The Quantitative Soil Pit Method for Measuring Belowground Carbon and Nitrogen Stocks

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Many important questions in ecosystem science require estimates of stocks of soil C and nutrients. Quantitative soil pits provide direct measurements of total soil mass and elemental content in depth-based samples representative of large volumes, bypassing potential errors associated with independently measuring soil bulk density, rock volume, and elemental concentrations. The method also allows relatively unbiased sampling of other belowground C and nutrient stocks, including roots, coarse organic fragments, and rocks. We present a comprehensive methodology for sampling these pools with quantitative pits and assess their accuracy, precision, effort, and sampling intensity as compared to other methods. At 14 forested sites in New Hampshire, nonsoil belowground pools (which other methods may omit, double-count, or undercount) accounted for upward of 25% of total belowground C and N stocks: coarse material accounted for 4 and 1% of C and N in the O horizon; roots were 11 and 4% of C and N in the O horizon and 10 and 3% of C and N in the B horizon; and soil adhering to rocks represented 5% of total B-horizon C and N. The top 50 cm of the C horizon contained the equivalent of 17% of B-horizon carbon and N. Sampling procedures should be carefully designed to avoid treating these important pools inconsistently. Quantitative soil pits have fewer sources of systematic error than coring methods; the main disadvantage is that because they are time-consuming and create a larger zone of disturbance, fewer observations can be made than with cores.

Estimating belowground stocks of C, nutrients, and pollutants is critical to understanding ecosystem responses to changes in land use, forest management, climate, and other environmental stresses. Soil is an important and dynamic component of the C cycle, and more accurately quantifying changes in soil and nonsoil belowground C stocks is necessary to improve global change models and to predict the effects of land-based mitigation activities (Nave et al., 2010; Schmidt et al., 2011).

The most common methods of sampling soils involve augers, corers, or the sampling of soil horizons from profiles exposed by excavation (Tan, 1996; Boone et al., 1999; Bélanger and van Rees, 2008). In soils that have been well mixed vertically and horizontally, augers and corers (push and hydraulic) provide representative plow-layer samples, and coring a known volume can yield an accurate estimate of bulk density, allowing chemical concentrations to be converted to content to the sampled depth (Ellert et al., 2008). Such methods are less satisfactory in heterogeneous soils, particularly on rocky, uneven terrain with a high degree of small-scale spatial variation in soil development, disturbance, horizon depth, and rock content. While soil cores are often used in such systems, variance is typically high and there may be large systematic biases related to the inability to sample below rocks larger than the corer (Harrison et al., 2003; Park et al., 2007). Recent work (e.g.,

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Diochon et al., 2009; Harrison et al., 2011; Lorenz et al., 2011) emphasizes the potential importance of changes in the often unsampled "deep" (>20 cm) soil horizons in ecosystem C balances, especially following disturbance.

For these reasons, rocky forest soils are often sampled by excavating pits and sampling from an exposed profile, usually by genetic horizon (e.g., Bailey et al., 2005). Bulk density is then measured at various depths with push-cores or by measuring the mass and volume of individual clods, while coarse fraction is estimated visually on exposed walls of the pit. This method allows for deeper sampling, more accurate assessment of bulk density and coarse fraction, and better recognition of genetic horizons than is possible with coring. However, it is not the best way to estimate soil mass or nutrient contents because of the difficulty of estimating rock volume.

Lyford (1964), citing earlier direct measurements of coarse fraction (Donahue, 1940; Bethlahmy, 1952), excavated rectangular access pits and quantitatively removed soils from a known adjacent volume. All material was sorted by size class and weighed, allowing direct measurement of coarse fraction and soil mass by horizon from a large representative volume. Hamburg (1984a, 1984b) adapted Lyford's quantitative approach, excavating 0.5 to 1.0 m^2 soil pits volumetrically by depth increment, and weighing soil and coarse fragments in the field. Soil was then subsampled for the determination of moisture, organic matter, and elemental concentrations. The major advantage of this method is the direct measurement of the mass of each soil layer, rather than calculating it from estimates of bulk density and coarse fraction. Like other pit methods, quantitative pits are a substantial improvement over cores, because there are fewer locations that cannot be sampled due to the presence of rocks. Deep soil horizons are also more accessible to pit methods than to coring methods, and large, representative samples can be taken with little contamination from surficial horizons. This method has been used in at least 40 studies totaling over 1100 pits (Supplemental Table).

Here, we use the quantitative pit method to conduct a comprehensive accounting of belowground C and N pools to the bottom of the B horizon across 14 northern hardwood forest stands in the White Mountain region of New Hampshire. In addition to total soil C and N, we quantified stocks in roots, coarse organic fragments, the top 50 cm of the underlying C horizon, and the soil adhering to rocks. We also review variations in quantitative pit methodology across published studies, summarize published mean and variance data for soil mass, carbon content, and root mass, and calculate statistical power and detectable change statistics. We intend our results to serve as a guide in designing future sampling efforts, particularly those intended to detect stock changes over time.

MATERIALS AND METHODS

Study Sites

We sampled 14 forested sites in the White Mountain region of New Hampshire (Fig. 1), between 320 and 630 m elevation. The most common soils were isotic, frigid Haplorthods developed on rocky ablation till derived from local granitic and metamorphic bedrock, and varying in texture from sandy loam to loamy sand. Six of the sites ("M" and "H" sites) sampled in 2003 had been previously sampled for forest floor mass and chemistry, and represent a range of northern hardwood stand ages following cutting (Yanai et al., 2000). Two other sites sampled in 2003 were a pasture (B1) and a woodlot (BW), abandoned in the 1940s (Hamburg, 1984b; Rhoads, 2005), now dominated by northern hardwoods mixed with spruce and hemlock, respectively. Six additional sites in the Bartlett Experimental Forest ("C" sites) were sampled in 2004 and also represent a range of northern hardwood stand ages following cutting (14–120 yr) (Park et al., 2007).

Field Methods

Three quantitative soil pits were excavated at each of the 14 sites for the purpose of quantifying belowground stocks of C and nutrients. We updated the method developed by Hamburg (1984a,1984b), modified by Huntington et al. (1988), and adopted widely (Supplemental Table). The method was modified to allow a more comprehensive accounting of a variety of belowground C and N stocks, and to provide samples for other analyses, including weathering profiles (Schaller et al., 2010).

Site Selection and Preparation

At each forest stand studied, the three replicate pits were located randomly, stratified among forest inventory subplots or transects. Study sites ranged in area from 0.25 to 1.0 ha; mean distance between pits within a site was approximately 50 m. We examined random candidate pit locations, choosing the first that satisfied all of the following criteria.

- Pit center was not within 50 cm of a tree >10 cm in diameter at breast height (DBH).
- Pit area (0.5 m^2) had <50% coverage of surface rock.
- There was no obvious recent soil disturbance (e.g., tip-ups, skid trails) in or adjacent to the pit footprint.
- At least three steel rods, including two on opposite sides of the pit, could be driven sufficiently deep into the soil to firmly secure the wooden reference frame.
- Microtopography allowed the reference frame to sit securely against the soil surface.

All together, approximately 30% of the candidate locations were rejected and relocated. Of these, most rejections were due to large rocks at or near the surface that prevented securing the frame adequately.

Aboveground woody debris and vegetation, including trees <10 cm DBH, were removed from the pit footprint before securing the frame. Fine woody debris not covered by leaf litter was clipped and discarded. We defined woody debris fully covered by leaf litter as a belowground stock. A square wooden frame with an interior area of 0.5 m^2 (70.7 cm on a side) was secured to the ground by driving lengths of 12 mm (1/2 in) rebar through predrilled holes and securing U-clamps against the frame. A grid of 25 measurement points and a ruler were used to measure the perpendicular depth to the top of the O horizon from the top surface of the frame, which served as an immobile reference plane throughout the excavation.

O Horizon Excavation

Relatively little attention was given to sampling fine roots early in the use of this method (Hamburg, 1984b; Huntington et al., 1988). In our 2003 soil pits, we dried and forcefully sieved the Oi and Oe horizons, which were collected together (hereafter "Oie"), resulting in a single sample of fragmented litter and roots. Picking root fragments from this material was extremely labor intensive even for small subsamples. In 2004, we subsampled the Oie by securing three 10-cm square blocks to the forest floor with long nails, carefully cutting around them with a finely serrated knife, and leaving them in place as we removed the remainder of the Oie by hand and with clippers, before bagging and weighing in the field. Subsamples under the blocks were bagged separately to be picked for fine roots (Park et al., 2007).

The Oa horizon was removed with stainless steel trowels and clippers, taking care to maintain the square shape of the excavated volume. Oa material was sieved onto a tarp through a large (~0.25 m^2) 6-mm stainless steel sieve in the field. Roots and woody fragments not passing the sieve were collected separately. Roots extending from the bottom and sides of the pit were clipped and added to the root sample. All removed O-horizon material was weighed in the field and brought back to the lab. Depth was measured again on a 25-point grid at the top of the mineral soil.

In 2003, representative subsamples of sieved soil from each depth increment were taken with a trowel, which may undersample roots long enough to tip off the trowel. In 2004, we used salad tongs, which would oversample long roots, except that roots protruding from the tongs were clipped with scissors (Park et al., 2007).

At six sites sampled in 2003, O horizons were also sampled using 10-cm square pin-blocks (10 blocks composited by transect; five 50-m transects per site), for comparison with previous forest floor measurements at these sites (Federer, 1984; Yanai et al., 1999). These measurements allow a comparison of soil pits, excavated downward, with the pin-block method in which blocks are inverted and mineral soil removed from the bottom.

Mineral Horizon Excavation

Mineral soil horizons were excavated by depth in increments that varied by sampling year (Yanai et al., 2006; Park et al., 2007). In 2003, we sampled from 0 to 10 cm (from the top of the mineral soil), 10 to 20 cm, 20 to 30 cm, and from 30 cm to the top of the C horizon, while in 2004 we sampled from 0 to 10 cm, 10 to 30 cm, 30 to 50 cm, and from 50 cm to the top of the C horizon. The C horizon was sampled to 50 cm (as two layers, designated C_{0-25cm} and $C_{25-50cm}$) in one pit per site, and in 2004 to 25 cm in the other two pits. In pits where C horizons

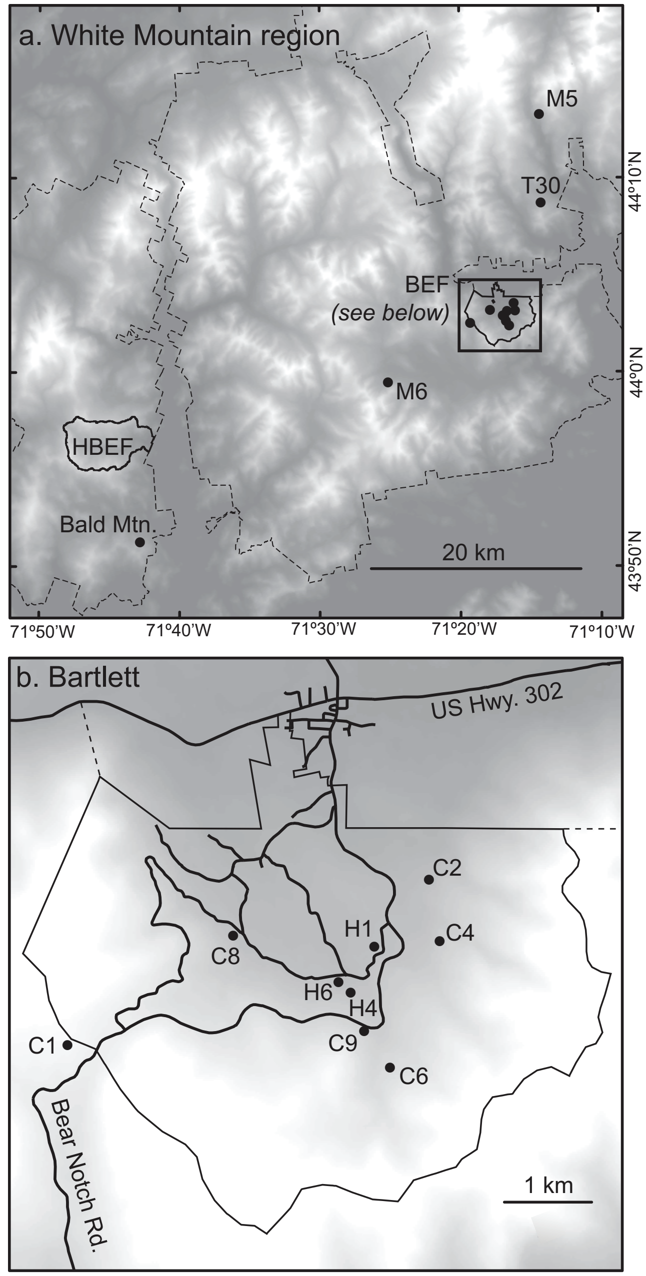

Fig. 1. Map of central New Hampshire forest sites used in this study. Grayscale shading indicates elevation (darkest gray is <200 m; white is >600 m). The dashed line shows the White Mountain National Forest boundary, and the solid lines show Hubbard Brook (HBEF) and Bartlett Experimental Forests (BEF). Sites B1 and BW are at Bald Mountain.

were not quantitatively sampled, a ~10 cm deep core was taken at the top of the C horizon.

Shovels and trowels were used to loosen and remove the soil from each layer. As digging proceeded, depth was checked often to avoid digging too far, and the width of the pit was verified with a 70.7 cm length of wood. Excavated material was sieved through a 12-mm stainless steel mesh in the field; roots and rocks not passing the sieve were weighed and subsampled.

Rocks that protruded from the pit walls and were <10 cm on any exposed side were removed if possible. Rocks that were judged to be at least half in the pit were included in the rock mass; others were discarded without weighing. The in-pit mass of larger protruding rocks was estimated by reweighing rocks approximately equal in volume to the part of the rock protruding into the pit.

After removing each layer, depth measurements were taken on the grid. Measurements that fell on rocks were noted. The sieved soil was thoroughly mixed and weighed in buckets. Samples were taken from the last shovelful filling each bucket before it was weighed, accumulating a composite subsample of ~2 to 4 kg for soil analysis and ~100 g for root picking, by trowel or tongs, as described above (Park et al., 2007).

Laboratory Methods

Soils

Roots and soil subsamples to be picked for fine roots were refrigerated until they were processed (see Yanai et al., 2006; Park et al., 2007). Other samples were air-dried on brown kraft paper on wire racks, and covered with paper to prevent contamination by dust. Air-dried mineral soil samples were sieved to 2 mm, and the <2 mm fraction weighed. A subsample of the <2 mm mineral soil fraction was oven-dried at 105°C. Air-dried samples of the Oie were milled to 2 mm, and all O-horizon subsamples were oven-dried at 60°C. Subsamples were split with a riffle box; some of each sample was archived at the Hubbard Brook Experimental Forest.

The dry mass of <2 mm soil in each layer was calculated using the moisture content, mass, and coarse fraction of the sieved material weighed in the field. The thickness of the depth increment was calculated, excluding points that landed on rocks. Coarse fraction volume by layer was estimated including the volume of rocks protruding from the bottom of each layer (assuming each rock occupies the entire 200 cm^2 grid cell it represents at the measured height) and the mass of rocks removed from each layer (including the 2–12 mm fraction) divided by a standard rock density of 2.65 g cm^{-3} (Telford et al., 1990). Bulk density was calculated by dividing the soil mass of the layer by the nonrock volume of each layer.

Subsamples (5–15 g) for C and N analysis were pulverized in a Spex mixer mill. Total C and N concentrations were measured on a CE Instrument Model NC2100 elemental analyzer. The mass of sample analyzed ranged from 8 to 25 mg, depending on organic matter concentration; 10% of samples were run in triplicate. The coefficient of variation (CV) of C and N concentration data for samples run in triplicate was generally <5% but occasionally approached 10%. For C-horizon samples, where N concentrations were near the detection limit, CV's were sometimes considerably greater. All C was assumed to be organic, due to the granitic parent material and low soil pH.

Roots

Subsamples of roots from the Oa and mineral horizons (to a depth of 50 cm) from the 18 pits excavated in 2004 were washed, dried at 60°C, pulverized, and analyzed for C and N content on a Vario EL elemental analyzer. Three diameter classes (<1, 1–5, and 5–10 mm) were analyzed.

O-horizon Coarse Organic Matter

Among the C and N pools we analyzed, in addition to soil, were woody fragments from the forest floor that would not pass a 6-mm sieve. In 2003, the Oie samples from all 24 pits were forced through a 6-mm sieve. Coarse (>6 mm) organic fragments from the Oie samples were analyzed for C and N. At each of the eight sites, we also selected one Oa sample from which to analyze organic material that did not pass the 6-mm sieve.

Mineral Horizon Coarse Fraction

To estimate the importance of soil adhering to rocks, subsamples of rocks in the 2- to 12-mm and 12- to 80-mm size classes were reserved from excavated mineral layers, including the C horizon. In two pits (H1-2 and H4-3) these samples were hand washed to collect soil material adhering to them. These soil samples were oven-dried, weighed, and pulverized for C and N analysis. A paired *t* test was used to test the hypothesis that these fines had the same C and N concentrations as the soil samples collected from the same depth increment. To estimate the C and N inside the rocks, rock subsamples from all layers in two other pits (C4-1 and C8-2) were washed, crushed, and pulverized for analysis. To identify geologic C and N from sources such as carbonate minerals and NH_4^+ in silicate minerals (Holloway and Dahlgren, 2002), a subsample of 12- to 80-mm rocks from the deepest layer in each of the two pits was heated to 450°C in a muffle furnace for 8 h to remove organic C and N before analysis. To broaden this analysis, representative bedrock samples of two local lithologies, Conway granite (Redstone Quarry, Conway) and Mt. Osceola granite (Bartlett Experimental Forest) were analyzed in the same way.

We estimated the C and N content of rocks by applying concentrations measured in each layer's 2- to 12-mm rock fraction to the mass of that fraction, and concentrations in the 12- to 80-mm rock fraction to all >12 mm rock mass in each layer.

Literature Review

We reviewed published studies that used quantitative pits to directly measure total soil and coarse fraction mass (Supplemental Table). We searched Google Scholar and ISI Web of Science for the terms "quantitative", "volumetric" and "soil pit", and also examined studies referencing Hamburg (1984a), Huntington et al. (1988), Johnson et al. (1991a, 1991b) or Johnson (1995) for methods. We excluded studies in which pit volume was measured by displacement or pits that were not sampled quantitatively to depths >10 cm into the mineral soil.

Where possible, we reported the mean and coefficient of variation (CV) of soil mass and soil C (O-horizon, mineral soil, and total), and root mass (total only) for each study site. For each site, we calculated the detectable change (based on an unpaired *t* test, $\alpha = 0.05$, power = 0.75) if resampling with the same number of pits, as well as the likelihood of detecting a 20% change with 95% confidence if resampled with the same number of pits. These calculations were conducted with R 2.10 software using the function *pwr.t.test* (Champley, 2009).

Table 1. Soil depth, coarse fraction, and mass by horizon at each of 14 forested sites in central New Hampshire sampled using the quantitative pit method in 2003 and 2004. In each site, *n* = 3 except where SD is not calculated (†) for samples taken from only one pit per site.

Year	Site	O horizon depth		O horizon mass <6 mm		Min soil depth to C horizon		Min soil coarse fraction		Min soil <2 mm mass to C horizon		C 0–25 cm <2 mm mass		C 0–25 cm coarse fraction	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
		– cm –		– kg m^{-2} –		– cm –		– % vol –		– kg m^{-2} –				– % vol –	
2003	B1	5.0	0.8	5.2	1.2	35.5	10.9	19	14	224	54	319	†	18	†
	BW	12.4	2.7	19.2	13.9	30.3	10.2	26	14	188	54	368	†	25	†
	H1	5.4	4.4	12.3	9.4	68.3	25.0	14	8	591	262	249	†	35	†
	H4	4.4	1.3	5.6	3.7	72.9	16.5	25	11	522	130	36	†	54	†
	H6	13.2	4.6	31.6	15.0	61.3	36.9	17	7	539	322	200	†	54	†
	M5	7.0	1.6	5.8	3.0	48.0	4.0	36	7	273	78	0	0	–	
	M6	5.2	2.9	7.9	2.3	65.9	6.4	34	17	371	131	171	†	38	†
	T30	5.7	3.8	7.2	3.1	47.6	29.9	23	8	309	159	273	†	46	†
2004	C1	2.3	0.4	7.1	4.8	74.2	9.1	36	13	406	188	153	85	50	13
	C2	4.5	2.5	9.7	1.9	72.6	26.1	26	11	428	107	196	69	37	5
	C4	5.0	3.3	10.4	5.7	77.6	19.7	15	1	534	174	229	26	15	2
	C6	6.3	2.4	9.2	4.2	38.5	31.3	15	18	252	193	243	49	7	0
	C8	3.5	1.6	8.6	3.5	73.8	32.5	31	21	436	181	265	54	34	35
	C9	7.7	3.9	13.3	6.2	85.2	9.3	33	18	503	140	212	91	39	25

RESULTS

Accounting of Belowground Carbon and Nitrogen Stocks

Soil Mass, Coarse Fraction, and Bulk Density

O-horizon depth averaged 6.3±3.1 cm across sites (all results are reported as mean±SD), and O-horizon mass averaged 10.9 ± 7.0 kg m^{-2}. Both depth and mass were notably high at BW, a former woodlot dominated by hemlock and northern hardwoods, and H6, where pin block samples in teh same year showed a much lower average (Table 1). The CV of mean O-horizon mass across the 14 sites (64%) was generally greater than the CV of replicate pits within sites, which ranged from 19 to 77% (Table 1).

Mineral soil mass (to the top of the C horizon) averaged 400 ± 130 kg m^{-2}, and correlated strongly with depth to the C horizon (R^2 = 0.73). Bulk density increased significantly with depth (Fig. 2), averaging 0.65 ± 0.12 g cm^{-3} in the 0 to 10 cm layer, 0.99 ± 0.28 g cm^{-3} in the 50 cm-C layer, and 1.50 ± 0.26 in the $C_{25-50cm}$ layer. At one of our sites (M5), we were unable to sample C-horizon material because soil rested on bed-

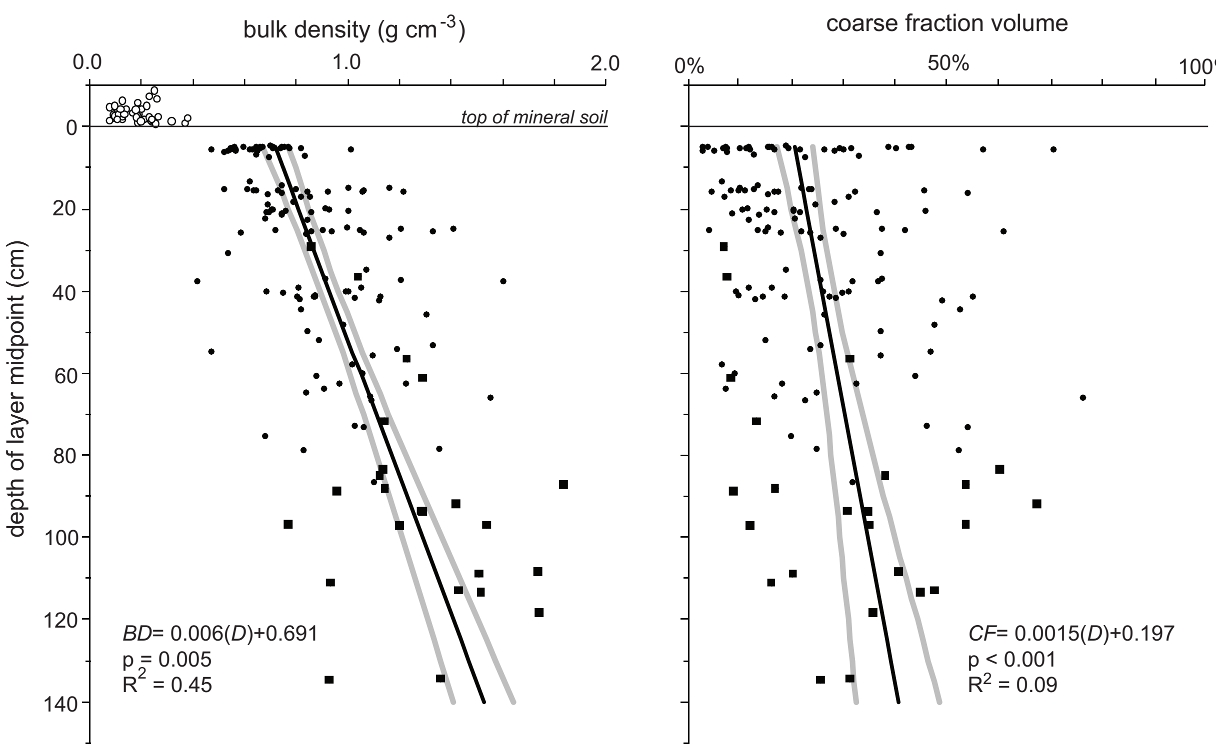

Fig. 2. Bulk density and coarse fraction with depth in 14 forested sites using quantitative soil pits excavated in 2003–2004. Open circles show O horizon samples; filled circles show mineral soils, and filled squares show C horizon samples. Linear regressions are shown with 95% confidence intervals. D = depth in cm; BD = bulk density in g cm^{-3}; CF = coarse fragment volume expressed as a fraction (e.g., 30% = 0.30).

rock in all three pits. In another site (H4), the pit designated for C-horizon sampling had approximately 10 cm of C horizon over bedrock. In 37 of 42 pits (88%) we were able to sample the C horizon as planned.

Coarse fraction volume showed a significant but poorly predictive relationship with depth (Fig. 2), and was slightly greater in C horizons (31±18%) than other mineral horizons (24±15%); (unpaired t test, $p = 0.05$). Coarse fragments ranged from gravel to large boulders. Soil particles adhering to coarse fragments accounted for an additional 3 to 8% of soil mass in the two pits where they were processed.

Carbon and Nitrogen in Commonly Sampled Pools

The Oie averaged 45.8±4.3% C and 1.69±0.33% N, totaling 933 ± 365 g C m^{-2} and 35 ± 16 g N m^{-2} (Table 2). The <6 mm Oa horizon averaged 29.2±8.4% C and 1.25±0.37% N, representing a stock of 2560 ± 2270 g C m^{-2} and 106 ± 83 g N m^{-2}. Nine of 42 sampled Oa horizons had <20% C, indicating that some of the material we included as Oa based on field properties did not meet the definition for this horizon (20% organic C). Because of the difficulties of distinguishing Oa from thin A horizons in the field (Yanai et al., 2000), soil studies in the region typically lump the O and A horizons together as the "forest floor", and mark the top of the mineral soil where the Oa or A transitions to E or B, which is easier to identify consistently (Federer, 1982; Yanai et al., 1999, 2000). At the six sites where the forest floor was sampled both by soil pits and forest floor pin-blocks (five lines of 10 composited samples per site) in 2003, pits estimated 9% greater C content and 2% greater N. Within stands, on average, the CV was greater for three pits (52%) than for five

Table 2. O horizon C and N stocks at each of 14 forested sites in central New Hampshire sampled using the quantitative pit method in 2003 and 2004. In each site, n = 3 pits. In 2004, Oie samples were not sieved; the fine and coarse fractions were analyzed together. The subsamples of Oie and Oa processed for C and N analysis include roots; here we subtract the roots analyzed from a different subsample.

Year	Site	Fine Oie (forced through 6-mm sieve; minus roots)		Coarse Oie (>6 mm)		Total Oie (minus roots)		Oie fine roots		Fine Oa (<6 mm, minus roots)		Coarse Oa (>6 mm)	Oa Fine roots (passed 6-mm field sieve)		Oa Coarse roots (did not pass 6-mm field sieve)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	Mean	SD	Mean	SD
		g m^{-2}														
		a. O horizon carbon content														
2003	B1	1095	75	179	28	1274	80	11	4	1268	520	22	48	26	54	37
	BW	1665	666	221	118	1886	676	61	44	3902	1605	106	166	77	1027	825
	H1	387	13	74	15	462	20	2	1	3695	3987	7	119	†	137	†
	H4	799	487	245	152	1043	510	22	15	932	843	101	50	29	70	29
	H6	886	178	199	43	1085	184	16	10	9540	3510	167	142	50	287	179
	M5	746	357	245	129	991	380	6	5	1277	1265	56	56	22	699	824
	M6	1067	299	266	150	1333	335	16	12	1856	916	4	82	22	128	90
	T30	1249	792	358	225	1607	823	52	43	1444	1126	21	158	158	106	65
2004	C1	–‡		–		412	202	8	7	580	184	–	25	5	80	88
	C2	–		–		997	421	42	30	2316	938	–	45	25	240	182
	C4	–		–		860	279	90	129	2299	2555	–	103	92	303	126
	C6	–		–		1061	352	116	67	2223	1398	–	73	44	277	203
	C8	–		–		410	81	36	6	1225	686	–	57	17	129	86
	C9	–		–		860	417	88	67	2145	1220	–	78	29	284	260
		b. O horizon N content														
2003	B1	37	0.4	1.8	0.1	39	0.5	0.3	0.1	50	20	0.2	0.8	0.4	1.0	0.4
	BW	63	22	2.8	1.9	65	22	1.4	1.1	178	73	0.8	2.3	0.9	11.4	8.6
	H1	15	2	1.1	0.4	16	2	0.04	0.01	160	169	0.2	1.5	0.0	1.8	0.0
	H4	32	20	3.7	2.4	35	20	0.4	0.3	39	35	1.4	0.8	0.6	1.0	0.3
	H6	40	9	3.5	1.2	43	9	0.3	0.2	350	136	2.1	2.0	0.7	3.6	1.9
	M5	31	15	3.1	1.8	34	16	0.1	0.1	77	71	0.6	0.8	0.3	8.2	8.6
	M6	52	14	3.1	0.5	55	14	0.3	0.2	88	42	0.1	1.4	0.5	1.6	1.0
	T30	57	34	6.0	3.5	63	34	1.0	0.7	62	44	0.4	3.0	3.6	1.4	0.7
2004	C1	–		–		14	6	0.1	0.1	24	8	–	0.4	0.1	1.0	0.9
	C2	–		–		19	10	0.7	0.4	89	36	–	0.7	0.3	2.9	1.9
	C4	–		–		26	14	1.1	1.3	95	105	–	1.5	1.2	3.5	1.3
	C6	–		–		44	16	1.6	0.8	98	56	–	1.4	0.9	3.3	2.1
	C8	–		–		14	2	0.6	0.1	55	27	–	1.0	0.2	2.0	1.0
	C9	–		–		31	13	1.7	1.4	102	53	–	1.4	0.6	3.9	2.8

† Indicates standard deviations not calculated due to only one sample per site.

‡ Dash indicates data not taken.

composite lines of blocks (30%), even though the pits sample three times more surface area, confirming that there is significant variation at scales larger than the soil pit. Notably, at H6, the pin blocks showed a distributio of O-horizon masses consistent with the other sites, as in previous measurements (Yanai et al., 2000), while the three soil pits were all quite high in O-horizon mass (Table 1).

Mineral soil C and N concentrations decreased rapidly and systematically with depth; log–log regressions were highly significant (Fig. 3). Nevertheless, mineral soil contained much more C and N than the forest floor layers, because of its much greater mass. The E+B horizons averaged 8990 ± 2230 g C m^{-2} and 420 ± 110 g N m^{-2} (Table 3).

Carbon and Nitrogen in the C Horizon

The C_{0-25cm} horizon contained 1070 ± 910 g C m^{-2} and 48 ± 36 g N m^{-2} where present, adding 6 to 37% to the mineral soil totals, depending on the site. Where present and sampled, the $C_{25-50\ cm}$ horizon contained 650 ± 720 g C m^{-2} and 27 ± 29 g N m^{-2}, adding 2 to 20% to the mineral soil totals. Across pits with both C_{0-25cm} and $C_{25-50cm}$ layers sampled, the $C_{25-50cm}$ layer had significantly lower carbon concentrations (Table 3; paired *t* test, $p < 0.01$). Carbon concentrations in the upper C horizon were non-significantly higher where soils were shallow (linear regression; $p = 0.08$ for pits with C_{0-25cm} samples and 0.41 for pits with cores at the top of the C horizon).

Carbon and Nitrogen in Coarse Organic Material

Belowground material that does not pass a sieve is often excluded from ecosystem budgets. The >6 mm material from the Oie (mostly twigs and wood fragments) ranged in mass from 108 to 1230 g m^{-2}, averaging 437 g m^{-2} across the 24 pits excavated in 2003, or 20% of the mean total sample mass. Concentrations of N were much lower than in the material that passed the sieve (0.73 vs. 1.87%), but C concentrations were similar (51 vs. 45%). The coarse material averaged 223 g C m^{-2} and 3.2 g N m^{-2}, accounting for 22 and 9% of the Oie totals. To simplify lab processing, we included coarse organic material in Oie samples collected in 2004, by milling the entire sample before analysis.

In the Oa horizon, the >6 mm material was mostly wood and bark. The mass of this material ranged from 8 to 322 g m^{-2}, averaging 123 g m^{-2}, or 1.5% of the mean total Oa mass from the eight pits in which it was analyzed (one per site in 2003). C concentrations were greater in the >6 mm material than in the material that passed the sieve (50 vs. 33% on average), but as in the Oie, N concentrations were smaller (0.76 vs. 1.41%). Carbon content averaged 61 g m^{-2}, and N content only 0.7 g m^{-2}. Overall, the coarse organic pool accounted for 3.3% of the Oa horizon C stock and 1.1% of the N stock.

Carbon and Nitrogen in and on Coarse Mineral Fragments

The C and N content of soil washed from coarse mineral fragments in two pits amounted to 2 to 10% (mean = 4.5%) of sieved soil C content of each layer, and 2 to 9% (mean = 4.8%) of the N content. The fraction of total layer C content found in

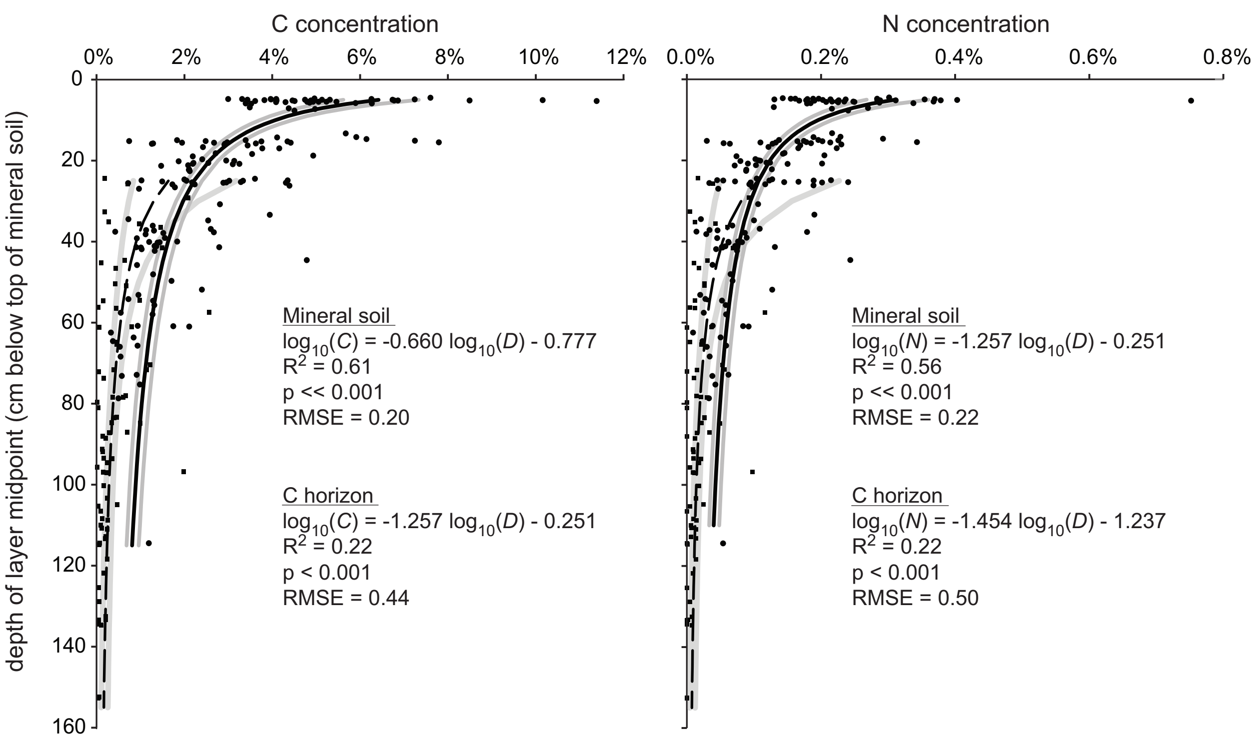

Fig. 3. Mineral soil C and N concentrations with depth in 14 forested sites using quantitative soil pits dug in 2003–2004, including both quantitative and nonquantitative C-horizon samples. Log-log regressions are shown with 95% confidence intervals, and are corrected for bias according to Smith (1993). D = depth in cm; C and N concentrations are expressed as fractions (e.g., 1% = 0.01).

Table 3. Mineral soil C and N stocks of 14 forested sites in central New Hampshire sampled using the quantitative pit method in 2003 and 2004. For mineral soil, n = 3 at all sites; n = 1 for all $C_{25–50cm}$ layers; n varies as noted in the $C_{0–25cm}$ layers. "BD" indicates that concentrations were below the detection limit.

Year	Site	Mineral soil		Mineral soil roots		C 0–25 cm soil			C 0–25 cm roots		C 25–50 cm soil	C 25–50 cm roots	Fines on coarse fraction	Washed coarse fraction
		Mean	SD	Mean	SD	*n*	Mean	SD	Mean	SD	Mean	Mean	Mean	Mean
		g m^{-2}												
		a. Mineral soil carbon content												
2003	B1	8,949	2248	1161	499	1	897	†	5	†	347	0	–‡	–
	BW	6,500	3392	624	544	1	690	†	0	†	136	0	–	–
	H1	11,360	3289	1289	608	1	897	†	52	†	554	29	323	–
	H4	12,955	4569	1852	1068	1	725	†	208	†	0	0	1056	–
	H6	9,088	4125	288	45	1	570	†	18	†	466	14	–	–
	M5	7,400	1977	1008	820	0	0	0	0	0	0	0	–	–
	M6	13,454	4958	636	165	1	1706	†	33	†	515	18	–	–
	T30	7,398	2989	795	81	1	2705	†	64	†	1883	14	–	–
2004	C1	7,302	1602	1225	526	3	418	104	20	9	467	32	–	–
	C2	7,512	792	844	154	3	597	299	41	31	124	8	–	–
	C4	9,331	163	1390	436	3	604	355	79	47	641	23	–	860
	C6	8,864	4087	754	77	3	3217	1062	127	70	2364	85	–	–
	C8	6,356	2003	913	132	2	479	22	19	17	39	1	–	410
	C9	9,349	2079	1214	146	3	446	320	24	16	210	2	–	–
		b. Mineral soil N content												
2003	B1	444	69	14	7		40	†	0.1	†	BD	0	–	–
	BW	286	92	7	6		18	†	0	†	17	0	–	–
	H1	458	145	14	6		53	†	0.6	†	30	0.4	17	–
	H4	618	179	21	11		36	†	2.3	†	0	0	49	–
	H6	381	92	3	0.5		31	†	0.2	†	32	0.2	–	–
	M5	458	75	11	9		0	0	0	0	0	0	–	–
	M6	634	265	7	2		85	†	0.4	†	15	0.2	–	–
	T30	381	138	9	1		89	†	0.8	†	42	0.2	–	–
2004	C1	330	104	15	7		24	5.8	0.3	0.1	27	0.5	–	–
	C2	317	75	10	2		28	3.7	0.5	0.3	BD	0.1	–	–
	C4	381	21	17	5		22	20.1	1.0	0.5	31	0.3	–	34
	C6	382	186	9	1		142	41.9	1.6	0.8	109	1.0	–	–
	C8	343	104	12	2		33	5.7	0.3	0.2	BD	0.02	–	22
	C9	523	148	15	2		26	16.5	0.3	0.2	16	0.02	–	–

† Indicates standard deviations not calculated due to only one sample per site.

‡ Dash indicates data not taken.

soil adhering to rocks showed a marginally significant correlation with coarse fraction volume ($R^2 = 0.40$; $p = 0.05$). Because these soil samples were not systematically different in C and N concentration from the corresponding bulk soil, additional C and N contents are similar to the mass proportions reported above. At the scale of a whole pit, this additional soil pool contained 323 to 1060 g C m^{-2} and 17 to 49 g N m^{-2}, the inclusion of which would add ~3% on average to total (O-horizon plus mineral soil) stocks (Table 3).

The rocks themselves had concentrations of 0.02 to 0.06% C and 0.001 to 0.023% N. Concentrations were lower in the 12 to 50 mm size fraction than in the 2 to 12 mm fraction, and decreased systematically with depth, consistent with a lesser weathered surface. We estimate that rocks contain an additional 410 to 860 g C m^{-2} and 22 to 34 g N m^{-2}, increasing the total belowground C content of each pit by 6 to 8%. Unweathered bedrock and C-horizon rock material treated in a muffle furnace to remove organic matter were near the detection limit for C and N (70–150 mg kg^{-1} C and 5–10 mg kg^{-1} N), indicating relatively little geologic contribution to these totals.

Carbon and Nitrogen in Roots

Carbon concentrations of roots in 18 pits varied little with depth or size class; for simplicity we used the mean value (48%) for all roots. Nitrogen concentrations, however, varied substantially with diameter. In the Oa horizon, roots <1 mm dominated the total mass and averaged 1.2% N. Mineral horizon roots <1 mm averaged 0.8%N, and roots >1 mm averaged 0.5% N. We used these means to calculate root C and N content across all pits.

In the O horizon, root C ranged from 113 to 1250 g C m^{-2} (mean of 399, or 12% of total) and root N ranged from 1.6 to 15.1 g N m^{-2} (mean 5.4, 4% of total; Table 2). The wide ranges may reflect differences in methods as well as natural variation across years and stands. Sieved Oie subsamples picked for roots

Table 4. Comparison of soil mass and the associated coefficient of variation (CV) measured with quantitative pits at sites reported in the literature, including those reported in this study. Pit size and area sampled are listed in the Supplemental Table.

Reference	Year sampled	Site	*n*	Pit size	Area	O horizon		Mineral soil		Total	
						Mean	CV	Mean	CV	Mean	CV
				m^2	ha	kg m^{-2}	%	kg m^{-2}	%	kg m^{-2}	%
This study	2003	B1	3	0.5	0.5	5.2	22	224	24	230	23
		BW	3	0.5	0.5	19.2	72	188	29	207	20
		H1	3	0.5	0.5	12.3	77	591	44	603	42
		H4	3	0.5	0.5	5.6	66	522	25	527	25
		H6	3	0.5	0.5	31.6	48	539	60	570	56
		M5	3	0.5	0.5	5.8	52	273	29	279	28
		M6	3	0.5	0.5	7.9	30	371	35	379	34
		T30	3	0.5	0.5	7.2	43	309	51	317	51
	2004	C1	3	0.5	0.75	7.1	68	406	46	413	44
		C2	3	0.5	0.75	9.7	19	428	25	438	24
		C4	3	0.5	0.75	10.4	54	534	33	545	31
		C6	3	0.5	0.75	9.2	46	252	77	261	72
		C8	3	0.5	0.75	8.6	40	436	41	445	40
		C9	3	0.5	0.75	13.3	47	503	28	516	26
Unpublished resampling of Hamburg, 1984a	1992	Bald Mt 3	3	0.5	0.5	3.6	23	347	16	350	16
		Bald Mt 4	3	0.5	0.5			389	10		
		Bald Mt 5	4	0.5	0.5	5.6	16	351	15	357	15
		Bald Mt 6	3	0.5	0.5	10.3	8	304	15	314	14
		Bald Mt 9	3	0.5	0.5			386	10		
	2005	Bald Mt 3	3	0.5	0.5	5.1	66	469	24	475	24
		Bald Mt 4	3	0.5	0.5			465	11		
		Bald Mt 5	3	0.5	0.5	6.2	40	425	27	431	27
		Bald Mt 6	3	0.5	0.5	6.0	42	402	6	408	5
		Bald Mt 9	3	0.5	0.5			458	16		
Johnson et al., 1995	1983	W5	59	0.5	22	8.7	73	317	51	325	49
	1986	W5	60	0.5	22	11.9	102	337	50	349	47
	1991	W5	60	0.5	22	7.5	111	332	56	339	55
Unpublished resampling	1998	W5	60	0.5	22	9.7	74	307	59	317	57
Ross, 2006	2005	DSL	3	0.5	0.36			1569	4		
		TNL	3	0.5	0.36			1597	14		
		TSL	3	0.5	0.36			1342	29		
Fernandez et al., 1993	1987–1988	all	24	0.5	0.4	10.6	38			329	24
Wibiralske et al., 2004	1992–1993	IB	40	0.25	40,600	20.0	38	496	16	516	15
		WB	20	0.25	40,600	15.5	37	469	17	485	16
		IF	19	0.25	40,600	12.2	52	564	11	577	11
		WF	20	0.25	40,600	12.7	49	495	10	507	10

in 2003 yielded only about 25% as much root mass as the intact Oie subsamples picked in 2004 (Park et al., 2007).

Roots in the mineral soil ranged in C content from 3 to 13% (by site) of the corresponding mineral soil <2 mm C stock, averaging 10%. For N, the range was 0.9 to 4.4%, averaging 2.7% (Table 3). Roots in the C horizon amounted to 5% of the C-horizon carbon stock and 1.4% of the N stock, on average.

Power Analysis for This and Other Studies

The CV of total soil mass across the three pits in each site varied widely, from 20 to 72%, averaging 37% (Table 4). The minimum detectable change in O-horizon mass (with 95% confidence, and accepting a Type II error rate of 25%), if three pits were to be measured at a future date with the same variance, ranged from 55 to 221%, averaging 140%. Clearly, such sampling schemes are not likely to detect modest stock changes. If only the forest floor is of interest, block sampling methods are much more efficient, because many small samples can be taken for the same effort as a few large soil pits. Thus many forest floor studies are capable of detecting changes as small as 20 to 30% (Yanai et al., 2003b). Across all studies on quantitative pits in the literature, the lowest detectable change for the forest floor was reported by Wibiralske et al. (2004), with a 23% detectable change with $n = 40$ pits. At Hubbard Brook W5, with 60 pits in each year sampled, the mean detectable O-horizon change was about 44%.

The CV of total soil C within a site ranged from 3% (site C2) to 63% (Johnson et al., 2011), averaging 24% across all the studies we surveyed (Table 5). In our study, with three pits per

Table 5. Soil carbon in organic horizon and mineral soil measured with quantitative pits at sites reported in the literature, including those reported in this study. For each site, we calculate the detectable change (α = 0.05, power = 0.75) if resampled with the same number of pits (det Δ), and the power to detect a 20% change with 95% confidence (pwr). Pit size and area sampled are listed in the Supplemental Table.

Reference	Year	Site	*n*	O Horizon				Mineral soil				Total			
				Mean	CV	det Δ	Pwr to detect±20%	Mean	CV	det Δ	Pwr to detect±20%	Mean	CV	det Δ	Pwr to detect±20%
				g m^{-2}	–%–			g m^{-2}	–%–			g m^{-2}	–%–		
This study	2003	B1	3	2,422	23	66	0.13	8,949	25	72	0.12	11,371	23	67	0.13
		BW	3	5,794	39	112	0.07	6,500	52	150	0.06	12,294	33	95	0.08
		H1	3	4,202	95	273	0.04	11,360	29	83	0.10	15,562	39	112	0.07
		H4	3	1,802	49	141	0.06	12,955	35	101	0.08	14,757	33	95	0.08
		H6	3	10,584	34	98	0.08	9,088	45	131	0.06	19,673	4	13	0.98
		M5	3	2,084	50	144	0.06	7,400	27	77	0.11	9,483	12	36	0.33
		M6	3	3,022	30	86	0.09	13,454	37	106	0.08	16,476	25	72	0.12
		T30	3	2,902	52	149	0.06	7,398	40	116	0.07	10,301	44	125	0.06
	2004	C1	3	1,025	33	94	0.08	7,302	22	63	0.14	8,327	19	54	0.17
		C2	3	3,400	15	44	0.24	7,512	11	30	0.43	10,912	3	9	>0.99
		C4	3	3,352	81	233	0.04	9,331	2	5	>0.99	12,683	22	62	0.14
		C6	3	3,474	50	144	0.06	8,864	46	133	0.06	12,338	24	68	0.13
		C8	3	1,728	40	116	0.07	6,356	32	91	0.09	8,084	25	72	0.12
		C9	3	3,171	34	97	0.08	9,349	22	64	0.14	12,520	10	29	0.46
Unpublished resampling of Hamburg, 1984a	1992	3	3	1,493	25	71	0.12	12,710	15	43	0.25	14,202	15	43	0.24
		4	3					12,446	9	25	0.58				
		5	4	2,122	27	60	0.14	9,138	18	40	0.27	11,260	18	40	0.26
		6	3	2,934	20	58	0.15	16,670	8	24	0.59	19,604	9	25	0.56
		9	3					13,385	9	26	0.54				
	2005	3	3	2,099	69	199	0.05	14,023	3	10	>0.99	16,123	10	28	0.48
		4	3					13,450	14	39	0.29				
		5	3	2,525	48	137	0.06	9,179	19	55	0.17	11,704	10	28	0.48
		6	3	2,423	33	94	0.09	14,235	30	88	0.09	16,658	25	72	0.12
		9	3					13,897	25	73	0.11				
Johnson et al., 1995	1983	W5	59	2,997	76	37	0.29	13,076	47	23	0.63	16,106	38	18	0.82
	1986	W5	60	2,925	112	54	0.16	1,4184	47	23	0.64	17,208	37	18	0.83
	1991	W5	60	2,165	105	51	0.18	11,709	49	24	0.59	13,874	45	22	0.67
Unpublished resampling	1998	W5	60	3,140	85	41	0.25	11,392	46	22	0.66	14,532	37	18	0.85
Ross, 2006	2005	DSL	3					1,189	17	50	0.19				
		TNL	3					1,226	34	97	0.08				
		TSL	3					1,280	38	110	0.07				
Fernandez et al., 1993	1987–1988	all	24	4,400	41	32	0.38					11,100	26	20	0.75
Bedison and Johnson, 2009	2005–2006	NH	20	5,800	17	15	0.94	22,700	21	18	0.83	28,500	17	15	0.96
		P	10	2,400	29	36	0.31	19,700	12	15	0.93	22,100	11	14	0.97
		SF	12	13,300	16	18	0.85	6,200	40	45	0.21	19,500	11	12	>0.99
Richter et al., 1989	not reported	ALL	36									13,500	27	17	0.87
Johnson et al., 2009	1990–1992	ALL	41					14,750	35	21	0.73				
Gaudinski et al., 2000	1996		2									8,800	15	79	0.13
Johnson et al., 2011	not reported	B	43									10,600	55	32	0.38
		P	53									8,000	63	33	0.37
Zummo & Friedland, 2011	2009	LD	4					9,330	9	20	0.73				
		MD	4					7,980	12	26	0.54				
		HD	4					7,010	12	26	0.52				
		M	4					8,510	9	20	0.75				

site per sampling date, the minimum detectable change (accepting a Type II error rate of 25%) ranged from 9 to 125%, averaging 57%. At Hubbard Brook, with 60 pits per sampling date, the detectable change was about 20%.

For total root mass, the CV among pits within a site in our data set ranged from 11% (site M6) to 90%, averaging 46%. Fernandez et al. (1993) and Rau et al. (2009) had CVs in this range (Table 6). At Hubbard Brook, the CV was considerably greater (153%), perhaps due to the range in soil depth and vegetation type in the large site sampled. In our study, with three pits per sampling date, the minimum detectable change ranged from

Table 6. Comparison of root mass and coefficients of variation measured with quantitative pits at sites reported in the literature, including those reported in this study. For each site, we calculate the detectable change (α = 0.05, power = 0.75) if resampled with the same number of pits (det Δ), and the power to detect a 20% change with 95% confidence (pwr). Pit size and area sampled are listed in the Supplemental Table.

Reference	Site	*n*	Depth	Mean	SD	CV	Det Δ	Pwr to detect±20%
				g m^{-2}		%		
This study	B1	3	to top of C	2642	896	34	98	0.09
	BW	3	to top of C	3912	2628	67	193	0.06
	H1	3	to top of C	3423	818	24	69	0.13
	H4	3	to top of C	4154	2488	60	172	0.06
	H6	3	to top of C	1526	537	35	101	0.08
	M5	3	to top of C	2729	2457	90	259	0.05
	M6	3	to top of C	1797	203	11	33	0.38
	T30	3	to top of C	2314	762	33	95	0.09
	C1	3	to 25 cm below top of C	3614	2232	62	178	0.06
	C2	3	to 25 cm below top of C	2524	580	23	66	0.13
	C4	3	to 25 cm below top of C	4094	881	22	62	0.14
	C6	3	to 25 cm below top of C	2808	440	16	45	0.23
	C8	3	to 25 cm below top of C	2404	322	13	39	0.29
	C9	3	to 25 cm below top of C	3864	973	25	73	0.12
Rau et al., 2009		24	52 cm	883	387	44	34	0.07
Fahey et al., 1988		59	to top of C	2676	4105	153	75	0.05
Fernandez et al., 1993		24	to top of C	1800	1314	73	56	0.06

33 to 259%. Even with 60 pits, the Hubbard Brook data (Fahey et al., 1988) only allow the detection of changes > 75%.

DISCUSSION

Distribution of Belowground Carbon and Nitrogen

Despite decreasing concentrations of C and N with depth (Fig. 3), the mass of the C horizon makes it an unexpectedly large stock of C and N (Table 3). Including the top 50 cm of the C horizon increased the measured soil C pool by as much as 49%. Most of our sites had C horizons deeper than 50 cm, but our quantitative sampling ended at this depth. Whether the C horizon should be considered depends on the study system, the specific questions, and the stability of C-horizon organic matter. The C horizon may have some importance to ecosystem budgets, as its top 25 cm contained 5% of all fine roots and the next 25 cm contained 2% (Park et al., 2007); similar C-horizon root abundances have been observed elsewhere in the northeastern United States (e.g., Donahue, 1940). The importance of these pools is unclear, as the turnover and activity of C-horizon roots is not well known.

Another pool typically not reported is the material not passing a soil sieve. In the O horizon, we found that 8% of C and 3% of N was in wood and bark fragments >6 mm. This material is also not usually measured in surveys of aboveground woody debris. This material can be included in the Oie sample for C and N analysis because it goes through a Wiley mill; in the Oa, it is processed separately, because the mineral content of the Oa precludes such milling. Coarse organic fragments appear to be highly variable in importance among ecosystems; they have been reported to account for 5 to 12% of C and 1 to 5% of N in the A horizon in coniferous stands in California (Black and Harden, 1995) and 34% of O-horizon mass in a conifer forest in Maine (Fernandez et al., 1993). Differences among sites may reflect differences in disturbance history as well as current input and decomposition rates for this pool.

Commonly, root fragments that pass a 2-mm sieve are included in analysis of the soil fraction. If root mass is independently estimated in an ecosystem budget, these roots are counted twice. On the other hand, if roots are not estimated by other means, the roots that do not pass a soil sieve are not counted at all. In our sites, roots amounted to 5 to 18% (mean 12%) of total soil C and 1 to 5% (mean 3%) of total soil N. Kulmatiski et al. (2003) similarly found that roots amounted to 10% of C and 2% of N of the 0- to 15-cm soil pools. Live and dead fine roots represent a dynamic and potentially very responsive C stock, and may be particularly important to monitor for change in manipulated and disturbed ecosystems.

Soil particles adhering to rocks accounted for a surprisingly large fraction of carbon in the two pits in which they were measured (3.5–5.6% of the mineral soil and C horizon combined), and a similar fraction of N (3.9–5.7%) (Table 3). The fraction of soil adhering to rocks likely varies widely with the size distribution of coarse fragments, soil structure and texture, and soil moisture when excavated; the amount of soil not weighed for this reason may be worth determining in other systems and sampling methods. However, our findings suggest that it is not necessary to analyze this soil for C and N concentrations, since they did not differ systematically from bulk soil. Harrison et al. (2003) found that soil adhering to the >2 mm fraction accounted for 3.5% of total soil C in a loamy sand from Washington, but 63% in a nearby very gravelly sandy loam. Whitney and Zabowski (2004) documented 0 to 35% of total soil N associated with the coarse fraction; this study did not distinguish ecosystem-derived organic matter from organic content in sedimentary rocks, or geologic

N in crystalline minerals (Holloway and Dahlgren 2002). In the granitic soils of the White Mountain region, geologic N appears unimportant. However, the small rocks we washed still had up to 0.6% C and 0.02% N from organic sources. Applying these concentrations to the mass of all rocks in the pits gave estimates of 400 to 860 g C m^{-2} in ecosystem-derived organic matter (Table 3); this is probably an overestimate, as larger rocks likely have lower concentrations of C and N far from the weathering front.

The size and variability of these largely unmeasured components of the belowground C and N pool shows their possible importance to belowground monitoring. If comparing ecosystems or monitoring change over time, it is important to be consistent in the treatment of roots, soil particles attached to coarse fragments, coarse material in the forest floor, and C horizon stocks.

Site Differences in Belowground Carbon and Nitrogen Stocks

Twelve of the sites we sampled were selected in part to represent a chronosequence of forest regeneration following commercial cutting. Unlike other such studies (Diochon et al., 2009; Neurath, 2011), we did not observe systematic differences in soil C content with time since harvest across the 12 sites with known harvest dates (Fig. 4). Mineral soil C content was below the mean in the three youngest stands sampled (14–19 yr), but it is not clear that this constitutes evidence of C loss due to harvesting. We regard the chronosequence approach as problematic in assessing changes in total C following disturbance, due to high pre-existing variability among sites and differences in harvest intensity and technique among stands (Yanai et al., 2000, 2003a). Repeating quantitative soil sampling across a variety of sites could help to improve estimates of soil C fluxes following harvest disturbance.

Reviewing the Quantitative Pit Method

The primary advantage of the quantitative soil pit method is the accurate, direct measurement of soil mass, obviating the need to measure bulk density and estimate coarse fraction, as is necessary with profile-sampling approaches, and reducing the potentially large sampling bias associated with core-based methods, which avoid rocks. In the 40+ studies that have employed quantitative pits (Supplemental Table), a variety of modified methods have emerged. Many studies (e.g., Kulmatiski et al., 2003; Hooker and Compton, 2003; Wibiralske et al., 2004) used pits only 50 cm square (0.25 m^2), which expedites the process, but limits the total depth that can be excavated cleanly; our 0.5 m^2 pits allow a person to work from inside the pit. Richter et al. (1989) excavated small pits, only 0.05 m^2, to a depth of 40 cm. Using smaller pits may allow for additional replication, particularly where only shallow horizons are of concern. Canary et al. (2000) did not remove large rocks, and instead continued digging only the portions of the pit where a large rock had not yet been encountered. Johnson et al. (1997, 2008, 2011) did not measure depth on a grid, but calculated the excavated volume from the soil mass and bulk density measured in pit-wall cores (this method may be preferable if bulk density is a parameter of interest, for example, in studying soil compaction as a disturbance effect). The critical similarity among these methods is the direct measurement of soil mass to a known depth in a unit area. This is important in rocky soils because estimating soil volume from rock volume is prone to error, especially when rock volume is high. The error associated with using mapped soil-unit estimates of coarse fraction rather than measuring the coarse fraction directly may be as large as 55% (Fernandez et al., 1993). The other advantage of pit methods is the large volume of soil sampled, which avoids the danger of taking concentration and bulk density samples that are inconsistent.

Because samples are collected while excavating downward, quantitative pit methods typically sample mineral horizons in depth increments, rather than by genetic horizon, except where horizon transitions are reliably sharp and predictable in appearance. Depth-based sampling may be advantageous when monitoring responses to disturbance that can change or mix soil horizons (e.g., harvesting; Martin, 1988). Sampling to a deep, recognizable transition, like the top of the C horizon, ensures that mineral soil organic matter is not systematically over- or underestimated by a repeated sampling strategy in a changing soil profile.

Quantitative Pits vs. Coring

Other studies have compared the effort required to sample using quantitative soil pits and soil cores for precisely measuring soil C and N stocks. For example, at 18 plots in Connecticut, Inceptisols and Entisols sampled to 15-cm depth differed by <12% in C and N concentrations between pit and core samples (Kulmatiski et al., 2003), though bulk density and coarse fraction were both significantly greater in pits than in cores. In the Pacific Northwest, cores underestimated soil C relative to pits by up to 70% in soils where the coarse fraction was an important C stock (Harrison et al., 2003).

In four of the sites where we excavated soil pits in 2004, both pits and cores were used to measure root biomass (Park et al., 2007). Fine (<2 mm) root biomass in the O horizon and top 10 cm of the mineral soil was 27% greater in cores than pits. These cores were taken with long PVC corers, and divided into depth increments after removal; soil compaction in the cores contributed about 10% to the systematic difference between cores and pits, with the rest attributed to obstruction by rocks and coarse roots. Motorized rotary coring, because depth increments are extracted sequentially, avoids bias from compaction and suffers fewer obstructions by rocks; in a desert system in Nevada, there was little systematic difference in root biomass estimates from 0.25 m^2 quantitative pits and 7.6-cm diam. powered rotary cores (Rau et al., 2009). Coarse roots (those >2 mm diam.) are sampled poorly by small-diameter cores (Park et al., 2007), which may explain the wide margin by which pit measurements of roots sometimes exceed core measurements (e.g., by 220% in the case of Kulmatiski et al., 2003). Even quantitative pits are not able to sample the coarsest roots, as sampling locations are rejected if they have large root crowns.

Cores taken with a powered rotary corer are attractive for several reasons. Unlike push-cores, they can sample through small rocks and large roots, access soils to a depth of ~1 m (Rau et al., 2009, 2011; Levine et al., 2012), and require far less effort per sample than quantitative pits. Like quantitative pits, they can sample by depth, but not by horizon, if the core is not removed intact. However, pits, unlike power cores, can stop at horizon transitions that are predictable in appearance (e.g., bottom of the B horizon). The grinding of rock and soil particles make power core samples unsuitable for some analyses (e.g., exchangeable cations, texture), and some contamination among horizons can occur when removing and re-inserting the corer (Levine et al., 2012). These differences may make power-core samples inappropriate for comparison with quantitative-pit or pit-wall profile samples. Where the objective is to quantify total C and N with depth, power cores occupy a middle ground between the lower bias of quantitative pits and the increased replication possible with coring (Rau et al., 2011). However, any method that cannot sample through rocks (including power cores on some soils; Levine et al., 2012) has an inherent sampling bias if there is soil unsampled below the rock.

Considerations for Repeated Sampling

Quantitative pits are labor-intensive to excavate. Our soil pits each took three to eight person-days to excavate and process in the field, with the C-horizon sampling taking a disproportionately large fraction of the total effort. Kulmatiski et al. (2003) estimated that a 0.25 m^2 pit took 3.5 person-hours to excavate to 15 cm, or 8 person-hours to 60 cm. Our experience with 0.5 m^2 pits is that two people can reliably excavate a pit to at least 30 cm and field-process the samples in a day. Below 50 cm, excavation slows considerably, especially in rocky or compact soils.

For repeated sampling, the disturbance associated with pit excavation must be considered. Within a radius of 1 to 3 m around each pit, there is substantial disturbance due to trampling, the piling of rocks and soil, occasional spillage, and the cutting of shrubs and small trees. Where the organic horizon is thick, compaction is often obvious after excavation. We sieved and piled soils on ~4 m^2 6-mil polyethylene sheets, and in level and reasonably accessible sites it may be feasible to minimize soil compaction by walking on wide planks. Careful planning before digging (locating sieved soil and rock piles on areas with little microtopography, or in previously disturbed areas) can also help. Because of the disturbance associated with excavation, we recommend locating paired remeasurement pits at least 3 m distant from previous sample points. Ideally, the locations of future pits would be marked in advance and the locations protected from disturbance (e.g., Huntington et al., 1988). It is not clear whether pairing pits improves statistical power; at Hubbard Brook W5, mineral soil mass was poorly predicted in 1986, 1991, and 1998 by the soil mass of the paired pretreatment pit 3 to 6 m away (R^2 = 0.03–0.16).

Choosing an approach to soil sampling depends on the questions being asked and the resources available. Quantitative soil pits accurately quantify soil mass and provide samples representative of relatively large volumes of soil. Many C budgeting applications demand both precision, for statistically significant change detection, as well as accuracy, for scaling up changes on a per-area basis. Where there is large variance in horizon thickness or other soil properties at scales larger than the pit area, pits likely yield less precise estimates of nutrient stocks than an equivalent (or smaller) effort devoted to coring. Future sampling efforts should be designed with consideration of the relative importance of accuracy vs. precision, shallow vs. deep soils, and cumulative site disturbance.

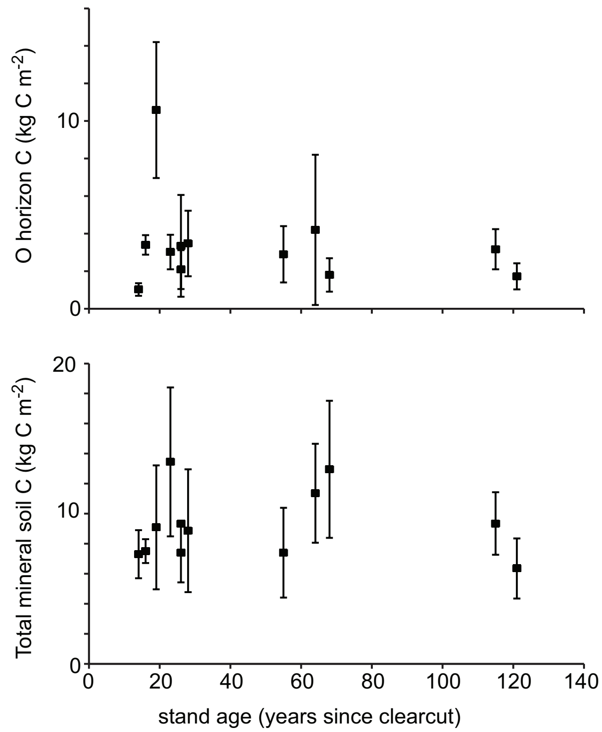

Fig. 4. Total carbon by horizon across plotted against time since harvest at 12 forested sites using quantitative soil pits dug in 2003–2004. Sites B1 and BW, with more complicated land-use history, are not included. Error bars show 1SD.

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