation is justified using the root recovery data from the 5-year-old trees in the Whakarewarewa effluent trial, which showed that the difference between mechanical and subsequent manual recovery of small roots <1 cm diameter from confined plots was sufficient to increase the root/shoot ratio by 1%.

To estimate root biomass, the root/shoot ratio given here for *P. radiata* should be applied to the above-ground biomass estimate. The root biomass estimate can be expected to be unbiased, provided that no root or crown pruning has occurred. The effect of root pruning prior to lifting on the biomass of nursery-raised seedlings was measured for several seedlots in this study. Crown pruning of young *P. radiata* stands is a common practice in New Zealand that also will alter the root/shoot ratio, depending on the severity of the pruning operation. Estimation of the effect of crown pruning on the root/shoot ratio requires methods additional to those described in this paper.

CONCLUSIONS

The research results presented in this paper add to the body of knowledge about *P. radiata* root and shoot biomass, and the environmental factors influencing variation in biomass.

While root/shoot ratios varied markedly among the studies assessed in this study, this variation was due predominantly to sampling and methodological limitations. When only acceptable studies were included, the root/shoot ratio was relatively constant across a wide range of stand ages, sites, and experimental treatments, with an overall mean of 0.19 (95% CI = 0.023). We recommend that a root/shoot ratio of 0.2 be adopted for *P. radiata*, to allow for losses of fine roots that were acknowledged to occur in most studies.

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