Estimating Root Biomass in Rocky Soils using Pits, Cores, and Allometric Equations

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Measuring root biomass is time consuming and prone to sampling error. We compared three different methods of measuring root biomass in six northern hardwood stands at the Bartlett Experimental Forest. We found that root coring, the most common method of root sampling, yields estimates of fine root biomass about 27% greater than the estimates based on roots sampled in soil pits. Soil compaction contributes about 10% to this difference; the other contributing factor is that cores cannot be taken through obstructions such as rocks and coarse roots. Pits are the only method allowing characterization of root distribution by depth in rocky soil. If the depth and diameter distribution of roots are not required, allometric equations, if available, provide the easiest method of estimating total root biomass. Equations developed at the nearby Hubbard Brook Experimental Forest predicted root mass measured in soil pits with a mean absolute error of 32%. Allometric equations systematically underpredicted observed soil pit root mass in the young stands, presumably because of mature root systems remaining from the previous cohort, and systematically overpredicted observed root mass in the oldest stands. Soil pits can accurately characterize roots up to about 2 cm; coarser roots are encountered too rarely to be estimated by this method. Soil cores sample only fine roots (up to 1–2-mm diameter) but are much less work than excavating soil pits. Root mass estimates made using cores are more accurate if larger diameter corers are used (5 cm rather than 2.5 cm); subsampling before picking roots can help to control labor costs in the face of larger sample sizes.

Abbreviations: dbh, diameter at breast height.

The primary reason that we know so little about belowground biomass and C allocation is that roots are so difficult to study. Fine roots are most easily collected by taking soil cores, but coring methods have limitations. Soil cores cannot be used to characterize roots coarser than about 2 mm in diameter (Vogt and Persson, 1991). Soil compaction with coring can make it difficult to ascertain the depth or volume of soil collected, and cores cannot be collected in stony soil or under coarse roots (Vogt and Persson, 1991).

Excavating soil pits is much more time consuming than coring, and shouldn't be undertaken unless the benefits justify the costs. We had the opportunity to measure root biomass collected from quantitative soil pits in northern hardwood stands of different ages, and used them to measure root biomass. This method allows roots to be collected throughout the soil profile, and also describes coarser roots than can be sampled with soil cores. We took advantage of this occasion to compare this method of root collection with other, less costly, methods of estimating root biomass.

Allometric equations have been widely used to estimate aboveground biomass based on tree inventory data (diameter and height; Brown, 2001). The accuracy of this approach can be tested by harvesting trees and weighing them (Siccama et al., 1994). Allometric equations are more rarely developed for belowground biomass (Jenkins et al., 2004) because of the difficulty of excavating root systems. Equations exist for belowground biomass of northern hardwoods in New Hampshire (Whittaker et al., 1974), and the data set on which these equations were based has recently been reanalyzed to allow the prediction of lateral root mass, excluding root crowns (Vadeboncoeur et al., 2006, unpublished data). The equations for aboveground biomass based on the same trees (Whittaker et al., 1974) have been validated and found to be accurate within 10% in each of three 0.25-ha plots (Siccama et al., 1994). The equations predicting root biomass are more difficult to validate.

In this study, we compared three methods of estimating root biomass. We excavated 18 soil pits in six northern hardwood stands ranging in age from 14 to 121 yr in and around the Bartlett Experimental Forest in New Hampshire. We compared these results to those obtained by collecting soil cores at the same sites, and we tested the effect of core size on variance in fine root biomass, expecting variance to be lowest for the finest roots. We measured the compaction associated with different sizes of root cores, expecting the effect to be more severe with smaller diameter cores. Finally, we used allometric equations based on data collected at the nearby Hubbard Brook Experimental Forest to predict lateral biomass and validated these against the biomass we measured using soil pits.

MATERIALS AND METHODS

Study Sites

We studied six stands at the Bartlett Experimental Forest in the White Mountains of New Hampshire (Table 1). All the stands were naturally regenerated following clearcutting. Two stands were young (14 and 16 yr old) and had a high proportion of basal area in early successional

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Table 1. Sites used in this study. Stand ages are given for 2004, the year in which roots were sampled. Species listed are those that comprise at least 10% of basal area, and are listed in order of dominance by basal area.

Site	Stand age	Latitude	Longitude	Elevation	Dominant species
	yr			m	
C1	14	44°02′N	71°19′ W	570	*Prunus pensylvanica, Betula papyrifera,Fagus grandifolia*
C2	16	44°04′N	71°16′ W	340	*F. grandifolia, Acer rubrum, P. pensylvanica, B. papyrifera*
C4	26	44°03′N	71°16′ W	410	*B. papyrifera, Populus tremuloides, F. grandifolia, P. pensylvanica, Betula alleghaniensis*
C6	29	44°02′N	71°16′ W	460	*B. alleghaniensis, F. grandifolia, A. rubrum, B. papyrifera, P. pensylvanica*
C8	121	44°03′ N	71°18′ W	330	*Acer saccharum, F. grandifolia, Fraxinus americana*
C9	114	44°03′ N	71°17′ W	440	*A. saccharum, F. grandifolia, B. alleghaniensis*

species including pin cherry (*Prunus pensylvanica* L.f.) and white birch (*Betula papyrifera* Marshall) (Fig. 1). Two stands were 26 and 29 yr old and in a transitional stage between dominance by early and later successional species. Two stands were 114 and 121 yr old and dominated by late successional northern hardwoods, including sugar maple (*Acer saccharum* Marshall), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britton). These stands are under study as part of a larger project describing nutrient cycling as a function of stand age, in which we characterize stands <30 yr old as "young" from the point of view of Ca cycling (Hamburg et al., 2003).

Root Collection: Pits

In each stand, one soil pit was sited in each of three replicate 50- by 50-m plots, based on a grid used for vegetation sampling in the larger project. The average distance between soil pits within a site ranged from 60 to 100 m (range 40–130 m). Sampling points were rejected if they fell within 50 cm of a tree >10-cm diameter at breast height (dbh), or if the pit area (0.5 m^2) had >50% coverage of surface rock or obvious soil disturbance, as these obstacles make sampling difficult and imprecise. Sampling points were also rejected if three pieces of rebar could not be driven at least 50 cm into the soil to secure the wooden frame. Approximately 30% of the selected pit sites were rejected and relocated. Of these, most were rock-based rejections.

Half-meter-square soil pits were excavated in July and August 2004 in the following layers: Oie horizon, Oa horizon, 0 to 10 cm of mineral soil, 10 to 30 cm, 30 to 50 cm, 50 cm to the C horizon, and 0 to 25 cm in the C horizon. In one pit per stand, we excavated an additional layer 25 to 50 cm in the C horizon. A total of 18 pits were excavated in six stands. Total soil pit depth ranged from 95 to 170 cm, with a mean of 139 cm (Table 2). This range reflects natural variation in the depth to the C horizon as well as our sampling methodology, which included one deeper pit at each site.

To collect roots from the Oie horizon, three 100-cm^2 samples were extracted by cutting around a template within the 0.5-m^2 area of each pit. The area was divided into nine equal squares, and three were selected randomly with the constraint that each row and column was sampled once; the samples were taken at the center of these squares. Because the Oie horizon is difficult to sieve in the field when moist, this material was weighed and returned to the lab for root picking.

Additional soil layers were removed and the depth measured relative to a reference frame at 25 grid points so that the volume of each layer could be precisely calculated (Hamburg, 1984). The soil was screened in the field using a 6-mm screen (Oa horizon) or a 12-mm screen (mineral soil). Roots that did not pass through the screen were returned to the lab for sorting and weighing. The material passing through the screens was weighed and a subsample was collected for root picking. To collect this subsample, approximately 30 cm^3 of soil was collected, using salad tongs, from each shovel full of sieved soil; roots sticking out from the edge of the tongs were clipped with scissors. Soil and root samples were kept cool in the field and during transport to the lab, where they were refrigerated for up to 2 wk until they could be processed.

Root Collection: Cores

Soil cores were taken in June 2004, in advance of excavating the soil pits, to precede the disturbance associated with the soil pits. The two oldest stands were not included in the coring study, because they had not been identified at the time the root cores were collected. In the young and young-transitional stands, two root cores (5-cm inner diameter) were collected 30 cm from the edge of the 0.5-m^2 area to be excavated, one to the north and one to the south (six cores per stand). In the young-transitional stands, we tested the effect of core size by taking two additional cores of each of two additional sizes (2.5- and 3.5-cm inner diameter) at each pit, in conjunction with the 5-cm cores. If obstructions (rocks or very large roots) were encountered, cores were attempted at a slightly different location.

Soil corers 50 cm in length were constructed from polyvinyl chloride pipe. To minimize soil compaction, the end of the tube was sharpened (angle <20°). The corer was cut in half lengthwise and the two halves of the corer were taped together before collecting each sample. The Oi horizon was removed before inserting the core. After collecting a core, the sample

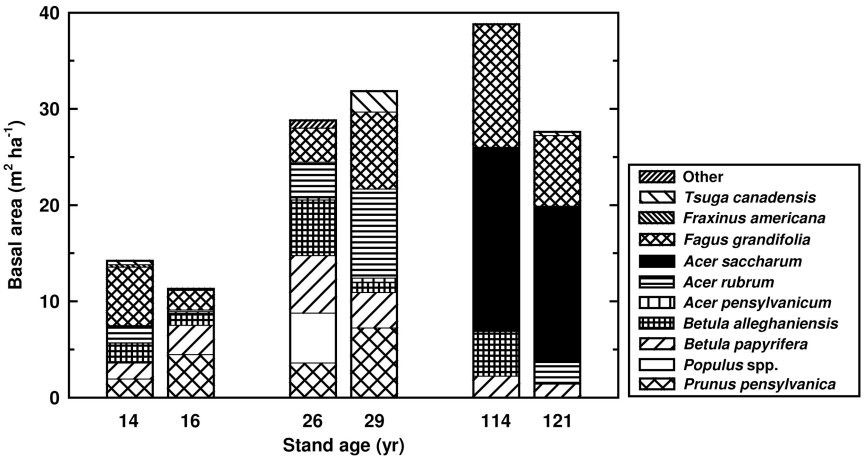

Fig. 1. Basal area, by species, of trees >2-cm diameter at breast height (dbh) within 3 m of the center of the pit and trees >10 cm dbh within 6 m of the center of the pit.

Table 2. Soil properties measured in the soil pits from which roots were collected, with standard error (n = 3 pits) in parentheses. The first two mineral soil layers were collected by depth and therefore vary little in measured thickness. The C horizon was found at variable depth. Samples were collected from either 0 to 25 cm or 0 to 50 cm in the C horizon. Some means have no standard error (na), where only one pit had a B horizon deeper than 30 cm and where only one pit reached the C horizon before being obstructed by rocks.

Layer	Stand age					
	14 yr	16 yr	26 yr	29 yr	114 yr	121 yr
			Layer thickness, cm			
Forest floor	4.5 (1.0)	2.3 (0.3)	5.0 (1.9)	6.4 (1.4)	7.7 (2.2)	3.5 (0.9)
0–10 cm	11.4 (1.6)	10.6 (0.3)	11.4 (1.2)	9.9 (0.2)	8.8 (2.4)	11.2 (0.7)
10–30cm	18.9 (1.7)	18.9 (0.5)	18.8 (0.6)	12.6 (2.8)	21.1 (1.8)	19.8 (1.1)
30 cm–C horizon	66.0 (28.1)	68.6 (8.8)	74.5 (21.6)	75.0 (na)	89.3 (11.6)	68.6 (34.4)
C horizon	38.3 (20.5)	42.0 (17.5)	42.1 (17.1)	41.5 (16.3)	42.8 (17.4)	49.1 (23.1)
			Coarse fraction, % by volume			
0–10 cm	16 (3)	19 (3)	9 (2)	9 (5)	20 (6)	26 (10)
10–30 cm	19 (2)	32 (11)	11 (0)	14 (7)	23 (7)	23 (12)
30 cm–C horizon	34 (8)	48 (13)	15 (3)	37 (na)	43 (16)	28 (20)
C horizon	31 (0)	48 (13)	15 (1)	7 (1)	41 (13)	9 (na)
			Bulk density, g cm^{-3}			
Forest floor	0.3 (0.1)	0.2 (0.0)	0.2 (0.0)	0.1 (0.0)	0.2 (0.1)	0.3 (0.1)
0–10 cm	0.6 (0.0)	0.5 (0.1)	0.7 (0.0)	0.6 (0.1)	0.6 (0.1)	0.6 (0.1)
10–30 cm	0.8 (0.1)	0.8 (0.0)	0.8 (0.1)	0.8 (0.1)	0.7 (0.0)	0.8 (0.1)
30 cm–C horizon	1.0 (0.1)	1.0 (0.1)	0.9 (0.2)	0.9 (na)	1.2 (0.1)	0.9 (0.0)
C horizon	1.3 (0.1)	1.3 (0.2)	1.1 (0.1)	1.1 (0.2)	1.2 (0.2)	1.0 (na)

was divided into forest floor, 0- to 10-cm, and 10- to 20-cm depth increments. The 10- to 20-cm depth increment could not be compared with the soil pits, which used a 10- to 30-cm depth increment, and these results are not presented here. The samples from north and south of the pit location were composited by soil layer before picking the roots from the soil.

Compaction by Soil Coring

Soil compaction by coring was measured in July 2004 at the Hubbard Brook Experimental Forest, in New Hampshire, about 40 km distant from our research sites at the Bartlett Experimental Forest. We used a site dominated by sugar maple (Tierney et al., 2001) west of Watershed 6. We used the same type of split corer described above in three diameters: 2.5-, 3.5-, and 5.0-cm inner diameter.

Compaction was measured at six locations spaced 5 m apart along a transect, with all three core sizes used at each location. Soil compaction was measured at three successive depths: 20, 30, and 40 cm. Soil compaction was reported as the difference between the depth to the soil surface inside the core and outside the core divided by the depth outside the core. This approach assumes that there is no compaction below the core. Our estimates of bias introduced by compaction are thus slightly overestimated, to the degree that some of the soil and roots in the depth increment to be sampled remain below the core.

Root Processing

We sorted the roots from the Oie horizon subsamples, which were not screened in the field; roots that did not pass through the screen; roots from subsamples of the soil that passed through the screens; and roots in the soil cores. We included dead roots of all sizes in our estimates of root mass, but did not divide them by size class. Dead roots were distinguished by resilience, brittleness, and color of the bark and xylem. We did not include roots of herbaceous plants. The roots from the Oie horizon and the screens were divided into the following size classes: 0 to 1, 1 to 2, 2 to 5, 5 to 10, 10 to 20, and 20 to 100 mm. In the case of roots from soil cores, 0- to 0.5-, 0.5- to 1-, and 1- to 2-mm classes were distinguished.

For all the sample types, we used subsampling to limit the amount of time spent sorting very fine roots. In the case of the Oie horizon and the roots from the screens, we picked out all roots >2 mm in diameter, and subsampled the finer roots before picking them. In the case of the samples of sieved soil and roots, we first picked all roots >1 mm in diameter. In the case of root cores, where finer diameter classes were distinguished, all roots >0.5-mm diameter and 5-mm length were picked before subsampling the remainder of the sample. Before picking out the finer roots, the sample of screened roots or soil was homogenized and divided into eight parts, one or two of which were selected for more exhaustive root picking. The weight of the whole sample and the subsample were used to scale the mass of the finest roots. To separate roots from soil, root core samples and samples of the sieved soil from the pits were stirred in about 500 mL of water. The floating roots were poured onto two layers of 0.5-mm mesh, and the roots were picked off the mesh. This procedure was repeated until few root fragments remained. The soil residue was also checked for roots.

All root samples were washed with tap water and sorted by size class. The roots were oven dried at 65°C and weighed.

Analysis of Root Data

For the roots collected from the soil pits, we tested the effect of stand age on root biomass by diameter class using ANOVA. To compare fine root biomass (<2 mm) from cores with fine root biomass from pits, we used t-tests. Soil compaction with coring was compared across core sizes within soil depth increments using ANOVA. Variation in root biomass was described by the coefficient of variation for each combination of root diameter and core size.

We compared the number of samples required to estimate fine root biomass with the same margin of error using pits and cores, using our observed standard deviations. The number of samples is $[(z\sigma)/m]^2$, where z is the percentile from a standard normal table, σ is the standard deviation, and m is the margin of error (Moore and McCabe, 1999).

Allometric Equations

To validate the allometric equations predicting lateral root biomass, we used data from the 18 quantitative soil pits in the six stands at the Bartlett Experimental Forest reported here (Table 1) and data from 18 additional pits excavated in six stands of similar forest type studied by the same methods in the previous year, 2003 (Yanai et al., 2006). We measured all stems >2-cm dbh within 3 m of the center of the pit and trees >10-cm dbh within 6 m of the center of the pit (Fig. 1) to use in predicting root biomass in the pits.

We estimated lateral root biomass per unit area using allometric equations (Vadeboncoeur et al., 2006, unpublished data) recently developed from 31 trees destructively sampled in 1965 at the Hubbard Brook

Experimental Forest (Whittaker et al., 1974). Because these equations were developed for fewer species than we had at our sites, we assigned our additional species to the four equations available, based on similarity of growth form. We used the equation for American beech to describe white ash (*Fraxinus americana* L.) and northern red oak (*Quercus rubra* L.). We used the equation for sugar maple to describe red maple (*Acer rubrum* L.), striped maple (*Acer pensylvanicum* L.), American basswood (*Tilia americana* L.), and eastern hop-hornbeam [*Ostrya virginiana* (Mill.) K. Koch]. The equation for yellow birch was applied to white birch, quaking aspen (*Populus tremuloides* Michx.), and pin cherry. Because the lateral root data for red spruce (*Picea rubens* Sarg., the only conifer species sampled in 1965) no longer exist, we used the proportion of total root biomass reported as lateral roots by Whittaker et al. (1974) to divide total conifer root biomass into lateral roots and crowns (Vadeboncoeur et al., 2006, unpublished data). Conifers, including red spruce, eastern hemlock [*Tsuga canadensis* (L.) Carrière], and balsam fir [*Abies balsamea* (L.) Mill.] constituted 5% or less of total basal area at all sites. We also tested the sensitivity of the estimates to the use of species-level equations by comparing them to biomass predicted by applying a generalized hardwood equation (Vadeboncoeur et al., 2006, unpublished data) to all species.

We compared the lateral root biomass predicted using these allometric equations, based on the vegetation surveyed around the pit, to the live root biomass <100 mm in diameter collected from the pit. The age classes we used in this analysis were young (14–16 yr, n = 2), young-transitional (19–29 yr, n = 5), and older (56–121 yr, n = 5). These age classes reflect changes in stand composition and structure with age (Table 1). The young category is dominated by root- and stump-sprouted hardwood stems, along with early successional species at high density. The young-transitional stands have a mix of early and later successional species, with high mortality among early successional species and rapidly thinning stem density. The older stands are dominated by mid- and late-successional species, with a high proportion of basal area in trees >30-cm dbh.

RESULTS

Pits

Live fine root biomass (<2 mm in diameter) measured using quantitative soil pits averaged 990 g m^{-2} (Table 3, Fig. 2) across all six stands. Roots <1 mm in diameter comprised 85% of this total. There was not a significant difference in fine root biomass between sites (P = 0.39) in a comparison of young (14 and 16 yr), young-transitional (26 and 29 yr), and older (114 and 121 yr) stands. Larger roots were less common in young stands than in the young-transitional and older stands (P = 0.03 for 2–20-mm roots); the difference was also significant for the 0- to 20-mm roots combined (P = 0.03). Very large roots (>20 mm in diameter) were quite variable, and differences between sites were not significant (P = 0.94).

Soil pits are a good way to sample roots at depth. We collected roots throughout the soil profile and into the C horizon in these 0.5-m^2 quantitative soil pits (Table 3). On average, 49% of fine roots (<2 mm) occurred above 10-cm soil depth (in the O horizon and the top 10 cm of the mineral soil). In other words, 51% of fine roots occurred below 10 cm in the mineral soil. On average, 28% of fine roots occurred below 30 cm. We found significant root biomass in the C horizon: 5% of the fine roots occurred in the top 25 cm of the C and 2% occurred in the 25- to 50-cm depth increment of the C horizon. We also observed fine roots below 50 cm into the C horizon, but these were not collected quantitatively.

Coarser roots were more concentrated toward the root surface than the finer roots (Table 3); this result is not surprising as root crowns extend from the base of the trees. For all live roots combined, 62% of root biomass occurred above 10 cm in the mineral soil and 16% occurred below 30 cm. For total biomass of live and dead roots, 57% of root biomass occurred above 10 cm in the mineral soil and 20% occurred below 30 cm.

Table 3. Root biomass distribution by soil depth measured in quantitative soil pits. Standard errors are given in parentheses (n = 2 stands). Roots are reported from the top 25 to 50 cm of the C horizon, depending on the pit.

Root diameter	Layer	Root biomass		
		Young stands	Young-transitional stands	Older stands
mm		g m^{-2}		
0–1	forest floor	90 (36)	172 (32)	261 (81)
	0–10 cm	260 (33)	236 (78)	227 (43)
	10–30 cm	139 (8)	180 (60)	267 (12)
	30 cm–C horizon	258 (98)	106 (65)	184 (28)
	C horizon	23 (6)	84 (21)	21 (4)
1–2	Forest floor	16 (8)	32 (5)	31 (5)
	0–10 cm	48 (10)	50 (4)	35 (9)
	10–30 cm	22 (5)	46 (26)	50 (13)
	30 cm–C horizon	25 (2)	33 (25)	34 (17)
	C horizon	2 (1)	19 (6)	3 (1)
2–5	Forest floor	20 (12)	69 (7)	51 (16)
	0–10 cm	78 (1)	84 (6)	89 (3)
	10–30 cm	45 (9)	64 (5)	106 (36)
	30 cm–C horizon	21 (7)	40 (30)	45 (35)
	C horizon	13 (12)	18 (8)	2 (1)
5–10	Forest floor	15 (7)	82 (63)	49 (28)
	0–10 cm	85 (28)	92 (13)	80 (4)
	10–30 cm	32 (6)	75 (7)	125 (6)
	30 cm–C horizon	9 (3)	43 (38)	62 (17)
	C horizon	8 (5)	18 (4)	0 (0)
10–20	Forest floor	53 (41)	163 (13)	75 (8)
	0–10 cm	86 (1)	210 (63)	66 (0)
	10–30 cm	46 (23)	134 (38)	98 (6)
	30 cm–C horizon	14 (14)	20 (20)	34 (14)
	C horizon	0 (0)	12 (2)	0 (0)
20–100	Forest floor	574 (322)	261 (106)	270 (253)
	0–10 cm	136 (23)	246 (199)	139 (139)
	10–30 cm	16 (16)	63 (16)	114 (114)
	30 cm–C horizon	16 (16)	0 (0)	0 (0)
	C horizon	0 (0)	5 (5)	0 (0)
Dead	Forest floor	82 (48)	224 (44)	138 (21)
	0–10 cm	273 (47)	200 (16)	133 (42)
	10–30 cm	212 (20)	167 (23)	177 (4)
	30 cm–C horizon	335 (168)	146 (105)	152 (37)
	C horizon	22 (2)	60 (23)	19 (2)

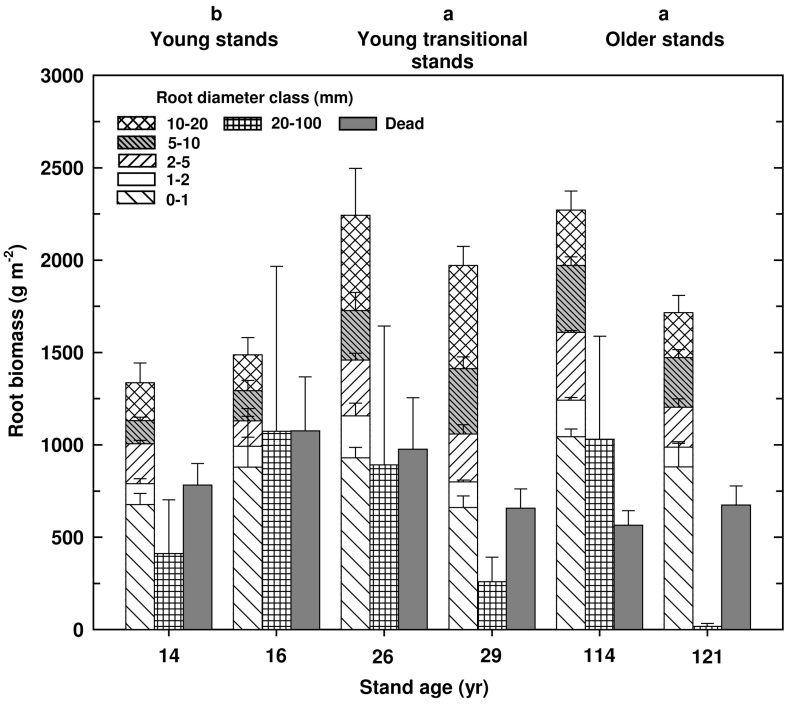

Fig. 2. Total live root biomass, showing the contribution of each root diameter class, and total dead root biomass in each of six stands. Vertical bars show one standard error (n = 3 pits). Age classes sharing a letter were not significantly different in live root biomass <20 mm in diameter at $\alpha = 0.05$. There were no significant differences in live root biomass 20 to 100 mm in diameter or in dead root biomass across these age classes.

Cores

Fine root biomass estimated by coring was greater than that estimated by the soil pit method (Fig. 3). The mean difference between the two methods was 27% for 0- to 2-mm roots (P = 0.05), with a difference of 28% for the 0- to 1-mm class and 19% for the 1- to 2-mm roots; the finer roots dominated the biomass, as described above. In the root cores, the average biomass reported to 10 cm was 570 g m^{-2}.

Two processes contribute to the higher estimates of root biomass by soil cores than by soil pits: the soil is compacted by inserting the cores and obstructions are avoided in sampling. We measured the compaction induced by coring (Fig. 4). Smaller diameter cores caused more compaction, as might be expected. A 2.5-cm-diameter core driven in to 20-cm depth resulted in 6 cm of compaction, on average, compared with only 2 cm by a 5-cm-diameter core (10%). Soil compaction also decreased with depth (Fig. 4).

One limitation to sampling roots using soil cores is the small volume of soil sampled. Larger cores give a more precise estimate of root biomass. This pattern is indicated by the CV, which consistently declines as larger core sizes are used (Fig. 5). This advantage falls off rapidly with core size because of spatial variation at scales too large to be sampled by cores: our pits, which have an equivalent diameter of 80 cm, had an average CV of 28% for the 0- to 1-mm roots and 45% for the 1- to 2-mm roots.

We compared the number of samples required to obtain the same margin of error using pits and cores, given the variance we observed (Fig. 3). To estimate live fine root biomass with a 20% margin of error at 95% confidence would require seven cores or five soil pits. A 10% margin of error could be obtained with 28 cores or 20 pits. Clearly, it is less effort to collect cores than to excavate pits, even taking into account the larger number of cores required.

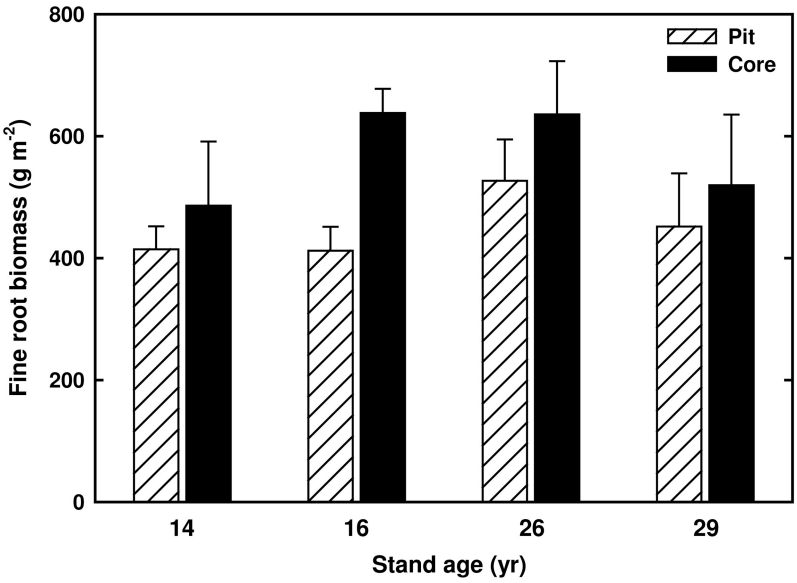

Fig. 3. Comparison of live fine root biomass (<2-mm diameter) measured by coring with fine root biomass measured in pits in young and young-transitional stands. Fine roots were collected in the forest floor and the top 10 cm of mineral soil in both cores and pits. Vertical bars show standard errors (n = 3 pits or cores).

Allometric Equations

We compared lateral root biomass predicted by allometric equations (Vadeboncoeur et al., 2006, unpublished data) with observed root biomass in our soil pits, using the six sites described here (Table 3, Fig. 2) along with six similar sites in which pits were excavated the previous year (Yanai et al., 2006). The mean absolute value of the difference between methodologies was 32% of the pit-based estimate across all 12 sites. The correspondence between measured and predicted root biomass <100 mm in diameter (Fig. 6) is remarkable, considering that the lateral root masses on which the equations were based were defined not by diameter, but by the method of excavating crowns and lateral roots (Whittaker et al., 1974).

Both the magnitude and direction of prediction errors depended strongly on stand age. In young stands (14 and 16 yr), lateral root mass predicted by the equations was only 26% of the mass observed in soil pits (Fig. 6). That there is more root biomass in the pits than predicted by the young trees is probably due to residual root systems from harvested trees having given rise to root and stump spouts. In the 14-yr old stand, an extreme example, measured lateral root biomass was six times greater than predicted using the near-pit tree data as input (Fig. 6). In contrast, in the young-transitional stands (19–29 yr) the

ratio of allometrically estimated root mass to observed soil pit root mass was 93%, and in older stands, the ratio was122% (Fig. 6).

Excluding the young stands (14 and 16 yr) reduced the mean absolute value of the difference between methodologies to 24% of the pit-based estimate. For the young-transitional and older stands, there was a good relationship between the measured biomass of live roots <10 cm in diameter and the predicted biomass of lateral roots (r^2 = 0.55, P = 0.01; Fig. 6).

Root masses in individual pits were not so well predicted by the equations, which is perhaps not surprising because the spatial scale of variation in root biomass is large compared to the size of the pits. The mean error for predicting individual pits based on the vegetation around the pit (calculated as the absolute value of the difference between the estimates divided by the pit estimate) was 54% across all stand ages.

Predictions made using the generalized hardwood equations were systematically greater than those made using the species-specific equations. The magnitude of this difference (3%) was small, however, compared with the differences in estimates between pit and allometric methodologies (absolute value 30%).

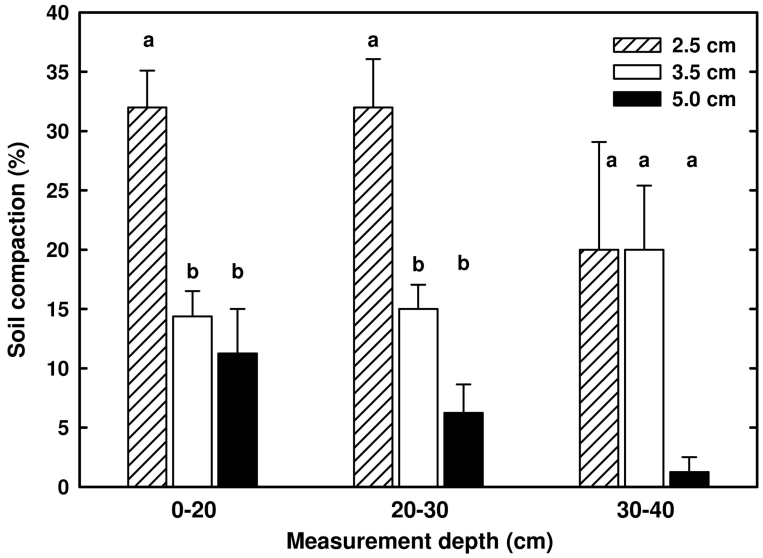

Fig. 4. Soil compaction associated with coring by various core sizes (2.5, 3.5, and 5 cm) and soil depth increments. Means within a depth increment sharing a letter are not statistically distinguishable at α = 0.05. Vertical bars show standard errors (n = 6 cores).

DISCUSSION

Challenges to Comparing Accuracy among Methods

Comparing measurement methods would be straightforward if one method were known to be the most accurate. In this study, we took the pit method of measuring root mass as our standard, and we evaluated the core and allometric approaches by comparison to it. Although the pit method would seem to provide an exhaustive accounting of roots in a 0.5-m^2 area, there is, unfortunately, considerable uncertainty introduced by subsampling the very large mass of sieved soil before picking roots.

For example, in this study, the mass of soil removed from the pits averaged 360 kg pit^{-1} (oven-dry mass). The mass of the subsamples collected for root picking averaged 2.3 kg pit^{-1}, and the mass of subsamples picked in the lab for the finest roots averaged 0.25 kg pit^{-1}. Thus an uncertainty of 0.1 g in root mass in sorting roots from all layers in a soil pit translates to an uncertainty of 0.26 kg m^{-2} in the soil pit, which is almost one-third of the fine root mass (Fig. 2). This uncertainty does not apply to coarse roots, which were removed from the pit or collected from the top of the soil screen. Roots >2 mm in diameter do not pass through the screen. For 0- to 1-mm live roots, 66% passed through the screen, and for 1- to 2-mm live roots, 15% passed through the screen. The uncertainty due to subsampling is greatest for dead roots, of which 83% passed through the screen.

In addition, the method of subsampling soil for root picking can introduce bias in the estimate of root mass. In a study similar to this one, conducted the previous year (Yanai et al., 2006), we used a trowel to sample soil from the pile beneath the sieve. Long, fine roots tended to tip off the trowel. For this reason, we used tongs for sampling in the present study. Tongs, in contrast to trowels, might tend to oversample fine roots, but our protocol involved clipping roots where they protruded from the tongs. The fine root biomass (<2 mm) was estimated by subsampling with tongs in 2004 was 72% greater than the biomass we estimated by subsampling six similar stands in 2003 using trowels. Some of the difference between the two studies might be attributable to other sources, such as differences between years affecting conditions for root growth. Whatever the cause, there is considerable cause for uncertainty in these estimates of fine root biomass.

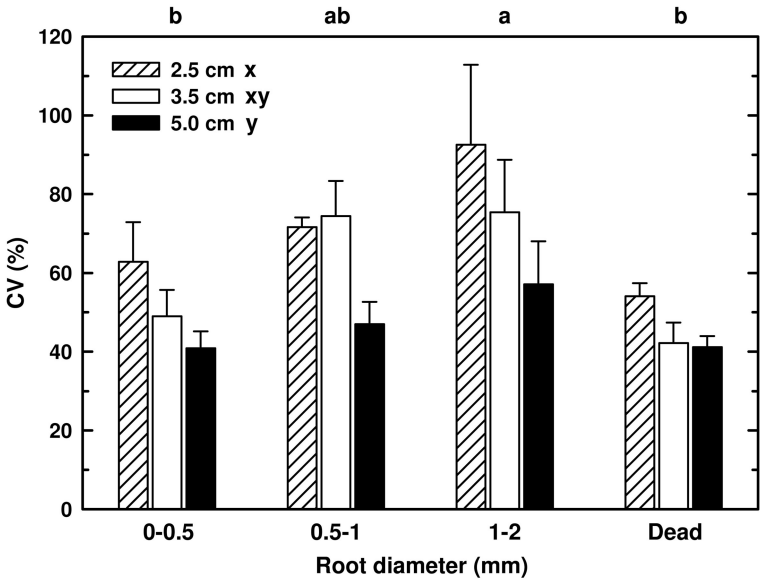

Fig. 5. Coefficient of variation (CV) of fine root biomass by root diameter (0.5, 1, and 2 mm) and core size (2.5, 3.5, and 5 cm). Diameter classes sharing a letter (a and b) and core sizes sharing a letter (x and y) are not significantly different in CV at α = 0.05. Vertical bars show standard errors (n = 6 cores).

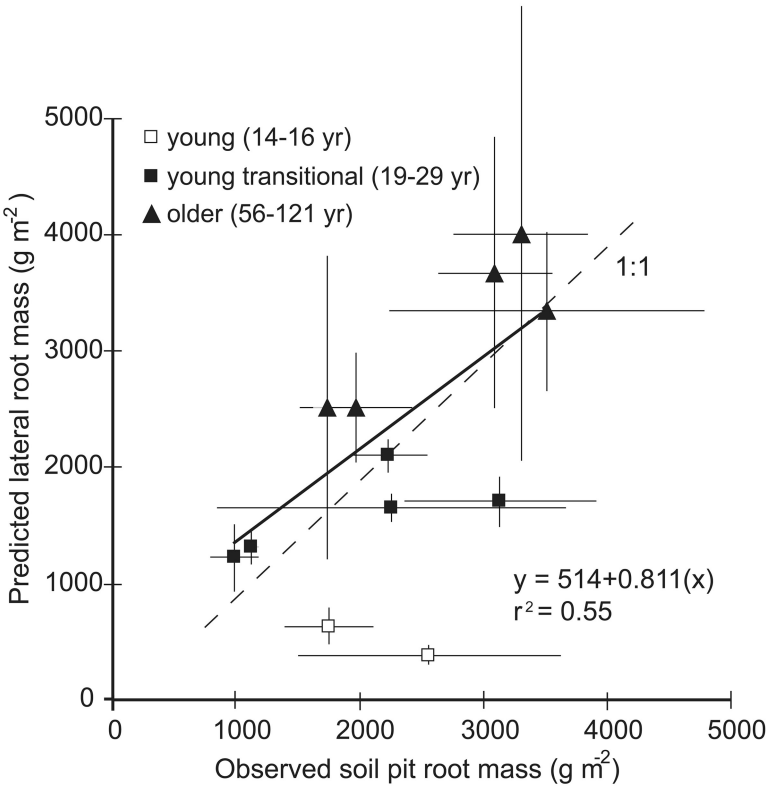

Fig. 6. Mean lateral root biomass (<10 cm) measured in three soil pits at each of 12 sites and predicted using species-specific allometric equations, based on trees within 6 m of each pit. The solid line shows the regression through the means for all sites excluding the youngest two (14 and 16 yr old), which are dominated by stump-sprouted trees. Error bars show standard errors.

Recommendations for Sampling Fine Roots

For measuring fine roots, cores are more efficient than soil pits. The time required for collecting cores is much less than for pits, even though more cores must be collected to produce a sample equivalent to one pit. To excavate a single quantitative soil pit takes a well-trained crew 3 to 8 person-days, depending on the depth to which they are digging, the number of depth increments, and the rockiness of the soil. The purpose of excavating soil pits is generally to quantify soil mass and chemistry, and pits are the only way to get this information with any accuracy in stony soils (Johnson et al., 1991). Two thirds of the time required for quantitative soil pits is not directly related to the collection of roots, but even at 1 to 3 person-days pit^{-1}, this approach is probably not cost effective as a means of collecting roots. Smaller pits might seem to offer time savings, but 0.5 m^2 is about the limit to accommodate a person digging in a pit.

If quantitative soil pits are required for other purposes, then collecting the roots from the screens in the field takes little additional effort. Screens capture all of the coarse roots in the pit (>2 mm in diameter). Fine roots <2 mm represent 46% of the live root biomass (Fig. 2), and only 52% of this mass is captured on the screens. Total root biomass in our young stands averaged 2.2 times the mass of roots collected on the screens, with a standard error of 0.3 g m^{-2} based on six pits. In the young-transitional and older stands, the ratio of total root biomass to biomass on the screens was 1.7 with standard errors of 0.2 and 0.1 g m^{-2}, respectively. If these ratios can be applied in other forests, then the roots collected on the screens need only be washed and weighed to obtain an estimate of lateral root biomass <10 cm in diameter.

If coring is used, care should be taken to minimize the effect of soil compaction, especially with small-diameter cores. Cores used for sampling roots range from 2 to 15 cm in diameter (Aber et al., 1985; Fahey and Hughes, 1994; Vogt et al., 1985) with 4 to 5 cm being most common. Compaction with coring is a known problem in bulk-density sampling, which is overcome by using corers >6 cm in diameter (Campbell and Henshall, 2001). Judicious use of subsampling can control the amount of time required to pick roots from samples, so the size of cores should not be limited by concerns about the volume of soil obtained. Unfortunately, larger cores can be impractical due to obstructions in rocky soil.

Using cores with thin walls and sharp edges also helps to reduce compaction (Campbell and Henshall, 2001); for this reason, using an auger to remove samples from a metal core might be more accurate than the method we used, which involved polyvinyl chloride pipe split lengthwise and taped. Since the potential for compaction is greatest in the organic surface horizons, some researchers have collected the surface layer as a block but used coring beneath it (Safford and Bell, 1972). Controlling the depth to which the core is driven is more accurate than reporting the length of the soil sample collected; neither method corrects for compaction below the depth of the core.

The other limitation of root cores is that they cannot be taken below the depth of obstruction of the core. Depths used for collecting roots with cores range from 10 to 50 cm (Joslin and Henderson, 1987; King et al., 2001; Vanninen and Mäkelä, 1999), with 30 to 40 cm being most common. In our soil pits, 28% of live fine root biomass <2 mm in diameter occurred below 30 cm in the mineral soil, on average; this fraction ranged from 20 to 42%, depending on the stand, which is a large uncertainty. The uncertainty of extrapolating to depth is even larger for individual pits, with a range of 13 to 58% of fine roots occurring below 30 cm. In addition to the problem of the depth of sampling, the locations that can be sampled by coring are limited in stony soil. The difference we found between cores and pits would probably be less in a less stony soil; our pits averaged 11% rock volume above 30-cm depth and 21% below that depth (Table 2).

High spatial variation is an important obstacle to accurate measurement of fine root biomass. For example, fine root biomass is significantly related to the size and proximity of tree stems (Yanai et al., 2006). Soil factors present another source of variation that is probably intractable to modeling. The best response is probably to optimize the number of samples taken, rather than to attempt to control for sources of spatial variation. The number of samples needed varies inversely with the square of the acceptable margin of error (Moore and McCabe, 1999). The effort required to collect samples should be estimated separately from the effort required to process them, since numerous samples can be composited and subsampled for root processing.

Recommendations for Sampling Lateral Roots

The best method for estimating lateral roots depends on the age of the stand. Older stands, which tend to be dominated by a small number of large trees, have a highly heterogeneous spatial root distribution, as indicated by the variance in the roots sampled from the soil pits (Fig. 6, Table 3). In such stands, allometric equations based on stand-level mensuration data may provide the most accurate estimate of the stand-level lateral root mass (Vadeboncoeur et al., 2006, unpublished data).

In the young stands (14 and 16 yr), allometric equations do not accurately predict root biomass in the soil pits (Fig. 6). In recently harvested stands, the mature root systems of cut trees can persist, giving rise to stump- and root-sprouted trees in many hardwood species (Burns and Honkala, 1990). The problems of highly variable root/shoot ratios and root systems shared among many shoots were encountered by Whittaker and Woodwell (1968) in developing allometric equations for oaks in fire-adapted forest systems. For this reason, pits may be the most reliable way to estimate live lateral root biomass in young stands with species that sprout, which include American beech and red maple. Note, however, that "legacy" root systems persisting after harvest will be heterogeneously distributed, as they were in the precut stand, and root masses from pits in these sites will have variance comparable with older sites (Fig. 6). The young-transitional stands (19–29 yr) we examined gave the best agreement between allometric equations and pits. In the system we studied, 20 yr appears to be long enough to have restored a relationship between roots and shoots, but not long enough for trees to become widely spaced.

The simplicity of implementing the generalized hardwood equation (Vadeboncoeur et al., 2006, unpublished data) makes it attractive, as it yields results similar to species-specific equations, and using it does not involve ad hoc decisions about which species are the best proxies for others.

Neither cores nor pits can provide estimates of total root biomass. Cores sample roots only up to about 2 mm in diameter. We found that pits provided estimates of root biomass up to 2 cm in diameter with reasonable variance; the 2- to 10-cm class was highly variable (Fig. 2). It is possible that roots up to 5 cm, or some other diameter limit, would be reasonably characterized by this method; we did not subdivide the 2- to 10-cm size class and so cannot estimate variance to other diameter limits. Root crowns are not sampled in soil pits; we rejected pit locations centered within 50 cm of a tree >10 cm dbh because proximity to large trees makes digging extremely problematic. Root crowns are widely spaced, compared to the size of a 0.5-m^2 soil pit, and three pits per stand would be a poor way to sample them, even if it were feasible to do so. Total root biomass can be estimated only by allometric equations developed by excavating entire trees. Such equations exist (Jenkins et al., 2004) but to our knowledge, they have never before been validated for total belowground biomass.

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