

Total Soil Nitrogen in the Coarse Fraction and at Depth

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ABSTRACT

Historically, studies estimating total soil N are based almost exclusively on the ≤ 2 -mm soil particles (fine soil fraction), and generally have not included that portion of soil > 2 -mm (coarse soil fraction) or soil > 1 -m depth. This study examined the underestimation of the total soil N pool by following traditional or standard soil sampling and analysis. Seventeen varied soil series plus one soil classified to the level of Great Group were sampled from Alaska, Oregon, Puerto Rico, and Washington. Total soil N in each profile was quantified for the soil fine and coarse fractions, as well as for soil depths > 1 m. In soils with a coarse fraction, the average percentage of total soil N contained in the coarse soil fraction ranged from 0.3 to 37%, increasing with an increase in coarse soil mass (the highest percentage of N for an individual profile was 67% in a Cryorthent with 92% coarse fragments). For soils with depths > 1 m, the percentage of soil N below 1 m relative to the whole profile ranged from 7 to 35%. An average of 0.03% N concentration in the coarse soil fraction was found for all major genetic mineral horizons. Results of this study indicated that up to one-half of the total soil N of a profile would have been missed by the combined exclusion of the coarse fraction and soil below 1-m depth from analysis. The coarse soil fraction may reflect storage and/or potential sources of N not considered in traditional soil N budgets.

NITROGEN CYCLING has been studied using in-depth examinations of sources, sinks, excesses, and deficiencies (Motavalli et al., 1995; Marion et al., 1981; Huntington et al., 1988; Amelung et al., 1998; Schimel and Firestone, 1985; Hackl et al., 2000; Perry et al., 1987; Dodd et al., 2000; Frank et al., 1995; Hart and Sollins, 1998; Ledgard et al., 1998). Historically, however, studies estimating total soil N have focused almost exclusively on the ≤ 2 -mm soil particles and not included the > 2 -mm soil fraction. In this paper, soil ≤ 2 mm will be referred to as the "fine soil fraction" (including sand, silt, and clay), with soil > 2 mm (including gravel, cobbles, and stones) referred to as the "coarse soil fraction." Ugolini et al. (1996) suggested that agricultural soils, which are often free of rock fragments, have received a large amount of attention, and as a result, techniques for soil analysis have been based on the fine soil fraction. While the coarse soil fraction has been evaluated more recently for its physical properties, traditionally it has been considered chemically inert and, therefore, has been discarded after initial sieving (Ugolini et al., 1996; Corti et al., 1998).

There are few researchers who have gone beyond traditional fine soil analysis to explore the potential

chemical properties of soil coarse fractions (Ugolini et al., 1996; Corti et al., 1998). In the Vallombrosa Forest near Florence, Italy, Ugolini et al. (1996) studied the mineralogical, physical, and chemical properties of both the fine and coarse soil fractions of three soil profiles, all within the Inceptisol order. Following separation of the fine and coarse soil fractions through wet and dry sieving, the authors found that the coarse soil fraction averaged 20 to 29% of the total soil profile mass and increased with depth (up to 56% in lower soil horizons). Separating the coarse fraction into slightly, medially and highly altered degrees of weathering, they found that with greater weathering there was generally an increase in porosity of the coarse fraction. It is believed that these rock voids allow the infiltration of the soil solution and result in enrichment in such nutrients as C and N. In two of the profiles with rock fragments of higher porosity, total N was actually found to be higher in the coarse fraction than the fine soil fraction. Similar findings were reported in a study by Corti et al. (1998), which included two of the profiles that Ugolini et al. (1996) described above, as well as an additional profile from Italy (Inceptisol), one from France (Inceptisol), and one from Sweden (Spodosol). Both studies suggest that excluding the soil coarse fraction from analysis can result in underestimating total soil N.

Another common practice in soil sampling is to limit soil sampling depth. Many studies report C and/or N quantities to depths < 1 m (Cole et al., 1968; Marion et al., 1981; Lamb et al., 1985; Schimel and Firestone, 1985; Perry et al., 1987; Amelung et al., 1998; Hart and Sollins, 1998; Huntington et al., 1988; Motavalli et al., 1995; Hackl et al., 2000; Prichard et al., 2000); few have carried sampling to depths > 1 m (Stone et al., 1993; Frank et al., 1995; Ugolini et al., 1996; Corti et al., 1998; Dodd et al., 2000), and with the exception of Ugolini et al. (1996), these studies have included only the fine soil fraction. Sampling performed to depths > 1 m increase total nutrient pools. For example, in a study of a northern Great Plains grassland Mollisol, total N for the soil fine fraction of the 0- to 30-cm depth was approximately 76 Mg ha⁻¹ (Frank et al., 1995). The same soil profile sampled to 1.07 m resulted in a total N pool of 144 Mg ha⁻¹, which is almost twice the total N in to the 0- to 30-cm depth. It is suggested then, that further underestimation of soil N pools may occur when soil sampling is limited to a depth < 1 m when the actual total soil depth is deeper, as well as when the coarse soil fraction is not analyzed.

When considering the global land area occupied by

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Abbreviations: CSM, coarse soil mass; CSN_{tot}, coarse soil total nitrogen; D_b, bulk density; Fr, percentage of coarse or fine fraction by weight; FSM, fine soil mass; FSN_{tot}, fine soil total nitrogen; H, horizon thickness; N_{con}, total nitrogen concentration; N_{tot}, total nitrogen.

soils containing a substantial coarse fraction and extending to a depth >1 m, the question arises as to what degree the soil total N pool is underestimated by using traditional soil sampling methods and analysis. The objectives of this study are to both: (i) quantify total soil N in the soil coarse fraction and (ii) quantify soil total N in soil >1 m, over a variety of soil types.

MATERIALS AND METHODS

Soil Sampling and Analysis

Seventeen varied soil series, and one soil classified only to the level of Great Group (hereafter referred to as the Cryorthent), from Alaska, Oregon, Puerto Rico, and Washington were chosen for sampling. These soils provide a variety of textures, coarse material quantities, parent materials, climate, and vegetative cover (Table 1). Three representative locations for each series were determined using USDA-NRCS soil surveys, while geologic and topographical maps, climate, and vegetation information were used to locate three sampling sites for the Cryorthent (Fig. 1). Thus, a total of 54 soil profiles ($n = 3$ for each series) were sampled for this study, encompassing all 12 U.S. soil order classifications. The soils ranged from very fine material with no coarse fraction, such as the Sumas silt loam formed in recent alluvium, to soils with >50% coarse material, such as the Alderwood gravelly, ashy, sandy loam formed in glacial till. Climate ranges from tropical to boreal, and includes a variety of vegetation types, such as forest, grassland, shrub-steppe, and agriculture.

Soil samples were collected in the field for chemical and physical analyses. At each location, soils pits were dug by hand and sampled by major genetic horizons to the C horizon, or to the lowest possible sampling point up to a depth of

2 m (flooding, cementation, and frozen soil prevented deep sampling in some profiles). Horizons were identified and recorded, along with horizon range and thickness, and profile depth. Photos were also taken of each site and soil profile. A representative volumetric sample of each horizon (up 3000 cm³ depending on horizon depth and size of the coarse fraction) was removed in the field to determine relative quantity of fine and coarse soil fractions. Bulk density (D_b) samples were also collected using one of three methods: a soil corer of a known volume, water displacement, or wax coating of soil clods. Water displacement or wax coating of clods was used for horizons containing coarse material, cemented horizons, and the organic horizons of the Seattle. All samples were sealed in plastic bags and kept on ice until returning to the lab where they were refrigerated at 3°C until processing.

The volumetric mineral soil samples were air-dried and separated into coarse and fine soil fractions using hand sieving with a 2-mm sieve and ensuring that all aggregates were broken. Any obvious roots remaining in the sieve were removed and discarded. All fractions were weighed to determine mass and percentage of coarse and fine material of each horizon. Subsamples of the fine fraction were ground for total C and N analysis. Coarse fraction subsamples were passed through a rock grinder (broken, first, with a sledgehammer if too large for the grinder) then finely ground with a mortar and pestle. Total C and N analysis was performed using a PerkinElmer 2400 CHN analyzer (PerkinElmer Corp., Norwalk, CT). Bulk density samples were dried to a constant weight at 105°C for a minimum of 48 h and weighed. Organic horizons were air-dried and, with the exception of the Seattle, were not separated into coarse and fine fractions. These samples were then ground to <0.5 mm using a Wiley mill and analyzed for total C and N as stated above for mineral samples. All data were corrected for moisture content and are reported on an oven-dried basis.

Table 1. Soil classification, type of vegetation, percentage of coarse soil material, and type of parent material for 18 soil series in Alaska, Oregon, Puerto Rico, and Washington.

Soil series	Classification	Vegetation	Coarse fraction	Parent material
Cryorthent†		mountain hemlock, vine maple, ocean spray, vaccinium, phlox, heather	50–75	granite
Reilly	Mollic Udifluent	bamboo, pasture grasses, sugarcane	25–50	sediments of gravel and sand
Sumas	Aquandic Fluvaquent	cabbage, strawberries, corn	0	mixed recent alluvium
Alderwood	Vitrandic Dystrocrept	Douglas-fir, cedar, red alder, sword fern, salal, Oregon grape	50–75	glacial till
Kerby	Typic Haploxerept	Oregon white oak, California black oak, Pacific madrone, Ponderosa pine, poison oak	25–50	alluvium from mixed origin
Jonas	Typic Hapludand	Douglas-fir, western hemlock, salal, Oregon grape, Oregon oxalis, swordfern	25–50	residuum/colluvium from andesite, an admixture of volcanic ash and pumice
Chinkmin	Andic Duricryod	mountain hemlock, Pacific silver fir, Douglas-fir	50–75	andesite, granodiorite, metasediments, metavolcanics
Bashaw	Xeric Endoaquert	wheat	<5	alluvium from igneous rock
Ephrata	Xeric Haplocambid	beets, corn	25–50	glacial outwash mixed with loess
Sagehill	Xeric Haplocalcid	juniper spp., sagebrush spp., bluebunch wheatgrass	<5	lacustrine deposits with a mantle of loess or eolian deposits
Athena	Pachic Haploxeroll	winter wheat, spring barley	0	loess mixed with volcanic ash
Dinkelmann	Vitrandic Haploxeroll	Ponderosa pine, Douglas-fir, pinegrass, serviceberry, snowberry	25–50	granite with some volcanic influence
Lickskillet	Lithic Haploxeroll	sagebrush spp., yarrow, bluebunch wheatgrass	25–50	colluvium mixed with loess, rock weathered from basalt or rhyolite
Langellain	Ultic Haploxeralf	Oregon white oak, grasses, common snowberry, rose spp.	5–15	colluvium/alluvium from sedimentary rock
Olympic	Xeric Palehumult	Douglas-fir, western hemlock, red alder, vine maple, salal, sword fern, red huckleberry	<5	weathered igneous rock
Bayamon	Typic Hapludox	grasses, pineapple	<5	sediments of mixed origin
Tanana	Typic Aquiturbel	paper birch, black spruce, aspen, willow spp.	0	alluvial sediments
Seattle	Hemic Haplosaprist	reed canary grass, western red cedar, red alder, sedge, rush, spirea, fern	<5	organic material

† Cryorthent is a Great Group and not an official soil series name.

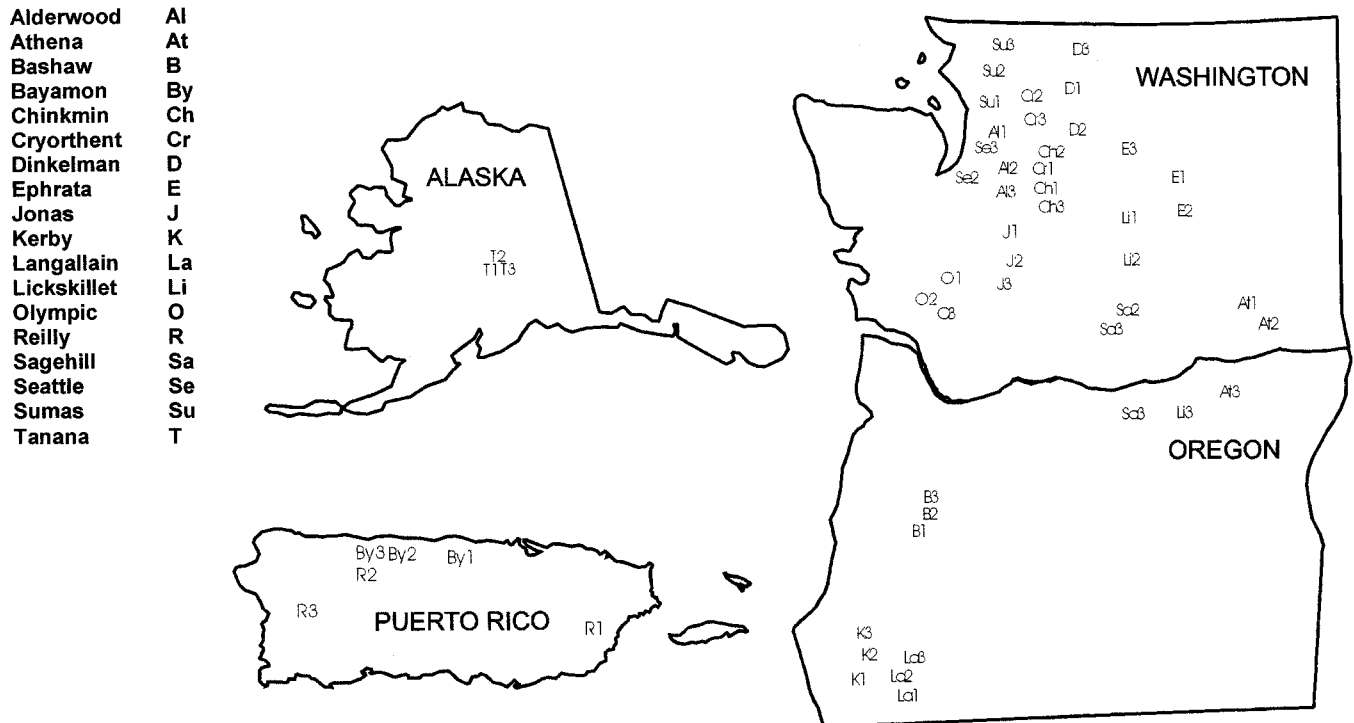


Fig. 1. Locations of 18 soil series sampled throughout Alaska, Oregon, Puerto Rico, and Washington. Each series included three representative profiles for a total of 54 profiles ($n = 3$ for each series). Series name and profile number are represented by a letter and number designation. For example, the first Athena series profile is labeled At1, the second profile is labeled At2, etc. Map units for each series are listed at the top left. Maps not drawn to scale.

The quantity of total N (N_{tot}) in each horizon for the coarse fraction and the fine fraction was calculated from horizon thickness (H), D_b , percentage of coarse fraction or percentage of fine fraction (Fr), and N_{tot} concentration for the coarse or fine fraction (N_{con}); particle densities of the coarse and fine soil were assumed to be equal:

$$N_{\text{tot}} = HD_b Fr N_{\text{con}} \quad [1]$$

Quantities were then summed according to major horizon designations (i.e., Bs1, Bs2, and BC would be summed as B) for the entire profile and for the portion of the profile below 1 m. When calculating N_{tot} below 1 m, N_{tot} in horizons found at depths both above and below 1 m (e.g., a Bt1 at a depth of 0.8–1.2 m) were calculated using the proportion of horizon depth below 1 m, and that value was summed with the N_{tot} of any additional horizons below 1 m. Percentage of coarse soil N_{tot} (%CSN_{tot}) and percentage of coarse soil mass (%CSM) were calculated for major horizon designations and the entire profile:

$$\% \text{CSN}_{\text{tot}} = [\text{CSN}_{\text{tot}} / (\text{CSN}_{\text{tot}} + \text{FSN}_{\text{tot}})] 100 \quad [2]$$

$$\% \text{CSM} = [\text{CSM} / (\text{CSM} + \text{FSM})] 100 \quad [3]$$

where CSN_{tot} represents coarse soil N_{tot} , FSN_{tot} is fine soil N_{tot} (Mg ha^{-1}), CSM is coarse soil mass (Mg ha^{-1}), and FSM is fine soil mass (Mg ha^{-1}). Percentage of CSN_{tot} and %CSM were each tested for significance from zero ($P = 0.05$) using the statistical package SPSS (2000) and comparing means with a one-tailed t test.

RESULTS AND DISCUSSION

Total Nitrogen and Depth of Profile

With the exception of the Histosol, whole-profile N_{tot} ranged from 5.3 Mg ha^{-1} in the Tanana series to 29 and

30 Mg ha^{-1} in the Sumas and Athena series, respectively (Fig. 2). The Sumas profiles developed in recent alluvial deposits, and both the Sumas and Athena were under cultivation with histories of N fertilization, which probably contributes to the total N in these soils. For individual horizons, both the Sumas and the Athena contained the largest quantities of A-horizon N_{tot} , with 20 and 21 Mg ha^{-1} , respectively, constituting approximately 70% of the total profile N. Again, alluvial deposition, cultivation, and N fertilization histories might be factors in the more N-rich A horizons of these soils. Additionally, the Athena is a Mollisol, a soil characterized by humus-rich surface mineral horizons, thus higher N_{tot} in an A horizon would be expected.

Greater than 50% of the whole-profile N_{tot} for mineral soil orders was found in the B-horizons of nine soil series. Percentages of N_{tot} in the B horizons of these profiles ranged from 54% in the Bashaw to 75% in the Bayamon. Both of these series consisted of only A and B horizons, and the Tanana series consisted of O and B horizons, thereby explaining the large percentage of N_{tot} in the B horizon of these soils. C-horizon N_{tot} was highest in the Sumas (9.1 Mg ha^{-1}) and the Reilly (5.0 Mg ha^{-1}), both of which developed in alluvial deposits. The high quantity of N_{tot} in the C horizons of these soils may be the result of flood deposition incorporating organic matter (OM) with alluvium. The Seattle (Histosol) profile N_{tot} was 38 Mg ha^{-1} , 22 to 86% greater than those series with mineral horizons, showing the potential N storage of an all-OM soil.

Spodosols sampled by Huntington et al. (1988) at the Hubbard Brook Experimental Forest in New Hamp-

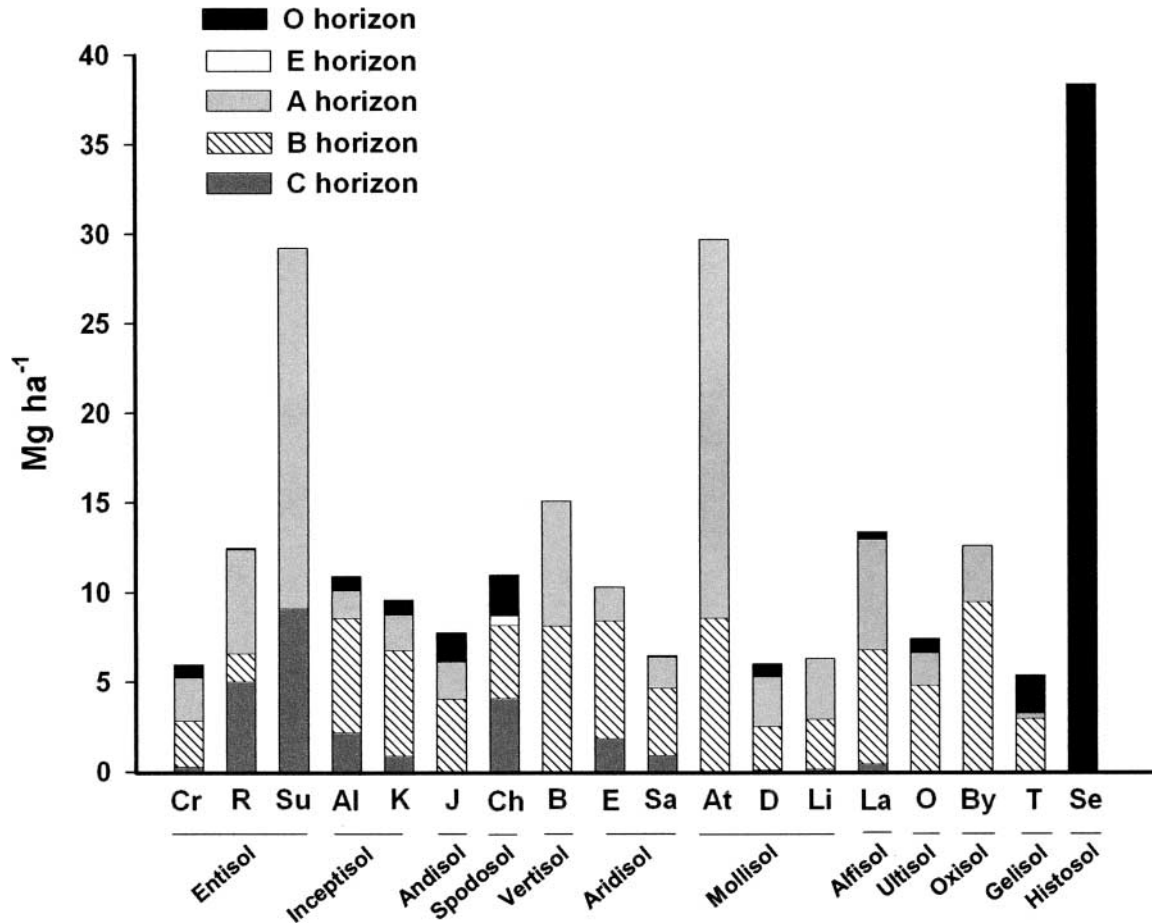


Fig. 2. Average soil total N (Mg ha^{-1}), by soil series, by horizon, and summed for whole profiles.

shire contained $5.9 \text{ Mg ha}^{-1} N_{\text{tot}}$ in the fine soil fraction sampled to the base of the B horizon. Our Chinkmin series, within the order Spodosol, averaged $3.6 \text{ Mg ha}^{-1} N_{\text{tot}}$ in the fine fraction and $1 \text{ Mg ha}^{-1} N_{\text{tot}}$ in the coarse fraction when calculating N_{tot} to the base of the B-horizon, totaling 4.6 Mg ha^{-1} . The smaller quantity of N_{tot} found in our study relative to that of Hubbard Brook might have been due to sampling depth, which averaged 48 cm to the base of the B horizon in the Chinkmin compared with 54 cm at Hubbard Brook. Variations in horizon depths and environmental factors also likely affected total N storage. When soil N_{tot} was extrapolated to 54 cm for the Chinkmin, the result was 5 Mg ha^{-1} when both fine soil and coarse soil fractions were totaled. The Hubbard Brook sites were under deciduous and mixed forests, which might have been influenced by OM to a greater degree than the coniferous forest of this study. However, there was often great variability among the replicate profiles of each soil series reported in this paper, therefore, differences found between the Hubbard Brook Spodosol and the Chinkmin of this study are not surprising.

The average sampling depth was $>1 \text{ m}$ for 13 of the 18 soil series, and the greatest average sampling depth was reached in the Sagehill Series (1.7 m, Fig. 3). Average A-horizon thickness was greatest for the Athena (110 cm), of the order Mollisol. Thirteen of the 18 soil

series had $>50\%$ of their profile depths in the B horizons, ranging from 51% in the Licksillet to 92% in the Tanana. Nine of the 13 series with the greatest percentages of B-horizon thickness were also those series having the greatest percentage of N_{tot} in the B horizon. The C horizons were thickest for the Sumas and the Reilly. Orders with the thickest A, B, and C horizons also had the largest quantities and percentages of N_{tot} for those same A, B, and C horizons. Horizon thickness is used to calculate soil N_{tot} (1), therefore thicker horizons would result in larger calculations of N_{tot} . Of the mineral soil profiles with O horizons present, O-horizon thickness was greatest in the Tanana, which is located in central Alaska where temperatures can inhibit decomposers. The Seattle profiles had an average depth of 1.3 m, with Oi, Oe, and Oa horizon thickness averaging 31, 47, and 50 cm, respectively. Despite mapped surveys estimating depths of 6.1 to 15 m for the Seattle profile locations (Rigg, 1958), greater sampling depths during our study were not possible due to shallow water tables.

In soils deeper than 1 m, total N below 1-m ranged from 0.48 Mg ha^{-1} in the Jonas to 10.2 Mg ha^{-1} in the Athena (Fig. 3). It is interesting to note that although the Jonas was lowest in N_{tot} below 1-m depth, both the Kerby and the Langellain were sampled to an equal or shallower depth (120 and 102 cm, respectively) than the Jonas (120 cm), yet contained more N_{tot} below 1-m depth

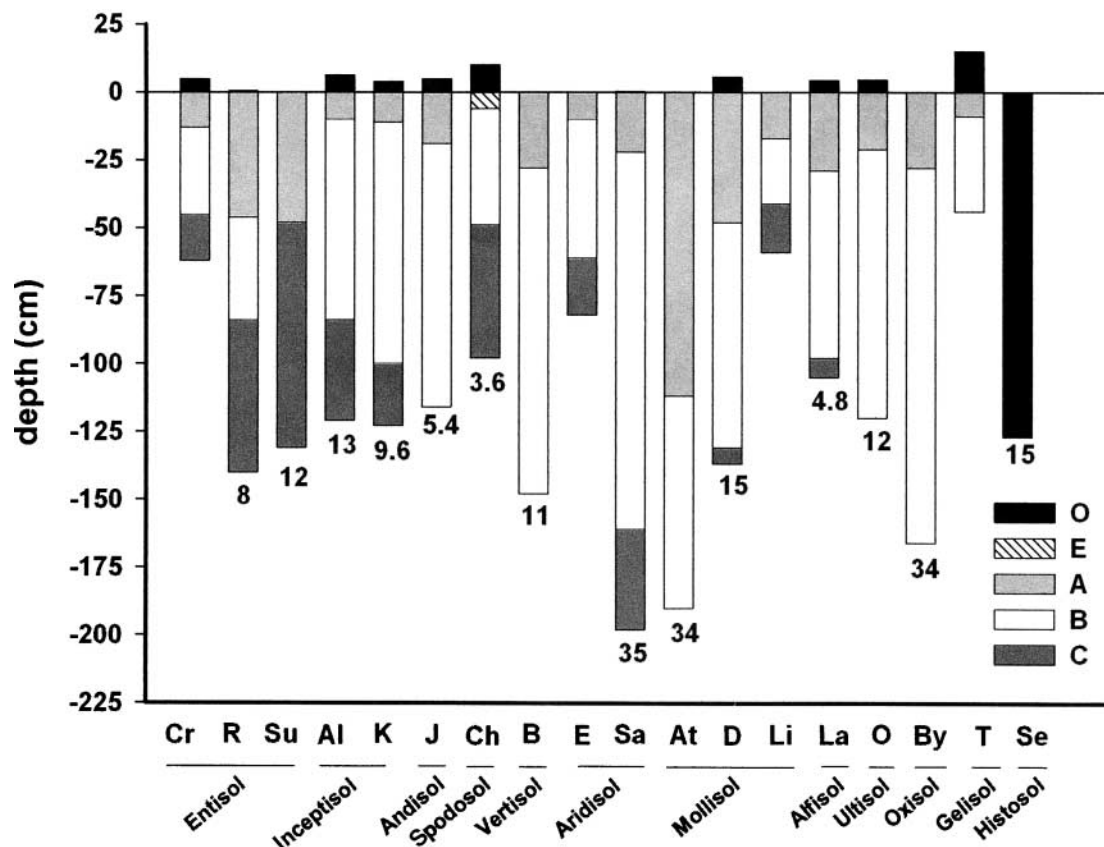


Fig. 3. Average soil profile depth and horizon thickness sampled for 18 soil series. Thirteen of the 18 series were sampled to a depth >1 m. Percentage of total N found below 1-m depth is shown below each bar.

with 1.1 Mg ha^{-1} . Of those orders with mineral soil horizons, the percentages of whole-profile N_{tot} deeper than 1 m ranged from 5.4% found in the Jonas to 35% in the Sagehill, and all were significantly greater than zero at the 0.05 confidence level. Thus of the soils sampled, up to one-third of the soil N_{tot} would have been missed in this study by sampling to 1 m only, and reports of total soil N in studies that limit sampling to ≤ 50 cm could be missing more than half of the total soil N (see Fig. 3). Similar results were found by Stone et al. (1993) who reported an overall average of 40% of total N below 1 m in Florida Spodosols. Dodd et al. (2000) also found approximately 25% of total soil N below 1 m in a Colorado Aridisol.

Fine and Coarse Soil Fractions

Fine soil N_{tot} was greater than coarse soil N_{tot} in all soil series (Fig. 4a). The Sumas and the Athena had the highest quantity of N_{tot} among the mineral soils, averaging 29 and 30 Mg ha^{-1} , respectively, while the Tanana was lowest with 5.3 Mg ha^{-1} . Each of these three soil series consisted solely of a fine soil fraction.

Total coarse soil N in soil series with mineral coarse soil fractions ranged from 0.02 Mg ha^{-1} in the Sagehill to 3.2 Mg ha^{-1} in the Alderwood. The Seattle, a Histosol, averaged 33 Mg ha^{-1} N_{tot} for the fine fraction, and 5 Mg ha^{-1} N_{tot} for the coarse fraction. As Histosols are characterized by their high organic matter content, it was not surprising that the quantity of N_{tot} in the Seattle was

similar to that found in the fine soil fraction of the Sumas and Athena, and of a greater quantity in the coarse soil fraction (woody material >2 mm) than any other soil series. All other soil orders where multiple series were sampled showed variability in the quantity of N_{tot} found in the coarse fraction.

Total soil mass of orders with mineral horizons ranged from 4500 Mg ha^{-1} in the Tanana to 31000 Mg ha^{-1} in the Athena, which represent the shallowest and one of the deepest soils sampled (Fig. 4b). Fine soil mass was greater than CSM in all soil series that contained a coarse soil fraction, with the exception of the Cryorthent, Alderwood, Chinkmin, and Licksillet. The Alderwood series had the greatest average CSM, containing 12000 Mg ha^{-1} , while the lowest CSM was found in the Sagehill series with 110 Mg ha^{-1} . Because of its low bulk density, the Seattle, though highest in soil N_{tot} , was lowest of all soil series in total mass.

Percentage of CSN_{tot} was lower than percentage of CSM of each soil series containing a coarse soil fraction, ranging from 0.3 to 37% of the total soil profile for mineral soils with coarse fragments (Fig. 5). The percentage of CSN_{tot} for all soil types examined was significantly different from zero ($p = 05$) suggesting that excluding the coarse fraction from soil analysis would omit a significant quantity of soil N_{tot} .

The Alderwood contained the greatest quantity of CSN_{tot} and CSM, and had the highest percentages of CSN_{tot} and CSM of any soil series. In contrast, the Sage-

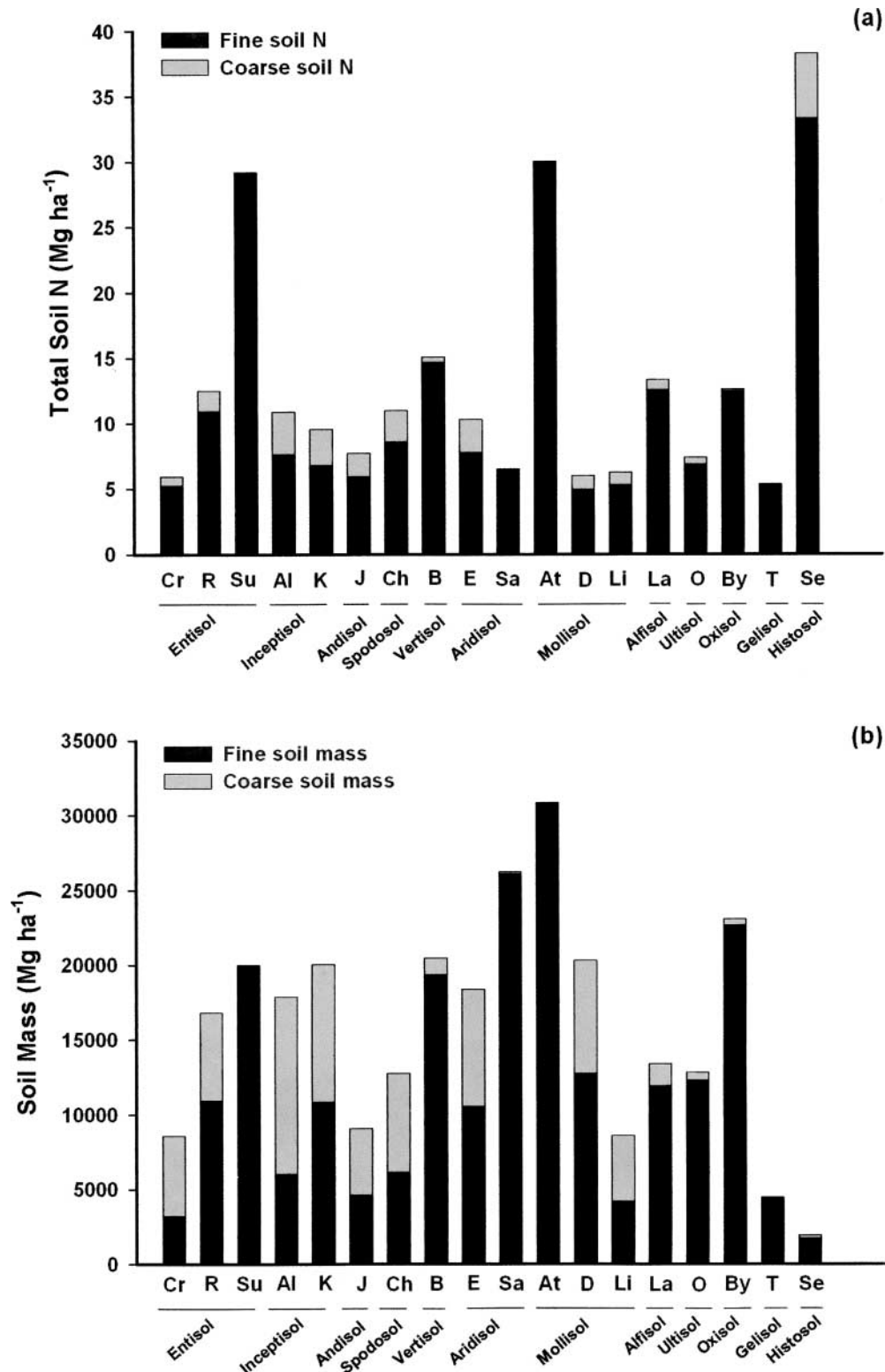


Fig. 4. (a) Total soil N (Mg ha^{-1}) by quantity contained in the fine and coarse soil fractions with O horizon N included with the fine soil; (b) Soil mass (Mg ha^{-1}) of fine and coarse soil fractions with mass of O horizons included with the fine soil.

hill contained the smallest quantity of CSN_{tot} and CSM, and was the lowest in percentage of CSN_{tot} . The average percentages of CSN_{tot} for the Alderwood and Kerby series, both Inceptisols, were somewhat higher than total N found in three Inceptisols of Tuscany, Italy, which

were reported to contain an average of 23, 14, and 21% N_{tot} for washed rock fragments throughout three profiles (Ugolini et al., 1996). Of the soils included in this study that had a coarse fraction, on average one-fifth of N_{tot} and one-third of the soil total mass would have been

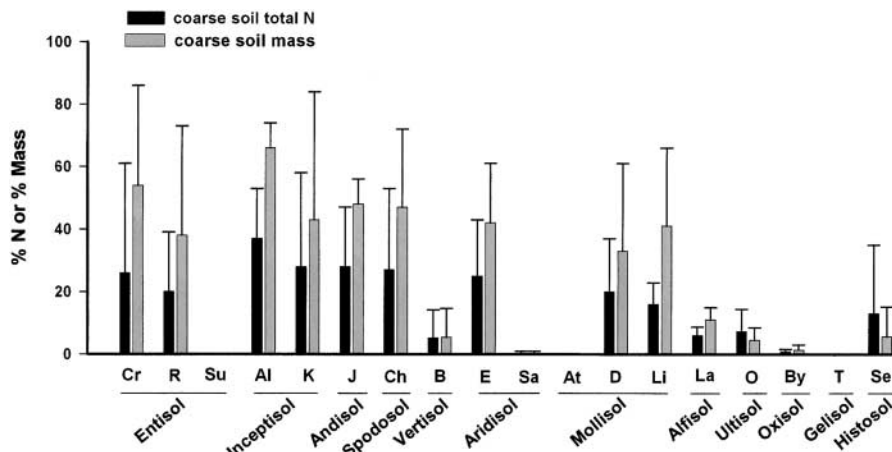


Fig. 5. Average percentage of total coarse mineral soil N compared with mineral soil mass of the coarse fraction (O horizons are not included with the exception of the Histosol) ($n = 3$). Standard deviations are indicated by error bars.

excluded from analysis if standard soil sieving procedure had been used.

A comparison of CSN_{tot} with percentage of CSM for all soils by profile suggested that N concentration (N_{con}) might change depending on percentage of CSM. Therefore, three categories of percentage of CSM were created: <10%, between 10 and 60%, and >60%. Coarse soil N_{tot} concentrations of master horizons within these categories were then averaged and standard deviations were calculated (see Table 2). Those horizons for each series without coarse soil fraction, and therefore without CSN_{tot} , were excluded. E horizons were also excluded due to the limited number of samples. Average FSN_{tot} is also shown in Table 2 for comparison. Concentrations of CSN_{tot} across all percentage CSM categories approached 0.3 g kg^{-1} for each horizon. A horizons had the highest average concentration of CSN_{tot} for percentage of CSM <60%, undoubtedly due to the high organic matter content of the surface horizons. The reason for a low N concentration of A horizons in the >60% CSM category was unclear. One factor may have been the limited number of soils with this percentage of coarse soil material ($n = 3$), which was also the case for those C horizons in the <10% CSM category ($n = 1$). It is possible that extent of pedogenic development, physical, chemical, and/or biological processes also influenced A horizon results.

B and C horizons were similar despite the variety of subordinate designations (i.e., Bt, Bk, Cg, Ck) found

within those horizons and despite changes in the percentage of CSM (Table 2). B horizons contained the largest concentration of CSN_{tot} for CSM > 60%, though the reasons for this are not obvious. One possible answer may have been found in the study by Ugolini et al. (1996), where the authors investigated mineralogical, chemical, and physical properties of the soil coarse fraction. They found that for two of the three soil profiles sampled in the study, total porosity of the rock fragments exceeded 50% of that in the fine soil, and in one of these profiles porosity of the rocks actually reached that of the fine soil in the deepest horizon sampled (BCb2). The authors suggested that the porosity (which changes according to lithology and degree of weathering) of these rocks allowed for the collection of N-bearing organics, and may ultimately have resulted in a coarse fraction with the same or higher N_{tot} than the surrounding fine earth, which was the case for two of their profiles. It is possible that N-bearing organics moving in solution through the soil profiles in our study may have been intercepted within the weathered voids of the B-horizon coarse soil fraction before reaching the C horizon. This, combined with a large percentage of CSM (>60%), could explain the higher concentration of CSN_{tot} in some B horizon. Nevertheless, variability of N_{con} in the coarse fraction of the B and C horizons was much less than that of the A horizon.

CONCLUSIONS

The common practice of excluding the coarse soil fraction and soil below 1-m depth from analysis is challenged by the data presented in this study. Where rocks and deep soils were present, the percentage of total soil N contained in the coarse soil fraction (0.3–37%) as well as in soil >1-m depth (7–34%) was significantly different from zero ($P = 0.05$). The percentage of total N found in the coarse soil fraction increased with an increase in coarse soil mass. Up to one-half of the total soil N in a profile would have been unmeasured by the combined exclusion of the coarse fraction and soil below 1 m from analysis. An average concentration of 0.3 g kg^{-1} of total N in the coarse soil fraction was estimated

Table 2. Average total soil N concentrations and standard deviations by horizon and separated by percentage of coarse soil material found in the total soil mass along with combined average total soil N for all mineral horizons with a coarse fraction. Average N concentration of the fine soil fraction is given for comparison. No C horizon with <10% coarse soil mass was sampled.

Horizon	Fine soil fraction	Coarse soil mass, %			Average
		<10	10–60	>60	
O	17.4 ± 7.4	–	–	–	–
A	1.7 ± 1.1	$.37 \pm .10$	$.40 \pm .20$	$.19 \pm .12$	$.33 \pm .11$
B	$.88 \pm .81$	$.28 \pm .13$	$.27 \pm .13$	$.30 \pm .17$	$.28 \pm .02$
C	$.53 \pm .35$	–	$.29 \pm .16$	$.24 \pm .10$	$.27 \pm .04$
A, B, C	–	$.25 \pm .14$	$.32 \pm .07$	$.24 \pm .06$	$.27 \pm .04$

for all major genetic mineral horizons, with less variability in the B and C horizon than in A horizons.

These results indicate that to obtain a true value of total soil N, the entire soil must be sampled, including the coarse soil fraction and soil below 1 m. This accurate appraisal of total soil N is important as it may reflect enhanced storage and/or a potential source of available N not generally accounted for in soil N research.

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REFERENCES

- Amelung, W., W. Zech, X. Zhang, R.F. Follett, H. Tiessen, E. Knox, and K.-W. Flach. 1998. Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. *Soil Sci. Soc. Am. J.* 62: 172–181.
- Cole, D.W., S.P. Gessel, and S.F. Dice. 1968. Distribution and cycling of nitrogen, phosphorous, potassium and calcium in a second-growth Douglas-fir ecosystem. p. 197–233. *In* H.E. Young (ed.) Primary productivity and mineral cycling in natural ecosystems. University of Maine Press, Orono.
- Corti, G., F.C. Ugolini, and A. Agnelli. 1998. Classing the soil skeleton (greater than two millimeters): Proposed approach and procedure. *Soil Sci. Soc. Am. J.* 62:1620–1629.
- Dodd, M.B., W.K. Lauenroth, and I.C. Burke. 2000. Nitrogen availability through a coarse-textured soil profile in the shortgrass steppe. *Soil Sci. Soc. Am. J.* 64:391–398.
- Frank, A.B., D.L. Tanaka, L. Hofmann, and R.F. Follett. 1995. Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing. *J. Range Manage.* 48:470–474.
- Hackl, E., S. Zechmeister-Boltenstern, and E. Kandeler. 2000. Nitrogen dynamics in different types of pasture in the Austrian Alps. *Biol. Fertil. Soils* 32:321–327.
- Hart, S.C., and P. Sollins. 1998. Soil carbon and nitrogen pools and processes in an old-growth conifer forest 13 years after trenching. *Can. J. For. Res.* 28:1261–1265.
- Huntington, T.G., D.F. Ryan, and S.P. Hamburg. 1988. Estimating soil nitrogen and carbon pools in a northern hardwood forest ecosystem. *Soil Sci. Soc. Am. J.* 52:1162–1167.
- Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Wheat fallow tillage systems' effect on a newly cultivated grassland soils' nitrogen budget. *Soil Sci. Soc. Am. J.* 49:352–356.
- Ledgard, S.F., S.C. Jarvis and D.J. Hatch 1998. Short-term nitrogen fluxes in grassland soils under different long-term nitrogen management regimes. *Soil Biol. Biochem.* 30:1233–1241.
- Marion, G.M., J. Kummerow, and P.C. Miller. 1981. Predicting nitrogen mineralization in chaparral soils. *Soil Sci. Soc. Am. J.* 45:956–961.
- Motavalli, P.P., C.A. Palm, E.T. Elliott, S.D. Frey, and P.C. Smithson. 1995. Nitrogen mineralization in humid tropical forest soils: Mineralogy, texture and measured nitrogen fractions. *Soil Sci. Soc. Am. J.* 59:1168–1175.
- Perry, D.A., C. Choquette, and P. Schroeder. 1987. Nitrogen dynamics in conifer-dominated forests with and without hardwoods. *Can. J. For. Res.* 17:1434–1441.
- Prichard, S.J., D.L. Peterson, and R.D. Hammer. 2000. Carbon distribution in subalpine forests and meadows of the Olympic Mountains, Washington. *Soil Sci. Soc. Am. J.* 64:1834–1845.
- Rigg, G.B. 1958. Peat resources of Washington. State of Washington Dep. of Conserv., State Printing Plant, Olympia.
- Schimel, J.P., and M.K. Firestone. 1989. Nitrogen incorporation and flow through a coniferous forest soil profile. *Soil Sci. Soc. Am. J.* 53:779–784.
- SPSS. 2000. SPSS Version 10.1 [computer software]. SPSS, Inc., Chicago, IL.
- Stone, E.L., W.G. Harris, R.B. Brown, and R.J. Kuehl. 1993. Carbon storage in Florida Spodosols. *Soil Sci. Soc. Am. J.* 57:179–182.
- Ugolini, F.C., G. Corti, A. Agnelli, and F. Piccardi. 1996. Mineralogical, physical and chemical properties of rock fragments in soil. *Soil Sci.* 161:521–542.