ESTIMATION OF DRY MATTER IN PINUS RADIATA ROOT SYSTEMS
I. INDIVIDUAL TREES

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ABSTRACT

Analyses are given of dry matter components of root systems of 97 **Pinus radiata** D. Don trees, 3 to 8 years old; estimating equations for total root dry matter, roots greater than 2 mm, and roots greater than 5 mm diameter are presented. Of all the components and dimensions tested, root dry matter is most highly correlated with that of foliage.

Compatibility of the estimating equations with root dry matter data for an additional 150 **P. radiata** trees (provided by earlier workers) encourages presentation of a general estimating equation for roots greater than 5 mm diameter, i.e.,

$$\log_e \text{(root o.d. wt)} = 2.73 \log_e \text{(d.b.h.)} - 5.009$$

(root o.d. wt in kilograms; d.b.h. in centimetres).

Relationships for estimating component root-length from o.d. wt. are also developed.

INTRODUCTION

The work summarised in this paper was intended to provide means of estimating the below-ground dry-matter components of the *Pinus radiata* biomass model in the Puruki Project, an interdepartmental project which was originally initiated under the aegis of both the International Biological Programme and the International Hydrological Decade. It includes a catchment that was planted with *P. radiata* in 1973, and in which the biomass is being assessed annually and the environment monitored continuously.

Although some data about the biomass of *P. radiata* root systems have been published, a major difficulty in making use of such information is that the data are seldom at comparable levels of resolution. Thus, Will (1966) measured the bulk of the root system (including the above-ground stump) down to a minimum diameter of 125 mm, and sampled for roots smaller than this. Ovington *et al.* (1967) severed their 100 trees at ground level and took care to extract all roots greater than 5 mm diameter. Smaller components remained unknown. Dargavel (1970) extracted the roots of 25 trees from 5- to 18-year-old plantations partially by digging, and then winching the root system out of the ground. The root-stock was kept separate from the stump above soil level, but not all the small roots were harvested. Heth & Donald (1978) used similar methods, winching the "main mass" of 20 trees (27–39 years old) from the ground, and then measuring the terminal diameter of all broken roots larger than 20 mm, as a means of estimating the oven dry weight (o.d. wt) of the missing portions. These were derived from a regression based on 450 roots that were excavated intact. Recently Somerville (1979) examined the root morphology of sixty-one 11½-year-old *P. radiata* from ripping trials in Eyrewell State Forest, but the dry-matter data do not include roots less than 10 mm diameter, nor more than 1 m from the tree's central axis.

It is apparent that the large amount of time and effort that must be invested in such studies imposes practical compromises that subsequently reduce comparability. In addition to the "pressing need" for consistency (Hitchcock & McDonnell 1977), it would be useful to bridge the gaps in comparability, if possible, and particularly to assess the mass of the components below 5 mm diameter that are frequently missed. Heth & Donald (1978) estimated that roots less than 5 mm diameter comprised *c.* 6% of total root biomass on their 36- or 39-year-old trees, and *c.* 18% on those that were 27 years old. It would be even higher on younger trees; but unfortunately the necessary detailed work on fine roots of *P. radiata* has been generally concentrated on problems of root distribution (Bowen 1964) and comparison between treatments (Moir & Bachelard 1969; Squire *et al.* 1978), wherein statistical problems of comparability within a stand supersede assessment of the total component. Questions of extraction technique, contamination, and arbitrary classification are no less important, whatever the objectives; but it is usually impossible to obtain complete recovery of individual root systems that are both attenuating and normally interlocked with those of other trees. The opportunity for the work reported here was provided by 12 trees grown to age 8 years in individual containers (cf. Fig. 1) and harvested *in toto* during 1973 (cf. Jackson *et al.* 1976). The root data from these trees have been supplemented, in the intervening years, by annual dry-matter determinations of individual trees grown in polythene-lined trenches to aid complete recovery.

METHODS

Sources of Data

The data were obtained from 97 *P. radiata* trees grown at the Forest Research Institute, Rotorua (38°07'S latitude; 287 m altitude), where the normal annual rainfall is 1511 mm, and the normal annual temperature is 12.1°C (cf. Station No. 886124, N.Z. Meteorological Service 1973). Twelve of the trees had been grown individually in containers of 2.72 m^3 capacity and were subjected to the various watering regimes described by Jackson *et al.* (1976). The trees were felled in June 1973, when a complete dry-matter analysis of crowns, stems, and root systems was done. In June 1974 another experiment was established on the same site, comprising a series of polythene-lined trenches (Fig. 2) ranging from 40 cm deep × 25 cm wide for the first harvest (1976), to 100 cm deep × 100 cm wide for the fourth harvest (1979). The trenches were back-filled with the soil (a pumiceous sandy loam) on-site; and topsoil and subsoil were replaced in normal positions. To aid free drainage the bottom of each trench was lined with the heaviest grade (95% shade) "Sarlon" cloth, overlapping with and glued to the sides of ordinary black polythene (0.25 mm thickness). Preliminary trials had shown that, provided the "Sarlon" cloth is carefully laid on a stable soil surface,

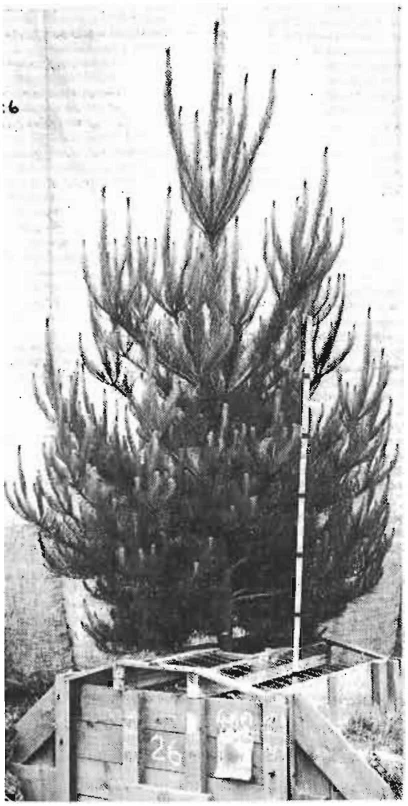

FIG. 1 (left)—Six-year-old **P. radiata** grown in individual containers (2.72 m^3 capacity). Trees were harvested for total dry matter components 2 years later, in June 1973 (scale in feet).

FIG. 2 (below)—Root-trench showing overlap and cementing of polythene sides to "Sarlon" mesh lining on bottom.

P. radiata roots are not able to penetrate it. This has been subsequently confirmed at each annual harvest.

The numbers of trees felled and extracted in each year, together with their mean diameter-at-breast-height and height, and the length of trench excavated for each tree, are summarised in Table 1. In so subdividing the trench along its length, it is assumed that the roots leaving any particular section are compensated for by roots entering it from the adjacent trees on each side.

TABLE 1—Container dimensions, and number, age, and mean dimensions of trees sampled in each year to provide root and crown dry-matter data

Year	1973	1976	1977	1978	1979
No. of trees	12	16	28	25	16
Age (years)	8	3	4	5	6
Mean d.b.h.* (mm)	143	21	48	59	67
Mean height (cm)	811	219	458	643	795
Trench depth (cm)	183	40	50	50	100
Trench width (cm)	122	25	50	50	100
Length of section (cm)	122	50	100	100	200

* d.b.h. = diameter at breast height 1.4 m

Root Extraction

Above-ground components of dry matter were determined for each tree by the methods given by Madgwick *et al.* (1977). After the top had been harvested, the section of trench from midway between adjacent trees was excavated manually and the soil spread out on wooden platforms and broken up. At this stage, all intact roots were picked out of each distributed batch of soil and deposited in containers of water to await sorting.

When the remaining soil and fine roots had dried sufficiently for the latter to become buoyant, they were passed through a battery of washers (as modified from Cahoon & Morton 1960) (Fig. 3), where the overflow carried residual roots, other organic matter, and low-density mineral matter (e.g., pumice particles) on to a series of sieves. Any intact roots that had been missed in the initial dry extraction were transferred from the sieves to the main batch for sorting. The final sieve retained all material greater than 0.8 mm.

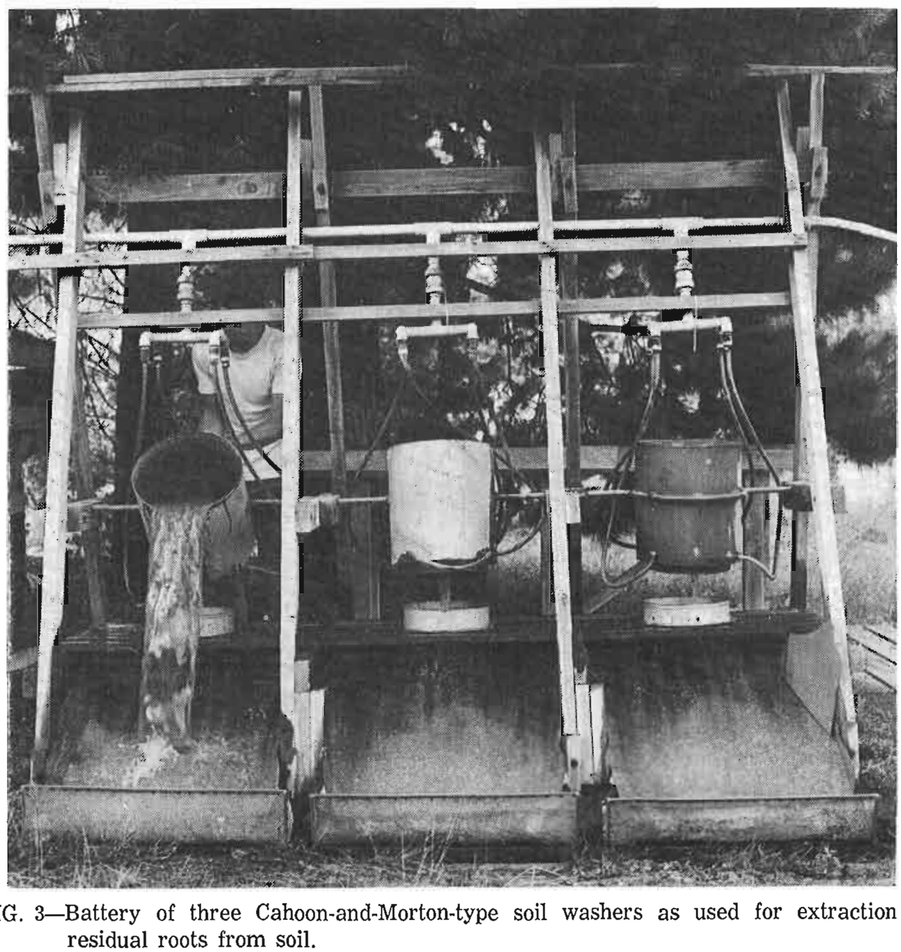

FIG. 3—Battery of three Cahoon-and-Morton-type soil washers as used for extraction of residual roots from soil.

After draining, thorough mixing, and weighing of this sieved material, a sub-sample was removed, weighed, and stored with 100 ml formalin-acetic acid in a sealed plastic bag. The sample was held in a cool-store for subsequent separation of the comminuted fine roots.

Root Classification

Extracted roots were separated into size classes by diameter, to provide alternative bases for comparison with previous work on *P. radiata* root systems. The classes were defined as follows:

Very large roots:	> 20 mm diameter over bark (o.b.)
Large roots:	between 10 and 20 mm diam. o.b.
Medium roots:	between 5 and 10 mm diam. o.b.
Small roots:	between 2 and 5 mm diam. o.b.
Fine roots:	< 2 mm diam. o.b.

This classification is identical with that advocated by Böhm (1979), except that his smallest category of "very fine roots" (< 0.5 mm diam.) is included in "fine roots" by us. Separation of roots into size classes was checked in marginal cases by using a simple slot-gauge run along the root. At the upper (proximal) limit of very large roots they merge with the main axis of the tree, the below-ground portion of which is termed the "rootstock" and which is continuous at ground-level with the stump. These two components of tree biomass are accounted for separately from the stem and root system, so that they can be allocated to above-ground and below-ground dry matter when required (cf. Table 2 which summarises the data overall).

TABLE 2—Summary of mean values, standard deviations (S.D.), and ranges of dry-matter components (kg)

Component	Mean	S.D.	Min.	Max.
Foliage	2.68	3.76	0.13	13.69
Branches	4.13	7.73	0.09	32.26
Stem (incl. stump)	8.47	10.45	0.38	41.30
Total above-ground d.m.	15.45	21.68	0.72	84.87
Roots > 5 mm diam.	2.53	3.37	0.04	12.68
Small roots	0.30	0.53	0.02	2.53
Fine roots	1.17	1.91	0.13	9.21
Total below-ground d.m.	3.69	5.68	0.20	22.06

At the distal limits of the root system, the "cut-off point" for fine roots was dictated by the fragmentation that occurred during processing. In Moir & Bachelard's (1969) comparison of extraction methods for fine roots, they defined these as ranging from 0.4 to 3 mm in diameter, following Bowen (1964); McQueen (1973) used an upper limit of 1 mm and Squire *et al.* (1978) used 0.5 mm. The level of resolution specified and the effect of extraction techniques on fragmentation, particularly of vulnerable young growing-tips and mycorrhizas, must affect the overall recovery of fine roots. Fragmentation becomes critical where mechanical methods of extraction are used to process large volumes of soil, as in this study. To reduce comminution to a minimum, the fine-root component was accordingly assessed in two categories as follows:

(1) "Intact fine roots": All those roots, less than 2 mm diam., which could be extracted manually, either at the initial sorting or from the sieves below the root-washers, without any intermediate sampling.

(2) "Comminuted fine roots": Estimated content of root fragments less than 2 mm diam., derived by sampling the material retained on the final 0.8-mm sieve after its total fresh weight had been determined. This sample had been stored in a plastic bag with 100 ml formalin-acetic acid until the root fragments could be extracted in the laboratory by a combination of methods involving washing through successive 5-, 3-, and 1-mm sieves and decanting. In the final stages of recovery there was always an indeterminate amount of foreign organic matter, as well as mineral pumice particles of similar density, mixed up with the last and smallest root fragments. These had to be manually recovered with an artist's brush or forceps, until a subjective judgment was made that further separation was no longer worthwhile. We consider that this is a more positive approach (particularly because it eliminates mineral contamination) than the converse procedure of deciding when to stop removing the foreign material from a sample. Moir & Bachelard (1969) indicated that, without manual sorting, organic contamination could amount to 38% of the o.d. wt. This figure is not an over-estimate, but it should be understood that the price of eliminating contamination from our data is that our estimates of the comminuted fine root o.d. wt. are slightly lower than the true value. Furthermore, this unknown error is multiplied by the ratio of total weight of final sievings to the weight of the sample taken. Dead roots, which were encountered only in the fine root component of these young trees, were not excluded from this assessment of dry matter. Because the extraction of comminuted fine roots is so time-consuming, it was undertaken only for the 1973, 1976, and 1977 samplings.

Adjustments for Ash Weight

Roots larger than 5 mm were scrubbed clean of adhering mineral matter at time of sorting, so that in proportion to total o.d. wt. any contamination of dry matter would be minimal. Ash weights were accordingly not determined for roots larger than 5 mm diam.

For the intact fine roots (< 2 mm diam.) most of the obvious soil contamination could be removed during manual extraction, by repeated washing. However, even for such visually "clean" roots, we found that the mineral component (after ashing in a furnace) could be as high as 30%, and was variable. For the comminuted fine roots both the variability and the proportion of ash were even greater. We have accordingly presented all fine root o.d. weights as net of ash content, i.e., the weight of volatile material only.

Alternatives are more equivocal for small roots (2–5 mm diam.). There is undoubtedly considerable inorganic material (clay particles, etc.) adsorbed on the outer surfaces of the rootlets, which cannot be freed by repeated washing. In our samples the mineral matter content of small roots averages about 2.9% of the gross o.d. wt., and the dry matter o.d. weights represent volatile material throughout the calculations that follow. One situation where this may prove inconvenient is in the estimation of root lengths from o.d. wt. data, and we have accordingly provided estimating equations based on both gross o.d. wt. and net o.d. wt. of small roots.

RESULTS*

Estimation of Root Components > 2 mm Diameter

Overall correlations between the weight of principal root components of the 97 trees, and d.b.h., total height, D^2H, and stem, branch, and foliage weights are summarised in Table 3 (alternate lines show the log/log correlations). Most of these components are self-explanatory, but it should be noted that stem weight refers to the whole of the central axis above the soil surface, and "roots > 2 mm diam." subsumes the whole of the root system, including the root stock, and down to, but not including, the fine root component. "Total intact roots" accounts for the whole root system except for the comminuted fine roots.

It is apparent that correlations with the composite variable D^2H (the square of d.b.h. (cm) times total height (m)) are higher than with either d.b.h. or height alone. However, the log of D^2H is not as closely correlated with any root component as is the logarithm of d.b.h. on its own. Furthermore, all these more convenient variables are superseded by the allometric relationships between root components and various above-ground dry-matter components, among which it seems that total foliage mass is pre-eminent.

To permit the main root components to be estimated from more easily measured above-ground components, simple linear regressions were computed for the more highly correlated variables. Coefficients of these estimating equations are summarised in Table 4, together with the appropriate standard errors. Choice of the appropriate equation will depend on the circumstances of proposed use: if tests of significance are to be performed, the log/log relationships will have to be used, since only with these relationships is the variance of the estimates reasonably uniform over the whole range of data. On the other hand, if good prediction at the upper end of the range is required, the logarithmic regressions are in fact most misleading (Zar 1968). Because this problem is particularly acute with our data, which are concentrated at the lower end of their range, the allometric equations were also fitted directly to the untransformed variables, using iterative procedures. The resulting equations for predicting the o.d. wt of roots > 2 mm or > 5 mm diam. are:

$$\text{(roots} > 2\,\text{mm diam.)} = 5.97\ (\text{d.b.h.})^{2.8068} \times 10^{-3} \quad (1)$$

$$\text{(root} > 5\,\text{mm diam.)} = 6.25\ (\text{d.b.h.})^{2.7382} \times 10^{-3} \quad (2)$$

(o.d. root weights in kilograms; d.b.h. in centimetres). R^2 values for the two equations are 0.899 and 0.900 respectively.

Alternatively, small roots can be estimated by any of the equations summarised in the top third of Table 4, and most precisely through its allometric relationship with total o.d. wt. of foliage.

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* Natural logarithms are used and referred to throughout

TABLE 3—Correlations between standard root components and principal above-ground dimensions and components (based on data for 97 sample trees)

Root component	d.b.h.	Total height	D^2H	Stem o.d. wt.	Branch o.d. wt.	Total foliage	Roots > 2 mm	Small roots
Intact fine	0.702	0.290	0.720	0.810	0.900	0.914	0.875	0.961
(log/log)	0.730	0.457	0.668	0.732	0.825	0.812	0.806	0.918
Small roots	0.773	0.390	0.792	0.854	0.915	0.944	0.933	1
(log/log)	0.833	0.592	0.782	0.842	0.910	0.889	0.921	1
> 5 mm diam.	0.895	0.543	0.903	0.936	0.926	0.967	0.998	0.911
(log/log)	0.961	0.774	0.929	0.623	0.508	0.958	0.998	0.900
> 2 mm diam.	0.888	0.530	0.898	0.935	0.934	0.975	1	0.933
(log/log)	0.955	0.760	0.921	0.959	0.971	0.963	1	0.921
Total intact	0.850	0.463	0.860	0.918	0.949	0.982	0.985	0.930
(log/log)	0.933	0.694	0.902	0.910	0.888	0.946	0.982	0.811

TABLE 4—Regression coefficients of estimating equations for main root components on most highly correlated above-ground parameters (d.b.h. in centimetres; height in metres; weight or mass in kilograms)

Component to be estimated (kg o.d. wt.)	Independent variable	S.E.* of estimate	Intercept (a)	Regression coefficient	S.E. of (b)
Small roots	d.b.h.	0.335	−0.412	0.1039	0.0086
(2–5 mm diam.)	D^2H	0.324	−0.043	0.0007	0.0001
	Branch wt.	0.213	−0.039	0.0620	0.0028
	Total foliage	0.174	−0.054	0.1329	0.0047
log (ditto)	log (d.b.h.)	0.694	−5.178	1.7239	0.1148
log (ditto)	log (D^2H)	0.783	−5.285	0.5952	0.0476
Roots > 2 mm diam.	d.b.h.	1.784	−3.411	0.8632	0.0458
	D^2H	1.711	−0.318	0.0055	0.0003
	Total foliage	0.870	−0.157	0.9997	0.0236
log (ditto)	log (d.b.h.)	0.446	−4.236	2.3258	0.0738
log (ditto)	log (D^2H)	0.590	−4.483	0.8226	0.0358
Roots > 5 mm diam.	d.b.h.	1.515	−2.999	0.7594	0.0389
	D^2H	1.457	−0.275	0.0048	0.0002
	Total foliage	0.859	−0.103	0.8667	0.0233
log (ditto)	log (d.b.h.)	0.437	−4.633	2.4491	0.0723
log (ditto)	log (D^2H)	0.585	−4.907	0.8688	0.0356

* One of the referees (Mr I. A. Andrew) makes the point that the S.E.s are not directly comparable with each other, since some are to a logarithmic scale and others are not.

Estimation of Fine Roots

Examination of Table 3 confirms the impression developed early in this work that there is a potentially useful correlation between the weights of small roots and their subtended fine roots, as represented by the last entry, 0.961, in the first line of Table 3. Although this correlation is concerned only with intact fine roots, and therefore does not include the comminuted portion, the high correlation indicates that the much more easily extracted and measurable small roots could provide a means of estimating the total fine root component.

Thus, the comminuted portion of the fine root extraction was measured whenever time and manpower permitted. The accumulated data now represent total o.d. wt. of fine roots for 56 of the 97 trees for which all other dry matter components were available. Correlation coefficients with the two most important of these are as follows:

	Total foliage o.d. wt.	Small root o.d. wt.
Total fine root o.d. wt.:	0.920	0.968

Allometric relationships between fine and small roots were explored, both by fitting log/log equations and by using iterative routines to solve for the coefficients in $y = a.x^b$ (y = fine roots, x = small roots) and $y = a + b.x^c$. The former gave a minutely better fit ($R^2 = 0.948$) to the available data than the simplest linear equation ($y = a + b.x$; $R^2 = 0.943$), but suffers from the obvious deficiency of predicting no fine roots when small roots are zero. This should be obviated by the equation $y = a + b.x^c$, but here the fit is considerably poorer ($R^2 = 0.899$) and, moreover, the resulting curve is concave upwards – which does not seem a very likely proposition. On balance, therefore, the simpler linear relationship is recommended, viz:

$$\text{(total fine root o.d. wt.)} = 79.92 + 3.601 \text{ (small root o.d. wt.)} \quad (3)$$

with standard errors for the two coefficients being 93.64 and 0.1203 respectively (weights in grams).

Alternatively, in the absence of data on the small root component, the total fine root o.d. wt. may be rather less precisely estimated from the total foliage o.d. wt. as follows:

$$\text{total fine root o.d. wt.)} = -121.35 + 0.526 \text{ (foliage o.d. wt.)} \quad (4)$$

with standard errors for the two coefficients being 93.22 and 0.0168 respectively (weights in grams).

Neither Equation (3) nor Equation (4) is suitable for estimating fine roots of trees less than 15 mm d.b.h., i.e., below the range of the data available to us. The ratio of fine to small roots increases very rapidly when the latter component diminishes below 50 g, and we consider that the simple relationship expressed by Equation (3) is unable to accommodate these changes.

Root Length/Weight Relationships

On 39 of the root samples from the 5- and 6-year-old trees, the cumulative lengths (to the nearest centimetre) of all the roots in each category larger than 2 mm diam. were measured when they were still fresh. This was also done to 10-g samples of intact fine roots from each of the sixteen 6-year-old trees. Correlation coefficients between root length and root o.d. wt. of each root class are recorded in the top line of Table 5. However, the very-large root category is omitted from this table as correlation was poor (0.333), due to inclusion of the very bulky root stock in this class. Thus it was not considered useful to develop length/weight relationships for the very large roots, particularly as their functions are mainly supportive and for storage; the surface area of these roots would be minimal by comparison with the ramifying components less than 20 mm diam.

Linear regressions of length on o.d. wt. were developed for each of the four smaller root categories, and the coefficients for these estimating equations are stated in the top half of Table 5, together with their corresponding standard errors. It should be noted that o.d. wt. of large and medium roots include their mineral (ash) content; but roots < 5 mm diam. have such a high and variable amount of mineral matter associated with them (both as a constituent proportion, and adsorbed on the outside surfaces of the nominally "clean" roots) that it is considered desirable to eliminate ash from the o.d. wt. data. However, as this subtraction may be considered a moot point for small roots (but not for fine roots), the length/o.d. wt. relationships are presented for both o.d. wt. including ash weight (i.e., gross weight) as well as for o.d. wt. net of ash weight for small roots.

The fact that the linear models for length on o.d. wt. do not pass through the origin, may be attributed to the incremental nature of the classification itself, i.e., that roots, as they grow through a class from its lower to its upper limit, pass from a

TABLE 5—Relationships and coefficients for estimating root length (cm) from o.d. wt. (g) of corresponding root components

	Length of standard root component				
	Large	Medium	Small		Fine
			(on gross wt.)	(on net wt.)	
Correlation with o.d. wt.	0.968	0.980	0.907	0.905	0.823
Ratio: length/o.d. wt.	1.65	6.57	27.82	28.21	455.97
Coefficients of the linear model ($y = a + bx$):					
Intercept (a)	20.47	38.53	178.27	188.50	437.64
Regression coeff. (b)	1.52	5.97	24.12	24.35	329.54
S.E. of estimate	58.13	80.68	374.14	382.35	518.79
Coefficients of allometric model ($y = a.x^b$):					
a	1.68	7.70	58.25	60.28	851.18
b	0.991	0.958	0.820	0.817	0.571

relatively high length/weight ratio to a relatively low one. Moir & Bachelard (1969) indicated that, within a category of roots from 0.4 to 3 mm diam., the proportion of roots in the upper part of the range tended to increase as the total weight of fine roots increased, which would result in the length/o.d. wt. ratio diminishing as total weight increased. For this reason it is considered that the model $y = a.x^b$, in the lower half of Table 5, provides a more appropriate basis for the estimation of length from o.d. wt. data.

Estimation of Total Root-system Dry Matter

Following on from the development of the above relationships, Equation (3) was used to derive the total o.d. wt. of fine roots for the remaining 41 trees of the whole data-set, and added to the o.d. wt. of roots > 2 mm diam., to obtain total o.d. wt. of the root system for all 97 trees. Correlations between above- and below-ground dry matter and conventional parameters are summarised in Table 6.

Total foliage o.d. wt. remains the best predictor variable for o.d. wt. of the whole root system, and the linear equation relating these is given by:

$$\text{(root system o.d. wt.)} = -0.274 + 1.479\ \text{(foliage o.d. wt.)} \qquad (5)$$

(weights in kilograms). $R^2 = 0.97$, and the standard errors of the two coefficients are 0.0182 and 0.0314 respectively.

Direct iterative fitting of the allometric equation ($y = a.x^b$) is again preferable to the log/log least squares solution for estimating total root dry matter from d.b.h., particularly for trees larger than 60 mm d.b.h. The calculated relationship is given by:

$$\text{(root system o.d. wt.)} = 5.87\ \text{(d.b.h.)}^{2.938} \times 10^{-3} \qquad (6)$$

(d.b.h. in centimetres; o.d. wt. in kilograms), for the whole root system below ground-line; $R^2 = 0.883$, but no direct estimate of overall confidence limits is possible, because of the derived nature of part of the data. (However, *see* Equation (7) in the Discussion.) Equation (6) will give estimates that are compatible with those for larger roots (Equations (1) and (2)) throughout the range of d.b.h. Unfortunately, predicting zero

TABLE 6—Correlations between total above- and below-ground dry matter, and various dimensions of individual trees

Tree component	d.b.h.	Total height	D^2H	Root o.d. wt.	Crown o.d. wt.	Whole tree	Total foliage
Total root o.d. wt.	0.865	0.495	0.876	1	0.960	0.975	0.979
(log/log)	0.927	0.709	0.885	1	0.970	0.980	0.965
Above-ground o.d. wt.	0.912	0.561	0.927	0.960	1	0.998	0.983
(log/log)	0.968	0.791	0.939	0.970	1	0.999	0.955
Whole-tree o.d. wt.	0.908	0.551	0.923	0.975	0.998	1	0.988
(log/log)	0.964	0.780	0.933	0.980	0.999	1	0.960

root dry matter when d.b.h. is zero does not accord with reality at the lower end of the range. An attempted resolution of this by fitting the model ($y = a + b.x^c$) gave a negative value for the constant term 'a', which is even less realistic.

The distribution of total root-system dry matter between root components is illustrated in Fig. 4. Here, the o.d. wt. of the component containing all roots > 5 mm diam. is expressed as a fraction of total root-system o.d. wt. and is plotted against individual height of all trees measured in the years 1976–79. The mean value for each year is shown (labelled 'L'), together with the corresponding means of the fine root fraction for 1976 and 1977 and the estimated value for 1979 (all labelled 'F'). During the phase of development represented by height increasing from 3 m to 7 m, the root system changes from being predominantly of fine roots (60% fine roots, 30% roots > 5 mm) to a state in which over 60% of its o.d. wt. comprises roots larger than 5 mm diam. The proportion of small roots (2–5 mm diam.) diminishes slightly from about 10% to 7% of total root o.d. wt. over the same period.

The "root/shoot ratio" (below-ground dry matter divided by total above-ground dry matter) has an overall mean value of 0.241, with a range from 0.101 to 0.480 (cf. Table 2). There is a slight negative correlation of this fraction with d.b.h., and a slightly stronger one with height ($r = -0.391$).

DISCUSSION

In Fig. 5 we have plotted Equations (1), (2), and (6), on a log/log scale, together with the original (and hitherto unpublished) data of Ovington *et al.* (1967) and Dargavel (1970). Regarding Ovington *et al.*'s (1967) information, for 100 *P. radiata* trees ranging from 3.9 to 21.6 cm d.b.h., the minimum diameter of root mass is explicitly stated as 5 mm, while Dargavel (pers. comm.) considers that "the weight of small roots is certainly under-estimated" in his (1970) data for 30 *P. radiata* trees, up to 46.6 cm d.b.h. At the upper end of the curves we have also plotted the 20 values recently published by Heth & Donald (1978), as a composite of their "main mass" roots plus their estimate of roots less than 5 mm diam. Despite the wide range of d.b.h. represented by these additional data (for trees ranging from 3.4 to 56.3 cm d.b.h.), two-thirds of the 150 new points fall within the band demarcated by Equations (2) and (6), i.e., where they should be, according to the definitions adopted in this paper. Even the points outside these limits are sufficiently close for us to consider it useful to pool all the available data for o.d. wt. of roots > 5 mm diam., and to fit a common estimating equation on d.b.h. Because the data at the lower end of the d.b.h. scale are no longer so preponderant in this augmented data-set, we have used the log/log equation on d.b.h. to provide a valid estimate of the variance. The least squares solution gives:

$$\log\ (\text{roots} > 5\ \text{mm diam.}) = -5.009 + 2.7296 \log\ (\text{d.b.h.}) \qquad (7)$$

(d.b.h. in centimetres; root o.d. wt. in kilograms); $R^2 = 0.97$, and the standard error of the estimate is 0.3609. The reconverted standard error, derived from the square of deviations of individual values from their estimates, is 16.96 kg. The alternative iterative solution gives:

$$(\text{roots} > 5\ \text{mm diam.}) = 7.25\ (\text{d.b.h.})^{2.70717} \times 10^{-3} \qquad (8)$$

which has a standard error of 16.95, equivalent to 68% of the overall mean (24.9 kg), and is virtually identical with that for Equation (7) (d.b.h. in centimetres; o.d. wt. in kilograms).

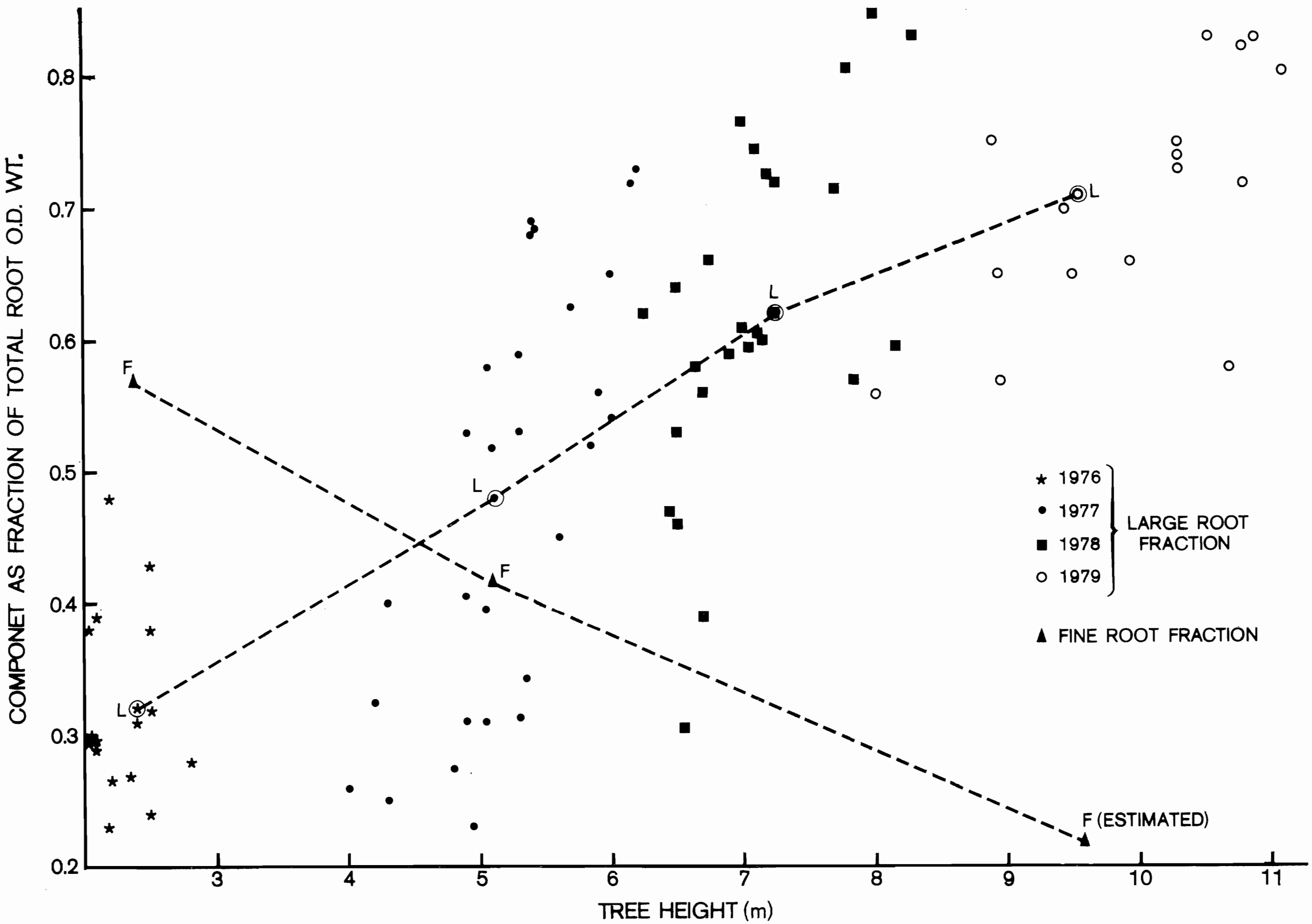

FIG. 4—O.d. wt. of roots > 5 mm diam. as a fraction of total o.d. wt. of whole root system, against tree height at ages 3 (★), 4 (●), 5 (■), and 6 (o) years. Values marked L represent means for the year; F denotes corresponding mean ratios of fine roots.

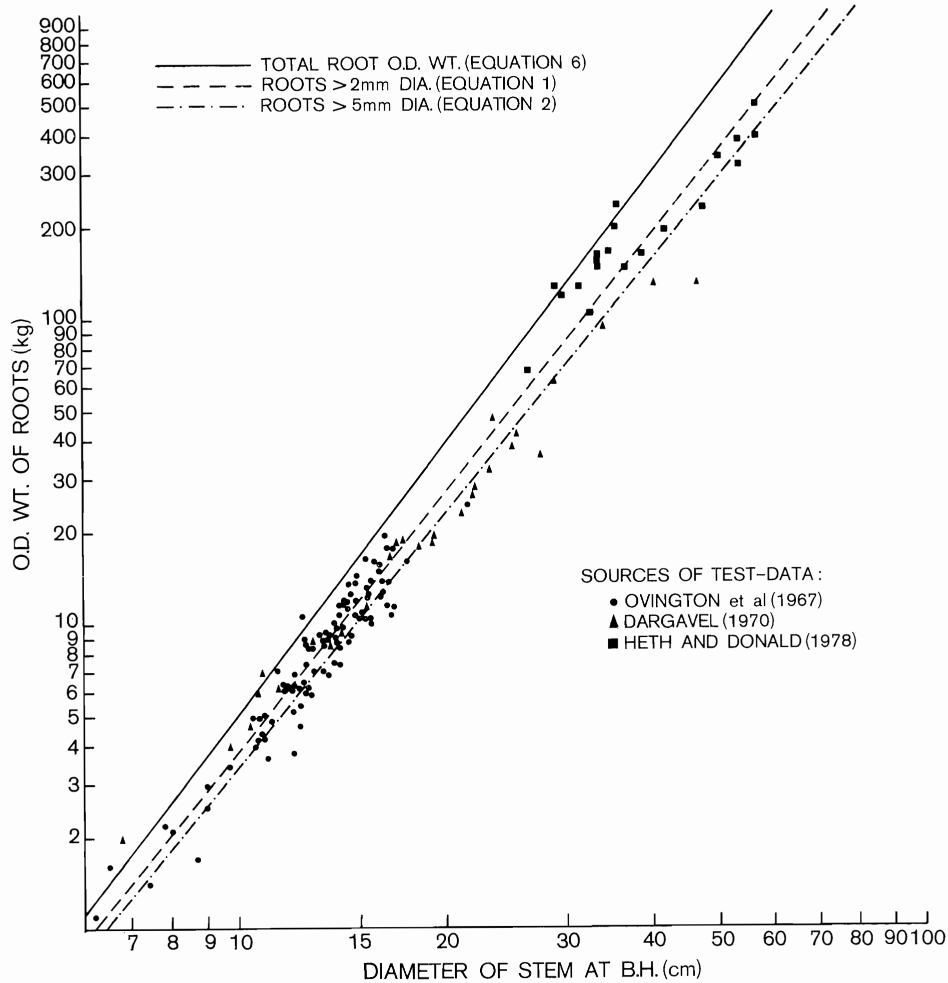

FIG. 5—Estimating equations for o.d. wt. of total root system, roots > 2 mm diam., and roots > 5 mm diam., with independent plotting of data from Ovington **et al.** (1967), Dargavel (1970), and Heth & Donald (1978).

The residual deviations of 227* of the values from their corresponding estimates by Equation (7) are plotted in Fig. 6 against foliage o.d. wt. Two points are omitted at the right-hand side for convenience of scale (–0.15 for 41.7 kg and –0.20 for 45.6 kg foliage weight, from Dargavel's (1970) data), and a cluster of points around zero at the left-hand end is omitted to avoid cluttering the diagram. All outlying points are plotted, without exception. Thus, the prediction of roots > 5 mm diam. by Equation (7) may be considered satisfactory for all except the smaller trees, where there is disproportionately high variance. The reason for this may be sought in Fig. 4, which

* i.e., excluding Heth & Donald's (1978) data, for which foliage weights are not available.

expresses the o.d. wt. of roots larger than 5 mm diam. as a fraction of total root weight, plotted against individual height of all those trees for which actual values of total root weight are available. It is apparent that between the time when a tree is 3 m tall (at about 3 years from planting) and when it has attained 9 m (at about 6 years), the distribution of o.d. wt. by root components changes radically; and that during this period the variance of the component larger than 5 mm diam. is particularly great. In Fig. 4 this is conspicuous in the set of data for 1977, for trees between 4 and 7 m tall. It may be anticipated that at later stages of growth, the normal allometric relationships between d.b.h., or height, and cumulative components of the tree will supervene, and Equation (7) will provide estimates for which confidence limits can be calculated, using the uniform variance (on a log/log scale).

Unfortunately it was not possible to incorporate either Will's (1966) or Somerville's (1979) data in these equations, for the reasons indicated in the introduction. We consider that, for a field of research that is so time-consuming and tedious, it is worth investing the extra effort to meet the specifications of a standard system of root classification, such as that propounded by Böhm (1979), to promote comparability of such hard-won data. We also hope that this paper has shown that it will permit more precise estimations of the finer root components than has been possible hitherto.

Although one of the objectives of our work has been to obtain complete recovery of individual tree root-systems, as a basis for improving techniques of estimation, it could be argued that even finer subdivision (e.g., by incorporating a class of very fine roots, defined by Böhm (1979) as less than 0.5 mm diam.) would have increased the overall recovery. We do not contest this: Squire *et al.* (1978), for example, separated all their *P. radiata* roots into only two categories, with their dividing line at 0.5 mm diam. However, the degree of resolution that is necessary with such small samples as are taken by soil-coring techniques is quite impracticable when recovering the whole root system, unless some method of sub-sampling that does not require mechanical extraction can be devised. The more fragile components, such as root-hairs, root-tips, and mycorrhizas, are particularly vulnerable to mechanical separation techniques; but we have as yet been unable to organise a system that would avoid bias, without also greatly increasing the work input. The most promising compromise may be to incorporate a systematic subdivision of the root volume to be sampled, along the lines indicated by Karizumi (1974).

The estimating equations developed from the data provide alternative methods, depending on the tree dimensions that are available for use as independent variables. In general, the allometric relationships based on total foliage o.d. wt. or on larger root-components have more precision, but are likely to be less useful. It may be considered curious that the equations using log (d.b.h.) alone proved to be better than those involving log (D^2H), which has become widely used in biomass studies (Hitchcock & McDonnell 1977). However, Karizumi (1974) reached much the same conclusion in his comparison of alternative formulae for estimating root biomass. In all cases, except for the o.d. wt. of the root stock, he found that the o.d. wt. of roots in any class could be more precisely estimated as a direct linear function of stem basal area than through log (D^2H). Note that the coefficients of log (d.b.h.) in Table 4 range between 1.7 and 2.4, i.e., they span the square of d.b.h.

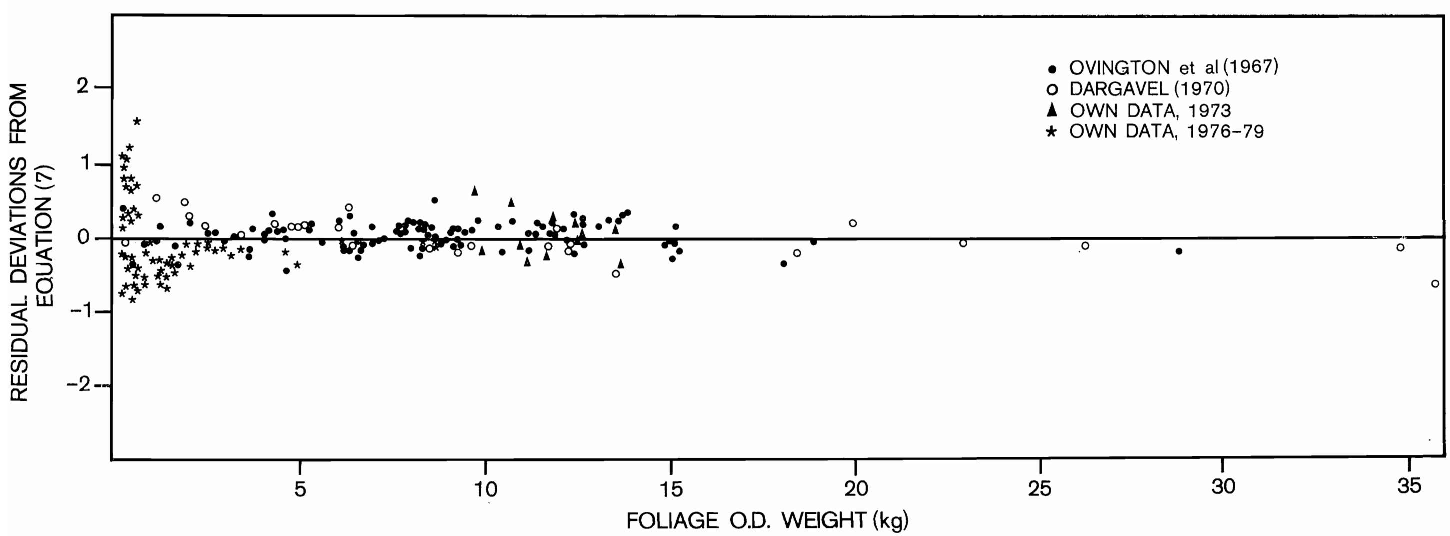

FIG. 6—Residuals from Equation (7) plotted against foliage o.d. wt.

With regard to the high correlations, in our data, between total foliage mass and any component of the root system (except for the root stock), we consider that this may provide a less precise estimate under plantation conditions, once the canopy closes. Firstly, the allometric relationships between larger components of the root system and the stem and branches will become more obtrusive as a tree increases in size. Secondly, once the lower branches begin to die, after canopy closure, the stand foliage mass becomes more or less constant (cf. Madgwick *et al.* 1977), whereas the woody components of both crown and roots continue to accumulate dry matter. And thirdly, the effect of foliage diseases, such as *Dothistroma pini* Hulbary or *Naemacyclus minor* Butin, will directly affect foliage mass, without necessarily affecting root mass commensurately. Stilwel (1960), for example, found that the recovery of pine rootlets lagged as much as 3 years behind foliage recovery after spruce budworm attack. Karizumi (1974) considered that the biomass of fine roots and that of foliage developed in parallel, as a stand ages; and it may well be that, after canopy closure, the fine root component will level off as root mortality supervenes and annual turnover becomes more important. These are questions that we intend to address more directly in an ensuing paper; but Fig. 6 does not indicate that there is likely to be any major gain in precision by using foliage weight instead of d.b.h. for estimating the o.d. wt. of roots of large *P. radiata.* The work involved in measuring foliage weight would, of course, be prohibitive.

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