Total Soil Carbon in the Coarse Fraction and at Depth

Darlene Zabowski, Nicol Whitney, Janita Gurung, and Jeffrey Hatten

Abstract: Historically, most studies estimating soil carbon have been based almost exclusively on ≤2-mm soil particles (fine soil fraction) and generally excluded soil >2-mm (coarse soil fraction) or soil at >1-m depth. In fact, many studies have not examined soil carbon below 20 cm. This study was conducted to determine how much total soil C is underestimated by following traditional, or standard, soil sampling and analysis for both particle size fractions and depth. Seventeen soil series and one soil classified to the level of Great Group, were sampled in Alaska, Oregon, Puerto Rico, and Washington. Total soil C was quantified for the soil fine and coarse fractions, as well as for soil >1-m deep. Results of this study showed substantial soil C contained in the coarse soil fraction (<1–25%) and in soil greater than 1-m depth (3–48%). The combined exclusion of the coarse fraction and soil below 1 m could miss as much as one-half of the soil total C of a profile. These results indicate that to obtain a true value of soil total carbon, the entire soil must be sampled, including the coarse soil fraction and soil below 1 m. FOR. SCI. 57(1):11–18.

Keywords: deep carbon, carbon pools, soil carbon concentrations, missing carbon

Soil contains approximately 2,344 Pg of global C and is the second largest actively cycled pool of C on the earth (Hedges and Oades 1997, Jobbagy and Jackson 2000). Of terrestrial pools, soil is the largest active C pool (Post et al. 1990). Historically, studies estimating soil C have been based almost exclusively on the fine (<2 mm) soil fraction and have not included the coarse (>2 mm) fraction. Whitney and Zabowski (2004) found that up to 37% of total soil N was in the coarse soil fraction with the highest concentration often found in forest soils. In addition to excluding the coarse soil fraction, another common practice in soil sampling is to limit sampling depth. These practices may result in a large component of soil carbon being missed, causing soil carbon stocks to be underestimated and potential treatment changes to remain undetected.

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. Whereas 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). Furthermore, the coarse fraction has often been considered to reduce the content of soil C. In fact, a widely cited work by Jobbagy and Jackson (2000) does not consider the >2 mm size fraction. Neglecting the contribution of coarse fragments to the soil C pool could exclude much of the total soil C pool, resulting in a failure to correctly account for important soil carbon fluxes affecting global carbon cycling (Ugolini et al. 1996, Corti et al. 1998, 2002). Homann et al. (2004) found up to 20% of soil carbon in the >2-mm fraction in some forest soils of the Pacific Northwest.

Many studies also limit soil sampling depth to the rooting zone, usually defined as the upper 20–30 cm or shallower. For example, O’Neill et al. (2005) suggested a sampling depth of 20 cm for long-term forest soil inventory analysis. Most studies have reported C quantities to depths less than 1 m (e.g., Huntington et al. 1988, Amelung et al. 1998, Hart and Sollins 1998, Prichard et al. 2000) or calculated carbon content to 1 m (Kern 1994). Few have carried sampling to greater than 1 m (Stone et al. 1993, Frank et al. 1995, Ugolini et al. 1996, Corti et al. 1998, Harrison et al. 2003); with the exception of Ugolini et al. (1996) and Harrison et al. (2003), these studies have included only the fine soil fraction. Although they did not include the coarse fraction, Jobbagy and Jackson (2000) calculated that 56% of the global soil organic C pool is below a 1-m soil depth. Trumbore et al. (1995) found that up to 67% of an Amazon forest soil carbon is between 1- and 8-m soil depth. Stone et al. (1993) found approximately 40% of soil carbon below 1 m in a Florida Spodosol, with 50% below 1 m in Humods. Deep soils can be important stores of soil carbon, but it may be missed by our standard soil sampling and sample processing procedures.

Much of the global land area is occupied by soils containing a substantial coarse fraction and extending to a depth greater than 1 m. Yet measures of global C are largely based on estimates of soil C to 1-m depths or less that do not include the coarse fraction. To what degree is the soil total C pool underestimated by following typical or traditional soil sampling and analysis? The objectives of this study were to quantify soil total C in soil >1 m over a variety of soil types, quantify soil total C in the soil coarse fraction,
and determine whether significant underestimation of total soil C routinely occurs due to the exclusion of these materials.

**Materials and Methods**

Eighteen soil series and one soil classified to the level of Great Group (hereafter referred to as the Cryorthent) from Alaska, Oregon, Puerto Rico, and Washington were sampled, providing a variety of soil textures, coarse material quantities, parent materials, climate, and vegetative cover (Table 1). Three replicate locations were chosen for each series using US Department of Agriculture (USDA) Natural Resources Conservation Service soil surveys; geologic and topographical maps, climate data, and vegetation information were used to locate three sampling sites for the Cryorthent (Figure 1). Thus, a total of 57 soil profiles ($n = 3$ for each series) that encompass the 12 US soil order classifications were sampled. The soils ranged from very fine material with no coarse fraction, as was found in the Sumas silt loam formed in recent alluvium, to those with >50% coarse material, such as the Alderwood gravelly, ashy, sandy-loam formed in glacial till. Climates ranged from tropical to boreal and included a variety of vegetation types, such as forest, grassland, shrub-steppe, and agriculture.

At each location, soils were sampled by major genetic horizons to the C horizon, to the lowest horizon possible using hand tools, or to 2 m. Horizons were identified and recorded, along with horizon range and thickness and profile depth. A representative volumetric sample from each horizon (up to 3000 cm$^3$ depending on horizon depth and size of the coarse fraction) was also removed in the field to determine relative quantity of fine and coarse soil fractions. Bulk density ($D_b$) of each horizon was also determined 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

<table>
<thead>
<tr>
<th>Soil series</th>
<th>Classification</th>
<th>Vegetation</th>
<th>% Coarse fraction</th>
<th>Parent material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryorthent*</td>
<td>Mollic Udifluent</td>
<td>Bamboo, pasture grasses, sugar cane</td>
<td>8–96</td>
<td>Mixed alluvium</td>
</tr>
<tr>
<td>Reilly</td>
<td>Aquandic Fluvaquent</td>
<td>Cabbage, strawberries, corn</td>
<td>0</td>
<td>Mixed alluvium</td>
</tr>
<tr>
<td>Sumas</td>
<td>Vitrandic Dystroxerupt</td>
<td>Douglas-fir, cedar, red alder, sword fern, salal, Oregon grape</td>
<td>25–84</td>
<td>Glacial till</td>
</tr>
<tr>
<td>Kerby</td>
<td>Typic Haploxerupt</td>
<td>Oregon white oak, California black oak, Pacific madrone, ponderosa pine,</td>
<td>0–94</td>
<td>Mixed alluvium</td>
</tr>
<tr>
<td>Jonas</td>
<td>Typic Hapudand</td>
<td>Douglas-fir, western hemlock, salal, Oregon grape, oxalis, sword fern</td>
<td>28–64</td>
<td>Residual/colluvial andesite, volcanic tephra and pumice</td>
</tr>
<tr>
<td>Barneston</td>
<td>Typic Vitixerand</td>
<td>Douglas-fir, salal, sword fern, <em>Rabu</em>s spp.</td>
<td>31–88</td>
<td>Outwash</td>
</tr>
<tr>
<td>Chinkmin</td>
<td>Andic Duricryod</td>
<td>Mountain hemlock, Pacific silver fir, Douglas-fir, beargrass, <em>Vaccinium</em></td>
<td>0–83</td>
<td>Andesite, granodiorite, metavolcanics</td>
</tr>
<tr>
<td>Bashaw</td>
<td>Xeric Endoaquert</td>
<td>Wheat</td>
<td>0–26</td>
<td>Alluvium from igneous rock</td>
</tr>
<tr>
<td>Ephrata</td>
<td>Xeric Haplocambid</td>
<td>Beets, corn</td>
<td>11–96</td>
<td>Glacial outwash and loess</td>
</tr>
<tr>
<td>Sagehill</td>
<td>Xeric Haplocalcid</td>
<td>Juniper, sagebrush, bluebunch wheatgrass</td>
<td>0–3</td>
<td>Lacustrine deposits with loess</td>
</tr>
<tr>
<td>Athena</td>
<td>Pachic Haploxeroll</td>
<td>Winter wheat, spring barley, <em>Ponderosa</em> pine, Douglas-fir, pinegrass,</td>
<td>0</td>
<td>Loess with volcanic ash</td>
</tr>
<tr>
<td>Lickskilllet</td>
<td>Lithic Haploxeroll</td>
<td>Sagebrush, yarrow, bluebunch wheatgrass</td>
<td>3–84</td>
<td>Residual basalt or rhyolite</td>
</tr>
<tr>
<td>Langellain</td>
<td>Ultic Haploxeralf</td>
<td>Oregon white oak, grass, snowberry, rose</td>
<td>1–41</td>
<td>Sedimentary colluvial/alluvium</td>
</tr>
<tr>
<td>Olympic</td>
<td>Xeric Palehumult</td>
<td>Douglas-fir, western hemlock, red alder, vine maple, salal, sword fern</td>
<td>0–56</td>
<td>Residual igneous rock</td>
</tr>
<tr>
<td>Bayamon</td>
<td>Typic Hapladox</td>
<td>Grasses, pineapple</td>
<td>0–5</td>
<td>Sediments of mixed origin</td>
</tr>
<tr>
<td>Tanana</td>
<td>Typic Aquiturbel</td>
<td>Paper birch, black spruce, aspen, willow</td>
<td>0</td>
<td>Alluvial sediments</td>
</tr>
<tr>
<td>Seattle</td>
<td>Hemic Haplosaprist</td>
<td>Reed canary grass, western red cedar, red alder, sedges, rushes, <em>Spirea</em></td>
<td>0–73</td>
<td>Lacustrine and wetland organic material</td>
</tr>
</tbody>
</table>

Data from Natural Resources Conservation Service 2008. Coarse fraction for the Histosol indicates woody material.

* Cryorthent is a USDA soil Great Group and has no soil series name.
containing coarse material, cemented horizons, and the organic horizons of the Seattle soil series. All samples were sealed in plastic bags and kept on ice until return to the laboratory 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 standard sieving procedures with a 2-mm sieve and ensuring that all aggregates were broken. All obvious roots remaining in the sieve were removed and discarded. Both fractions were then weighed to determine mass and percent content of coarse and fine material for each horizon. Subsamples were ground for total C analysis and corrected for moisture content. Coarse fraction subsamples were passed through a rock grinder (broken, first, with a sledgehammer if too large for the grinder) and then were finely ground with a mortar and pestle.

Total C analysis was performed using a PerkinElmer 2400 CHN analyzer. Bulk density samples were dried to a constant weight at 105°C for a minimum of 48 hours and weighed. Organic horizons were dried and, with the exception of the Seattle Series (Histosol), were not separated into coarse and fine fractions. Subsamples were ground to <0.5 mm using a Wiley Mill and analyzed for total C as for mineral samples. Carbonate carbon was determined by weight difference after treatment with HCl using the method of Goh et al. (1993).

The quantity of total C (C\textsubscript{tot}) in each horizon for the coarse fraction (C\textsubscript{SC\textsubscript{tot}}) and the fine fraction (FSC\textsubscript{tot}) was calculated from horizon thickness (H), Db, mass of the coarse fraction relative to total soil mass (C\textsubscript{f}) or mass of the fine fraction relative to total soil mass (F\textsubscript{f}), and C concentration for the coarse (CSC\textsubscript{con}) or fine fraction (FSC\textsubscript{con}) using the equation

\[
C_{\text{tot}} = (H \times D_b \times F_f \times FSC_{\text{con}}) + (H \times D_b \times C_f \times CSC_{\text{con}}).
\]

Particle densities of both the coarse and fine soil were measured separately for 12 randomly selected soils of each fraction and determined to be equal; therefore, the whole soil bulk density was used. Carbon quantities were then summed by master horizon, the entire profile, and the profile below 1 m. When C\textsubscript{tot} below 1 m was calculated, some horizons were found at depths both above and below 1 m (e.g., Bt1 at a depth of 0.8–1.2 m). Total C in these horizons was calculated according to the proportion of horizon depth below 1 m, and that value was then summed with the total C of any additional horizons below 1 m. Percentage of CSC\textsubscript{tot} and percentage of coarse soil mass (%CSM) were calculated for major horizon designation and the entire profile:

\[
\%CSC_{\text{tot}} = \frac{CSC_{\text{tot}}}{CSC_{\text{tot}} + FSC_{\text{tot}}} \times 100,
\]

\[
\%CSM = \frac{CSM}{CSM + FSM} \times 100,
\]

where CSC\textsubscript{tot} represents coarse soil C\textsubscript{tot}, FSC\textsubscript{tot} is fine soil C\textsubscript{tot} (Mg ha\textsuperscript{-1}), CSM is coarse soil mass (Mg ha\textsuperscript{-1}), and FSM is fine soil mass (Mg ha\textsuperscript{-1}). A one-tailed t test was used to determine whether the percentage of CSC\textsubscript{tot} and %CSM were significantly different from zero (P = 0.05).

An equation was developed that would calculate the CSC\textsubscript{con} from commonly measured soil variables such as FSC\textsubscript{con}, D\textsubscript{b}, horizon depth, and "Ff. Stepwise removal of...
variables was conducted until a statistically significant ($P < 0.10$) model was produced using SPSS (SPSS, Inc. 2000). The averages of FSC$_{con}$, D$_b$, and F$_c$ and the maximum depth of each major genetic horizon (A, B, and C horizons) were calculated for each replicated pit. Linear models were produced for all horizons (A, B, and C horizons together). Both CSC$_{con}$ and FSC$_{con}$ were not distributed normally (Kolmogorov-Smirnov test $P = 0.000$ for both). A log transformation was conducted on these data before linear regression analysis. The linear models produced were compared with data from 26 sites across Europe and Canada (Corti et al. 2002). To test the success of this model, Pearson correlations were generated between the observed values from Corti et al. (2002) and the predicted models from this study.

Results and Discussion

Total, Fine and Coarse Soil Carbon Fractions

The average $C_{tot}$ of each soil series measured ranged from $<50$ to approximately 750 Mg ha$^{-1}$ (Figure 2a). Of the soils sampled, a mineral soil in the Sumas series, an alluvial Entisol used for agriculture had the greatest $C_{tot}$; the next highest quantities of C occurred in the Chickmin (forested Spodosol) and Athena (cropped Mollisol). Other Entisols and Mollisols measured were much lower in $C_{tot}$, showing the wide variation that can occur within a soil order. Whole-profile $C_{tot}$ for mineral soil orders ranged from 43 Mg ha$^{-1}$ in the Ephrata to 375 Mg ha$^{-1}$ in the Sumas soil series (Figure 2a). Both the Ephrata and Sumas soils developed in recent alluvial and outwash deposits and have been under cultivation. The Seattle series, the only Histosol examined, averaged 720 Mg ha$^{-1}$ and contained more carbon than any mineral soil.

Soil mass for those orders with mineral horizons ranged from 4,500 Mg ha$^{-1}$ in the Tanana to 31,000 Mg ha$^{-1}$ in the Athena (Figure 2b); the former was the shallowest (digging was limited by permafrost), whereas the latter was one of the deepest soils sampled (Figure 3). FSM was greater than CSM in all soil series that contained a coarse
soil fraction, with the exception of the Cryorthent, Alderwood, Barneston, Kirby, and Lickskillet. The Alderwood series had the greatest average CSM, containing 12,000 Mg ha\(^{-1}\). Because of its low bulk density, the Seattle series, a Histosol, was lowest of all soil series in total mass at 550 Mg ha\(^{-1}\) despite having the highest C\(_{\text{tot}}\).

The greatest quantities of C\(_{\text{CSC}}\) were found in forested soils: one Andisol, one Inceptisol, and a Spodosol (Figure 2a). The Inceptisol sampled also had the greatest quantity of C\(_{\text{CSM}}\) (Figure 2b). One Aridisol (the Ephrata series) and one Mollisol (the Dinkelman series) also had a high coarse soil mass but did not have a very high concentration of carbon associated with it, thereby contributing little to C\(_{\text{tot}}\). Although all soil series having both fine and coarse fractions had a greater FCS\(_{\text{con}}\) than CSC\(_{\text{con}}\), up to 25% of C\(_{\text{tot}}\) could be excluded by not assessing CSC\(_{\text{tot}}\). Even though the coarse woody material of the Histosol was a notable fraction, the tremendous amount of C present in the F\(_{\text{F}}\) still made the percentage of CSC\(_{\text{tot}}\) fairly low (Figure 2).

Carbonate carbon was a notable quantity of C\(_{\text{tot}}\) only in the Aridisols and two Mollisols. Only two soil series sampled had measurable carbonate C in the coarse fraction (the Ephrata and Lickskillet series), and neither contributed substantially to C\(_{\text{tot}}\) despite considerable coarse material (Figure 2). This study did not sample any soils forming specifically in calcareous parent materials, which could contain a considerable fraction of C\(_{\text{tot}}\) in their coarse materials (Corti et al. 2002).

A comparison of percent C\(_{\text{F}}\) with percent CSC\(_{\text{con}}\) shows the variability among soils and soil orders (Figure 3). The extensive variability among soil profiles within a soil series is also evident in Figure 3 from the large standard deviations. Although there was extensive variability in the coarse soil mass of profile replicates within a soil series, variability in percent CSC\(_{\text{con}}\) also resulted from differences in horizon depths, concentrations, and bulk densities within a soil series.

Table 2 shows average C concentrations of both the coarse and fine fractions by different mineral horizon types along with percent coarse mass (E horizons were excluded because too few were sampled). Fine and coarse soil C concentration generally decreased with profile depth and decreased relative to fine soil C concentration. Regressions of CSC\(_{\text{con}}\) by individual horizons were not significant and are not reported here.

Nevertheless, a comparison of percent coarse mass with percent total coarse soil carbon summed for each soil shows that if there is a substantial coarse fraction in a soil (greater than 20%), then it is likely to have substantial C content in

<table>
<thead>
<tr>
<th>Horizons</th>
<th>&lt;2-mm soil</th>
<th>≥2-mm soil</th>
<th>% Soil mass ≥2 mm</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, Ap, AB</td>
<td>3.6 ± 0.5</td>
<td>0.8 ± 0.2</td>
<td>25 ± 3.6</td>
<td>34</td>
</tr>
<tr>
<td>B</td>
<td>4.2 ± 1.8</td>
<td>1.3 ± 1.1</td>
<td>27 ± 1.3</td>
<td>3</td>
</tr>
<tr>
<td>Bw</td>
<td>0.7 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>46 ± 5.3</td>
<td>26</td>
</tr>
<tr>
<td>Bs</td>
<td>2.9 ± 1.0</td>
<td>0.7 ± 0.2</td>
<td>57 ± 7.7</td>
<td>9</td>
</tr>
<tr>
<td>Bk</td>
<td>1.9 ± 0.7</td>
<td>0.36 ± 0.1</td>
<td>53 ± 25</td>
<td>3</td>
</tr>
<tr>
<td>Bt</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>9.7 ± 2.2</td>
<td>14</td>
</tr>
<tr>
<td>BC, B/C</td>
<td>0.6 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>40 ± 11</td>
<td>9</td>
</tr>
<tr>
<td>C, CB</td>
<td>0.3 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>61 ± 6.0</td>
<td>19</td>
</tr>
</tbody>
</table>

Data are average ± SE and number of samples (n) are also given for each horizon type. Only horizons that contained both a fine and coarse fraction are included.
the coarse fraction (greater than 10% of total carbon) (Figure 3). Because many studies do not measure CSC\textsubscript{con} but do commonly measure horizon depth, FSC\textsubscript{con} \textsubscript{Db}, and Ff, several linear models were developed that may be used to approximate the concentration of carbon in the coarse fragments. The linear models generated through stepwise regression all removed depth as a factor, as it did not increase the predictive power of the model (Table 3). Because \( F_f, D_{bh}, \) and FSC\textsubscript{con} all have significant trends with depth, it seems reasonable that depth would not increase the predictive power of these models. Thus, only \( F_f, D_{bh}, \) and the natural log of FSC\textsubscript{con} were used in a model of CSC\textsubscript{con} with data from all soils including all ecosystem types.

Where the greatest percentage of total coarse C was found, it was both a forest soil and had a high coarse fraction. Thus, forested and nonforested soil horizons were separated for additional stepwise linear regressions. For the forested sites, the predictive power of the initial all-ecosystems model was increased (adjusted \( R^2 \) increases from 0.418 to 0.629) with the linear model using only data from forested sites. The linear model developed from the nonforested soil data was also statistically significant; however, it did not have an adjusted \( R^2 \) as high as the combined ecosystems model. Therefore, use of the all-ecosystems model would be recommended to predict the CSC\textsubscript{con} of soils at nonforested sites (rangelands, agriculture land, grasslands, and others).

Pearson’s \( R \) in Table 3 also shows how these models performed using an independently published data set from Corti et al. (2002). The models developed in this study predicted the Corti et al. (2002) data with a Pearson’s \( R > 0.726 \). The results might have been even better if it were not for differences in sampling and sample processing methodologies between this study and Corti et al. (2002). For example, Corti et al. (2002) washed the coarse fraction, thereby lowering the amount of C that might be associated with the fragile coatings attached to the surface of the coarse material.

Because other research has also found substantial C in the coarse fraction (Ugolini et al. 1996, Corti et al. 2002), it is apparent that the coarse fraction of soil can contain a substantial quantity of carbon, but its source is uncertain. Carbon occurs as coatings on rock fragments, and when porosity of rocks increases through weathering, soluble materials could enter rock pore spaces. Possible sources include organic acids, roots, mycorrhizae, microorganisms, and colloidal organics. Organic acids can precipitate on rock surfaces due to increases in soil pH (Stevenson 1994). Root and mycorrhizal fragments attached to rock surfaces and exudates released by roots or mycorrhizae could also contribute to coarse carbon content. Colloidal organic matter could also be transported in the soil solution and trapped through filtration in the pores of weathered rocks. Agnelli et al. (2002b) found that the mean residence time of humic substances in highly weathered rock fragments of A horizons was shorter than that of humic substance isolated from the fine fraction, suggesting that there are differences in biological activity and that the coarse fraction is biologically active. Agnelli et al. (2002a) also found differences in chemical structure of humic acids between the fine and coarse fractions. Thus, inclusion of the coarse fraction in measures of soil carbon seems necessary to completely assess soil carbon and the dynamics of soil carbon throughout a soil profile.

**Total C and Profile Depth**

The average depth of each soil series examined varied (Figure 4). The fine-textured Athena, Sagehill, and Bayamon were three of the deepest soils in this study. Most mineral soils examined had extensive B horizons as shown in Figure 4. Although C concentrations in the B and C horizons were typically much lower than that of A horizons (Table 2), the greater depth and mass of the B horizons in most soil profiles resulted in more C occurring below the A horizon. This was particularly true in many forested soils. For example, in the Alderwood soil series, a forested Inceptisol, 63% of C\textsubscript{tot} was in the B and C horizons. In the Chinkman series (forested Spodosol), 77% of C\textsubscript{tot} was below the O and E horizon. A forested Alfisol, the Langellian series, had 28% C\textsubscript{tot} below the A horizon. In contrast, an agricultural Mollisol (the Athena series) only had 26% C\textsubscript{tot} below the A horizon, but the A horizon was deeper than 1 m. A forested Mollisol (the Dinkelman series) also had 21% of C\textsubscript{tot} found in the B and C horizons, but the A horizon was much shallower than that of the agricultural Mollisols.

Because soils are often sampled to 1 m, the percentage of C\textsubscript{tot} below the 1-m depth was calculated for all soils that were deeper than 1 m. The percent C\textsubscript{tot} found below 1 m ranged from 3 to 48%. Of the soils examined, the Sagehill, a rangeland soil with carbonates, had the greatest percentage of C\textsubscript{tot} deep in the soil profile. Many forested soils had more than 10% of C\textsubscript{tot} below 1 m. Stone et al. (1993) found approximately 40% of soil carbon below 1 m in a Florida Spodosol, with 50% below 1 m in Humods.

The Seattle series 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 6–15 m for the Seattle profile locations (Rigg 1958),

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**Table 3.** Linear models of CSC\textsubscript{con} generated from stepwise linear regression of FSC\textsubscript{con} \textsubscript{Db}, and Ff

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Equation</th>
<th>Adjusted ( R^2 )</th>
<th>( P )</th>
<th>Pearson’s ( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>( \text{exp}(0.330 \cdot \ln \text{FSC}<em>{\text{con}} - 1.081 \cdot D</em>{bh} - 0.008 \cdot F_f + 0.506) )</td>
<td>0.418</td>
<td>0.000</td>
<td>0.726*</td>
</tr>
<tr>
<td>Forested</td>
<td>( \text{exp}(0.404 \cdot \ln \text{FSC}<em>{\text{con}} - 1.135 \cdot D</em>{bh} + 0.245) )</td>
<td>0.629</td>
<td>0.000</td>
<td>0.789*</td>
</tr>
<tr>
<td>Nonforested</td>
<td>( \text{exp}(0.443 \cdot \ln \text{FSC}<em>{\text{con}} - 0.631 \cdot D</em>{bh} - 0.7745) )</td>
<td>0.366</td>
<td>0.000</td>
<td>0.756*</td>
</tr>
</tbody>
</table>

* Models were applied to data from Corti et al. (2002); goodness of fit between observed and predicted data is shown by Pearson’s \( R \).
* * Correlation statistically significant (\( P < 0.001 \)).
greater sampling depths during this study were not possible because of the shallow water table. Thus, the C_{\text{tot}} for this soil is probably at least 5 times less than the actual C_{\text{tot}} found for this Histosol if the total soil depth could have been sampled.

Sampling soils to shallow depths may give good comparative values of surface horizons examining specific management treatments are examined but will not accurately assess total soil carbon or treatment effects at depth. Global estimates of soil carbon must include this carbon deeper in the soil profile or estimates of both the soil pool and potential sequestration will not be accurate. In addition, long-term studies of treatments that assess changes in carbon storage should include this deeper carbon or accurate changes may not be quantified. Deeper carbon is likely to be more persistent in soils and would affect measures of changes in overall soil pools.

Conclusions

The traditional practice of excluding the coarse soil fraction and soil below 1-m depth from analysis is challenged by the data presented in this study, which found substantial soil total C contained in the coarse soil fraction (\(<1\rightarrow25\%\)) and in soil greater than a 1-m depth (3\(\rightarrow48\%\)). As much as one-half of the soil total C of a profile could be ignored by the combined exclusion of the coarse fraction and soil below 1 m. These results indicate that to obtain a true value of soil total carbon, the entire soil must be sampled, including the coarse soil fraction and soil below 1 m. This accurate appraisal of total soil C is important because it may reflect enhanced storage and/or a potential source of C not previously considered by traditional soil or ecosystem C research.

Literature Cited


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