Subsurface Carbon Contents: Some Case Studies in Forest Soils

Dale W. Johnson, James D. Murphy, Benjamin M. Rau, and Watkins W. Miller

Abstract: This article evaluates the importance of deeper soil horizons for soil C inventories in forest ecosystems. For non-Spodosols, we categorized soils as to the degree of convexity of the cumulative soil C content profile. Soils with a highly convex or asymptotic soil C content profile contained a significantly lower fraction of their total C (36 ± 8%) below 20 cm than those with less convex (nonasymptotic) profiles (51 ± 2%), even though the more convex soils were 12 cm (23%) deeper. Spodosols contained the most C below 20 cm (66 ± 3%) as a result of the presence of spodic horizons. Spodosols also contained substantially more total soil profile C than non-Spodosols even though the average depths of sampling were similar. Langmuir and logarithmic equations predicted C contents of deeper horizons fairly well for most non-Spodosol soils, whereas C content declines systematically with depth. These equations were very poor for Spodosols, however, because of the increases in soil C with depth that often occur with spodic horizons. Two case studies from the Sierra Nevada mountains suggested that C concentration varies to a greater degree than does bulk density or fine earth (% <2 mm) content, thus illustrating the importance of obtaining good estimates of the large stone content, which can offset differences in C concentration when C content is calculated in the normal fashion (i.e., ignoring the >2-mm fraction). These case studies do not support the idea of estimating bulk density from soil C concentration. FOR. SCI. 57(1):3–10.

Keywords: carbon, deep horizons, equations, forest soils, Langmuir, logarithmic

THERE ARE MANY METHODOLOGICAL PROBLEMS with sampling soils for C and nutrient content, including accurate measurements of bulk density, accurate measurements of coarse fragments, especially in rocky soils, and the maximum depth to which soils should be sampled (Hamburg 1984, Ponder and Alley 1997, Burton and Pregitzer 2008).

Deeper soil horizons can be responsive to changes with management. For example, Turner and Lambert (2000) found large losses of soil organic C from deeper horizons (to 50 cm) after planting of radiata pine (*Pinus radiata* D. Don) on sites formerly occupied by native eucalyptus forests. Using stable isotopes, Bashkin and Binkley (1998) found that planting of eucalyptus on former sugar cane plantations caused increases of organic C in the surface 10 cm layer, but this was offset by decreases in the 10–55 cm layer. Hooker and Compton (2003) found that subsoil (20–70 cm depths) organic C increased over time due to reforestation of former agricultural soils in New England whereas surface soils (former Ap horizons, 0–20 cm) showed no change.

Sampling deeper soils for C concentrations is not especially problematic, but obtaining estimates of C contents (Mg ha^{-1}) requires measurements of bulk density and percent coarse fragments (% >2 mm) also, and the latter can be quite tedious and difficult to obtain. Bulk density can be measured using various methods (clod, core, excavation, and radiation), which are fully reviewed by Blake and Hartge (1986). These methods have been developed largely for agricultural soils that are typically low in large coarse fragments, whereas wildland soils in forests and arid lands often contain substantial coarse fragments. Sampling coarse fractions by excavation methods is difficult, time-consuming, and destructive to the site being sampled (Hamburg 1984, Johnson 1995, Harrison et al. 2003, Johnson et al. 2007, 2008). Harrison et al. (2003) compared four methods for determining bulk density and coarse fragment contents in two forest soils in the Pacific Northwestern United States: (1) large pit excavation, (2) dug pit with 54-mm hammer core, (3) 31-mm punch auger, and (4) the clod method. They found that the soil core methods underestimated the >2-mm fraction because the sampling necessarily avoided large rocks and that the clod method often did not work because soils did not form stable clods. They found that the large pit excavation method was the most reliable but by far the most time-consuming and labor-intensive. They also found a substantial amount of soil C in the >2-mm fraction of the more rocky soil. Soil C inventories (Mg C ha^{-1}) indicated that the top 15–20 cm of the <2-mm fine earth fraction contained 53 and 54% of total soil C to depths of 105 and 180 cm, respectively, in the two soils. In the more rocky soil, the >2-mm fraction contained more C than the <2-mm fraction even though the concentrations were much lower in the >2-mm fraction.

The study by Harrison et al. (2003) showed that it takes considerable time and energy to obtain accurate estimates of soil C contents in deeper horizons, especially in rocky soils. Thus, there is a tendency to either ignore C and nutrient stores in deeper soil horizons, perhaps producing significant bias in soil C in global scale modeling efforts (Post et al. 1982, Post and Kwon 2000) or to resort to modeling soil C contents of deeper soil horizons (Arrouays and Pélissier 1994, Kern 1994, Bernaux et al. 1998, Jobbágy and Jackson 2000).

Dale W. Johnson, Department of Environmental and Resource Sciences, University of Nevada, Reno, NV 89557—Phone: (775) 784-4511; Fax: (775) 784-4583; dwj@unr.edu. James D. Murphy, University of Nevada, Reno—dwj@unr.edu. Benjamin M. Rau, University of Nevada, Reno—dwj@unr.edu. Watkins W. Miller, University of Nevada, Reno—wilymalr@cabnr.unr.edu.

Manuscript received February 3, 2009, accepted July 21, 2010

The two questions being addressed in the symposium from which this and other articles have arisen are basically how important is deeper horizon soil C to total soil C inventories and how do these deeper soil C pools respond to management? The second question is more difficult to answer, and the answer probably varies considerably among sites and treatments. In this article, we attempt to address the first question using published data from a variety of studies in forest ecosystems.

Sites and Methods

Published soil C data from the Integrated Forest Study (IFS) sites (Johnson and Lindberg 1991), four forested sites in the Sierra Nevada, and one forested site from Central Nevada were used in the first part of this analysis. The IFS was a multisite field-based assessment of the effects of atmospheric deposition on nutrient cycling in forests. As a part of this study, a complete inventory of C, N, S, P, K, Ca, and Mg in soils, detritus, and vegetation was conducted at each site, with soil data reported as contents (kg ha^{-1}) by sampling depth. The sites received no treatment other than ambient atmospheric deposition. The Sierran and Central Nevada sites were established primarily to assess the effects of fire. In this analysis, only data from unburned plots was used. A summary of the basic characteristics of the IFS, Sierran, and Central Nevada sites is presented in Table 1. For more detailed information on IFS sites see Johnson and Lindberg (1991). For detailed descriptions of the Sierran sites see Johnson et al. (1997, 2007, 2008) and for detailed descriptions of the Central Nevada site see Rau et al. (2009).

Soil C contents by depth at the various sites were estimated from bulk density and coarse fragment (>2 mm) data taken from quantitative pit measurements similar to those described by Hamburg (1984). The soil weight data thus derived were then multiplied with C concentration data from samples taken from the pits and from auger samples near the pits. Carbon analyses were typically done by Walkley-Black for the IFS data and by combustion methods (LECO or PerkinElmer) for the newer Sierran and Central Nevada sites. See Johnson and Lindberg (1991), Johnson et al. (1997, 2007, 2008), and Rau et al. (2009) for details of sampling methods, analytical procedures, and results.

Table 1. Location, climatic conditions, soils, parent material, and vegetation of the IFS sites, the Sierran forest sites, and the Underdown Canyon site

Code	Site name	Location	Mean annual temperature (°C)	Mean annual precipitation (cm)	Parent material	Soil type	Dominant vegetation
CH	Coweeta hardwood	Coweeta, NC	12.5	138	Metamorphic	Typic Hapludults	Southern hardwoods
CP	Coweeta pine	Coweeta, NC	12.5	144	Metamorphic	Typic Hapludults	*Pinus strobes*
DF	Douglas-fir	Thompson, WA	9.8	114	Glacial till	Dystric entic Durocrept	*Pseudotsuga menziesii*
DL	Duke loblolly	Duke, NC	14.5	113	Igneous rock	Typic Hapludults	*Pinus taeda*
FL	Findley Lake	Findley Lake, WA	5.4	270	Volcanic ash over andesite	Typic cryohumods	*Abies amabilis*
FS	Florida site	Bradford, FL	21.0	112	Marine sands	Haplaquods	*Pinus elliottii*
HF	Huntington Forest	Huntington, NY	5.4	97	Glacial till	Typic Haplorthods	*Northern hardwoods*
LV	Little Valley	Little Valley, NV	5.0	45	Granite	Aquic Cryumbrepts	*Pinus contorta, Pinus jeffreyi*
LP	Oak Ridge Loblolly pine	Oak Ridge, TN	14.3	114	Alluvium	Fluventic Dystrochrepts	*Pinus taeda*
MS	Maine site	Howland, ME	5.0	79	Basal till	Haplorthods	*Picea rubens/Abies balsemea*
NS	Norway spruce	Nordmoen, Norway	4.3	107	Outwash sand	Typic Udipsamments	*Picea abies*
RA	Red alder	Thompson, WA	9.8	114	Glacial till	Dystric entic Durocrepts	*Alnus rubra*
SB	Smokies beech	Clingman's Dome, NC	6.0	151	Shale	Umbric Dystochrepts	*Fagus grandifolia*
SH	Sagehen	Sagehen, CA	4.8	87	Andesite	Ultic Haplumbrepts	*Pinus jeffreyi*
SS	Smokies Becking	Clingman's Dome, NC	6.0	151	Sandstone	Umbric Dystrochrepts	*Picea rubens/Abies fraseri*
ST	Smokies Tower	Clingman's Dome, NC	6.0	203	Sandstone	Umbric Dystrochrepts	*Picea rubens/Abies fraseri*
TL	Turkey Lakes	Turkey Lakes, ON, Canada	4.0	121	Glacial till	Haplorthods	*Northern hardwoods*
WF	Whiteface	Whiteface, NY	4.8	115	Anorthosite	Typic Cryohumods	*Picea rubens/Abies balsamea*
GO	Gondola pine	Stateline, NV	8.0	87	Decomposed granite	Typic Cryosamments	*Pinus jeffreyi, Abies balsamea*
TK	Truckee fire site	Truckee, CA	4.8	94	Andesite	Ultic Haploxeralfs	*Pinus jeffreyi*
UD	Underdown Canyon	Underdown, NV	11.1	50	Ash flow tuff	Typic Haploxerolls	*Pinus monophylla*

Soil C content in the top 20 cm depth is of interest because it is the depth called for by the current US Forest Service Forest Inventory and Analysis (FIA) protocol (O'Neill et al. 2005). Because soil C content to the exact depth of 20 cm was measured in only a few of the study sites, values for the top 20 cm in the other sites were estimated by simple linear interpolation between the depths bounding 20 cm, as described by

$$C_{20} = \frac{(C_{\mathrm{i-j}})(20 - d_{\mathrm{i}})}{d_{\mathrm{i-j}}} + \sum C_{\mathrm{i}}, \qquad (1)$$

where C_{20} is the estimated C content (Mg ha^{-1}) to a depth of 20 cm of the horizon with upper (i) and lower (j) depths bounding 20 cm, $C_{\mathrm{i-j}}$ is the reported C content (Mg ha^{-1}) of the horizon with upper and lower depths bounding 20 cm, d_{i} is the upper depth of the horizon with upper and lower depths bounding 20 cm, $d_{\mathrm{i-j}}$ is the thickness of the horizon in question, and ΣC_{i} is the cumulative C content (Mg ha^{-1}) to depth d_{i}.

Soil C content profiles were fitted to the Langmuir and logarithmic equations: The logarithmic model is of the form

$$C_{\mathrm{t}} = a^{*}\ln(d) + b, \qquad (2)$$

where C_{t} is the carbon content to a given depth d (Mg ha^{-1}), d is depth (cm), and a and b are fitted constants. The Langmuir equation is of the form

$$C_{\mathrm{t}} = \frac{(C_{\mathrm{t}}\,\mathrm{max})(b)(d)}{1 + (b)(d)}, \qquad (3)$$

where C_{t} is the carbon content to a given depth d (Mg ha^{-1}), d is the depth (cm), C_{t}max is the maximum carbon content in the profile (Mg ha^{-1}) (a fitted constant, asymptote), and b is a fitted constant.

Statistical analyses in this study were conducted using DataDesk software. Statistical analyses included analysis of variance and regression (linear and logarithmic) analyses. Pairwise comparisons of soil C contents for the three categories of soil C content profiles (asymptotic, nonasymptotic, and Spodosols) were conducted using least significant differences, $P \leq 0.05$ (Carmer and Swanson 1973).

Results and Discussion

Relative Importance of Soil C Content in Deeper Horizons

Cumulative soil C contents with depth for the IFS, Sierran, and Underdown sites are shown in Figure 1. The plots are grouped according to profiles that are more convex and appear to approach an asymptote (Fig. 1A), those with little convexity that show little or no tendency to approach an asymptote (Fig. 1B), and Spodosols (Fig. 1C). Spodosols are plotted separately for reasons that will become apparent in later discussion. The tendency to approach an asymptote seems to have little relationship to region, climate, vegetation, or parent material. For example, the SS site is located only 2 km from the ST site, and both have the same parent material and vegetation cover, yet the SS soil shows an asymptotic characteristic, whereas the ST soil shows very little such tendency. Possible exceptions with regard to parent material effects are the soils of the southwestern United States: the GO and LV sites, which have granitic parent material and C concentrations much greater in surface horizons than in subsoils; and the TK and SH soils, which have volcanic parent material for which the C concentration profiles are much flatter (Johnson et al. 1997). The Spodosols data set contains some soils that seem to reach an asymptote of cumulative soil C content with depth (FL, FS, and MS soils) and others that do not (HF and TL soils).

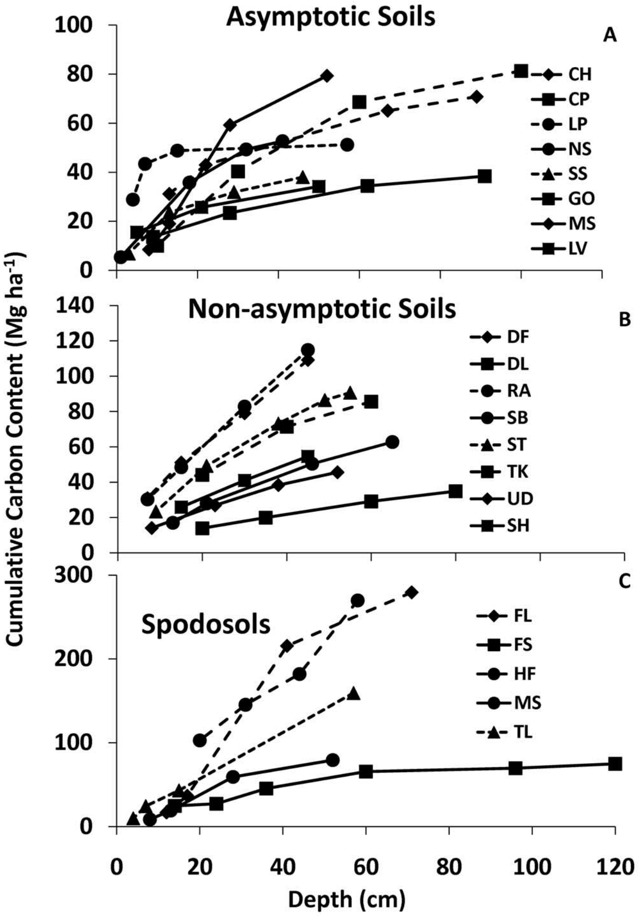

Figure 1. Cumulative soil C contents. A. Sites with greater convexity in profiles (Coweeta Hardwood [CH], Coweeta Pine [CP], Oak Ridge loblolly pine [LP], Gondola [GO], Norway spruce [NS], Smokies Becking [SS], and Little Valley [LV]); B. Sites with little convexity (Douglas-fir [DF], red alder [RA], Duke loblolly pine [DL], Smokies beech [SB], Smokies Tower [ST], Truckee pine [TK], Underdown Canyon [UD], and Sagehen [SH]). C. Spodosols (Findley Lake [FL], Florida site [FS], Huntington Forest [HF], Maine site [MS], and Turkey Lakes [TL]). See Table 1 for more detailed information on these sites.

Figure 2 shows the percentage of total cumulative soil C content (to the measured depth) that exists at each sampling depth. The degree of convexity of these curves indicates the relative importance of upper soil horizons in the total C content to the measured depth. The LP soil (Fig. 2A) stands out as one in which soil C is very much concentrated in the surface, with a full 56% of total soil C to a depth of 57 cm contained in the top 4 cm. The other non-Spodosols that showed an asymptotic tendency also showed convexity but to a lesser extent. The soils with little or no tendency to

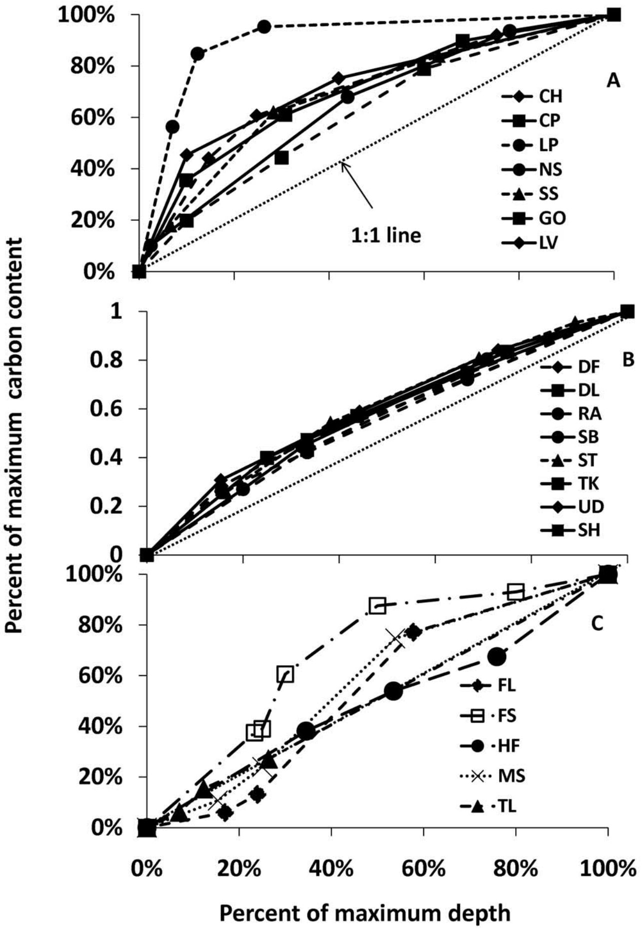

Figure 2. Percent total cumulative C content versus percent total depth. A. Sites with greater convexity in profiles B. Sites with little convexity. C. Spodosols. See legend to Figure 1 for identification of sites and Table 1 for more detailed information on these sites.

asymptote showed little or no convexity (Fig. 2B). Among the Spodosols, FL and to a lesser extent MS soils showed concavity in the upper horizons (Fig. 2C), indicating that they are disproportionately low in C content compared with the entire soil profile. The FS, MS, and FL soils showed significant convexity in the lower soil depths, reflecting the accumulation of C in the spodic horizons. Spodosols are often characterized by accumulations of C in spodic horizons, a direct result of the podzolization process (Lündstrom et al. 2000). Accumulations of soil C in the spodic horizons are well known to occur and may, in fact, contain half or more of total soil C content (e.g., Stone et al. 1993).

Figure 3 shows the percentage of total soil C above and below the measured depth of 20 cm. For the asymptotic soils, the percentage of soil C content below 20 cm ranges from 4% (LP site) to 68% (GO site) with an average of 36 ± 8% (mean ± SE). The values for the nonasymptotic soils ranged from 48% (RA, ST, and TK sites) to 60% (DL site) with an average of 51 ± 3%. The percentage of total soil C below 20 cm for the Spodosols ranged from 59% (MS site) to 79% (FL site) with an average of 66 ± 3%. The differences in the percentage of soil C below 20 cm among these three soil categories was significant ($P = 0.005$), and each category was significantly different from the other (Table 2).

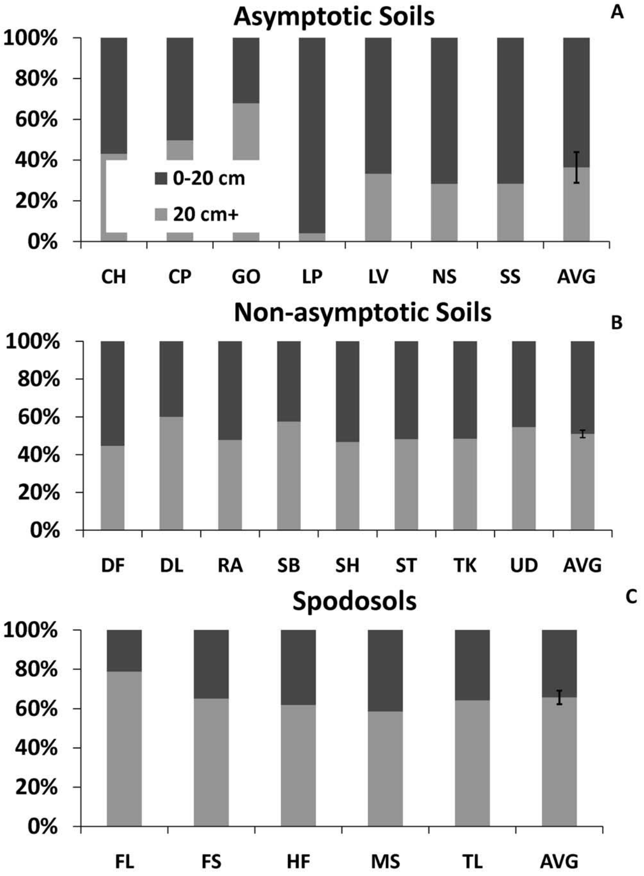

Figure 3. Percent total soil C above and below 20 cm for (A) soils with greater convexity, (B) soils with little or no convexity, and (C) Spodosols. See legend to Figure 1 for identification of sites and Table 1 for more detailed information on these sites.

A significant source of variability in the data presented thus far is the total depth of soil sampled. In some cases, that depth was prescribed by lithic or fragipan contact (DF and RA sites), whereas in others it was prescribed either by safety regulations or the depth to which investigators were willing to dig (LP, GO, TK, and UD sites). Studies in the tropics have shown that some soils can have substantial reserves of soil C at depths below 1 m (Fisher et al. 1994, Nepstad et al. 1994); the same is undoubtedly true of deep temperate soils.

So how deep must we dig in such cases? One approach would be to simply fit an equation to the soil C profiles shown in Figure 1 and interpolate to some arbitrary depth, assuming that such a depth is attainable. This approach has been used by several other authors to estimate soil C contents in deeper horizons (Arrouays and Pélissier 1994, Bernaux et al. 1998, Jobbágy and Jackson 2000). In this analysis, we used the logarithmic and Langmuir equations (the details of which are described in the Sites and Methods section), albeit there is no theoretical basis for the application of either of these equations to the issue of predicting deep soil C. The Langmuir equation was initially developed to model the adsorption of molecules on a solid surface to gas pressure or concentration of a medium above the solid surface at a fixed temperature.

Table 2. Analysis of variance probabilities for differences among soil categories

Measurement	ANOVA *P*	Post hoc tests (LSD probabilities) A-N	A-S	N-S
Depth	0.391			
Total C content	0.004	0.404	0.001	0.006
Estimated C content to 20 cm	0.152			
Estimated % of total C content >20 cm	0.005	0.042	0.001	0.065

ANOVA, analysis of variance; LSD, least significant difference; A, asymptotic soils; N, nonasymptotic soils; S, spodosols.

Of greatest interest for this exercise are the predictions for total soil profile C rather than the overall goodness of fit for the values throughout the soil profiles. The measured versus predicted cumulative soil C content at the measured sampling depths are presented in Table 3. The average total C content of the Spodosols (171 ± 28) was nearly three times that of both the asymptotic (51 ± 6) and nonasymptotic (75 ± 11) soils. Differences between the Spodosols and the other two soil categories were significant, but differences between the non-Spodosol categories were not (Table 2). Interestingly, the Langmuir equation predicted values within 5% of measured values for all of the asymptotic soils except for the most asymptotic site, LP, for which it overpredicted by 14%. The logarithmic equation predicted more poorly, coming within 5% of measured values for only six of the eight sites, underpredicting by 10% in the GO site and overpredicting by 37% in the GO site. On average, however, the predicted values for total soil C came within 1% of measured values for the Langmuir equation and 2% for the logarithmic equation among the asymptotic sites. Among the nonasymptotic soils, the Langmuir equation predicted within 5% of the measured values for total C in only four and the logarithmic equation in only three of the eight sites. On average, the Langmuir equation predicted within 2% and the logarithmic equation within 7% of average measured values for the nonasymptotic soils. Among the Spodosols, only the predictions for the FS site came within 5% of measured values, and predictions for the other sites were very poor, including negative soil C values by the Langmuir equation for the FL and MS sites.

With the use of these models, the projected values for soil C to a depth of 100 cm for all soils are presented in Table 3, with the theoretical percentage increases in total soil C content shown as well. The theoretical increases in

Table 3. Measured and estimated soil C contents to the depths reported as estimated by the Langmuir and logarithmic equations, estimated C contents to 100 cm using the Langmuir and logarithmic equations, and resultant percent increases in total soil C

Site	Sampling depth (cm)	Soil C content to measured depth: Measured	Estimated Langmuir	Estimated log	Interpolated soil C content to 100 cm (and % increase): Langmuir	Log
				(Mg ha^{-1})		
Asymptotic soils						
CH	89	71	70	71	72 (2)	73 (3)
CP	91	38	37	38	39 (2)	39 (2)
GO	100	81	84	81	84.2 (4)	80.8 (−1)
LP	57	51	58	70	52 (2)	58 (13)
LV	50	34	34	34	36.6 (7)	39.1 (16)
NS	41	53	51	49	61 (16)	62 (18)
SS	46	38	38	37	45 (18)	46 (21)
Average ± SE	68 ± 9	51 ± 6	52 ± 6	52 ± 6	54 ± 6 (6)	55 ± 5 (10)
Nonasymptotic soils						
DF	45	109	94	90.6	143 (31)	134 (23)
DL	80	35	34	32.5	38 (9)	37 (6)
RA	45	115	100	94.1	159 (39)	142 (24)
SB	65	63	65	59.2	82 (31)	74 (18)
SH	45	53	60	53.3	82 (51)	73 (35)
ST	55	91	92	88.0	123 (36)	111 (22)
TK	60	86	86	86.1	106 (23)	105 (24)
UD	52	46	42	42.9	52 (14)	54 (18)
Average ± SE	56 ± 4	75 ± 11	72 ± 9	68 ± 9	102 ± 16 (35)	95 ± 14 (26)
Spodosols						
FL	71	279.4	−228.1	302.3	−2012 (−820)	341 (22)
FS	120	74.9	78.4	78.0	72 (−4)	72 (−4)
HF	58	269.8	207.8	181.9	329 (22)	261 (−3)
MS	52	70.8	−818.9	82.6	318 (349)	106 (50)
TL	57	159.3	282.2	76.9	279 (75)	178 (12)
Average ± SE	72 ± 8	171 ± 28	95 ± 125	144 ± 27	−203 ± 282 (−76)	192 ± 31 (15)

See Table 1 for explanation of sites. Averages ± SE of non-Spodosols and Spodosols and probability values for Student's *t* tests of means (one-tailed) are given.

soil C content by interpolating to 100 cm varied considerably, depending on the actual depth of sampling and the soil C profile. In the asymptotic soils, the percent estimated increase by sampling to 100 cm ranged from 2–3% (CH, CP, and LP soils) to 18–21% (SS soil), averaging 6% for the Langmuir and 10% for the logarithmic estimates, respectively, with an average increase in depth of 32 cm (47%). The CH and CP soils were sampled to nearly 100 cm, so the slight increases in estimated soil C to 100 cm are quite predictable; for the LP site, the slight increase reflects the highly convex soil C profile (Figure 2). Among the nonasymptotic soils, the estimated increases in soil C to 100 cm range from 6 to 9% (DL soil) to 35 to 51% (SH soil), averaging 35 and 26% for the Langmuir and logarithmic equations, respectively, with an average increase in depth of 44 cm (78%). The values for predicted soil C to 100 cm in the Spodosols are shown for the sake of completeness, but they have little meaning given the poor fit of the equations for the Spodosols. It should also be noted that the calculations of predicted soil C to 100 cm are not meaningful for sites with lithic or fragipan contact before 100 cm (e.g., DF, RA, TK, and MS soils); these calculations are included only for the sake of comparison and are not meant to serve as predictions.

Another simpler (and perhaps more meaningful) way to evaluate the effect of sampling depth on soil C inventories is to simply plot total C content against sampling depth. This is illustrated in Figure 4. There are no significant correlations between total sampling depth and total soil C content for any of the three soil categories. There is a slight but nonsignificant ($P = 0.175$) trend toward higher C contents with depth among the asymptotic soils and, surprisingly, a slight nonsignificant ($P = 0.123$) trend of greater C contents at shallower depths in the nonasymptotic soils.

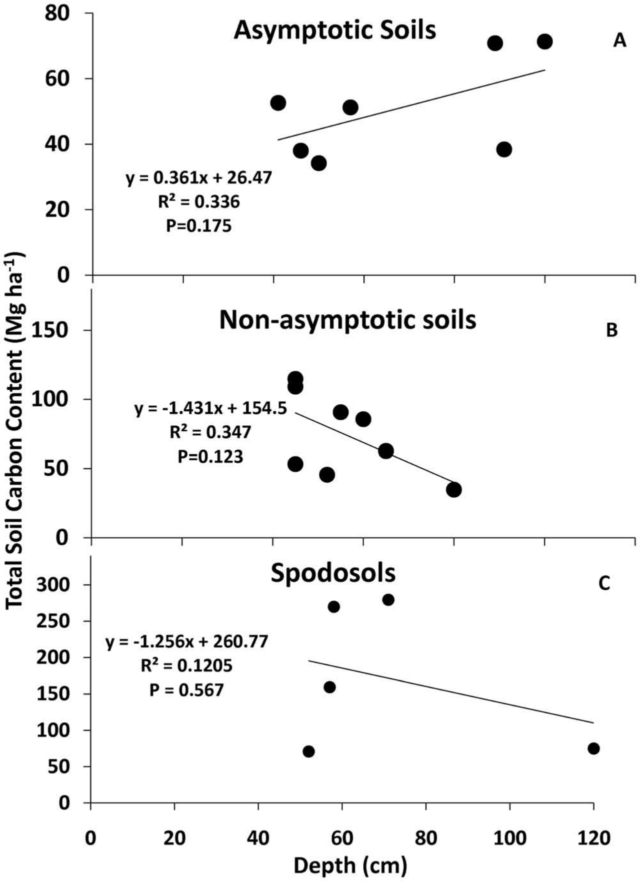

Figure 4. Total soil C content versus sampling depth for (A) soils with greater convexity, (B) soils with little or no convexity, and (C) Spodosols.

Case Studies in Two Sierran Soils

The data presented thus far represent one soil pit per site. Some of the IFS report two replicate pits, but the second replicate was not included in this analysis. For the Sierran sites, however, we have access to data for several replicate pits. In this study analysis, we will use data for the GO and TK sites, for which we have seven replicate soil pits in the control (no burning and no harvesting) treatment blocks. The GO and TK sites are underlain by the two most common parent materials in the area (decomposed granite and andesite, respectively), which lend properties to these two soils that may affect the C contents.

Factors affecting the C content (Mg cm^{-1}) include horizon thickness (cm), C concentration (mg g^{-1}), and soil mass (Mg ha^{-1}). Soil mass, by common convention, is calculated from bulk density (g cm^{-3}) and the fine earth fraction (% $<$2 mm). Although we are cognizant of the possibility of a substantial amount of C contained in the $>$2-mm fraction (e.g., Harrison et al., 2003), we are constrained by a lack of data on the C concentrations in that fraction and thus will exclude the C content of the $>$2-mm fraction from our comparison.

Figure 5 shows the average and standard errors for profile C concentration, bulk density, % $<$2 mm, and the resultant cumulative C content for seven replicate quantitative pits in the GO and TK sites. The TK soil has greater C concentrations than the GO soil, reflecting the greater clay content and organic matter-absorbing Fe and Al hydrous oxides in the soil of volcanic origin (Johnson et al., 1997). Whole-soil bulk densities are similar in magnitude, but the TK soil has much lower % $<$2 mm (i.e., contains more stones, cobbles, and rocks) than the GO soil. Thus, despite the approximately twofold differences in C concentration at shallow depths, the two soils differ by only 25% in total C content to a depth of 60 cm. We have no data as yet on C concentrations in the $>$2-mm fraction, and given the experience of Harrison et al. (2003), these data could change the picture considerably.

Peterson and Calvin (1986) noted that there are three sources of error in soil sampling: sampling error, where error is associated with the fact that only a selected subsample of the entire population of samples is taken; selection error, where some sample types are not adequately represented (i.e., rocky areas or deeper horizons); and measurement error, where the value measured is not the true value for the unit. Among the input parameters used to calculate C content, coefficients of variation were lowest for bulk density (ranging from 2 to 4% for GO soil and from 4 to 6% for TK soil) and % $<$2-mm-size fraction (1–5% for GO soil and 6–9% for TK soil) and greatest for C concentration (8–19% for GO soil and 6–11% for TK soil)

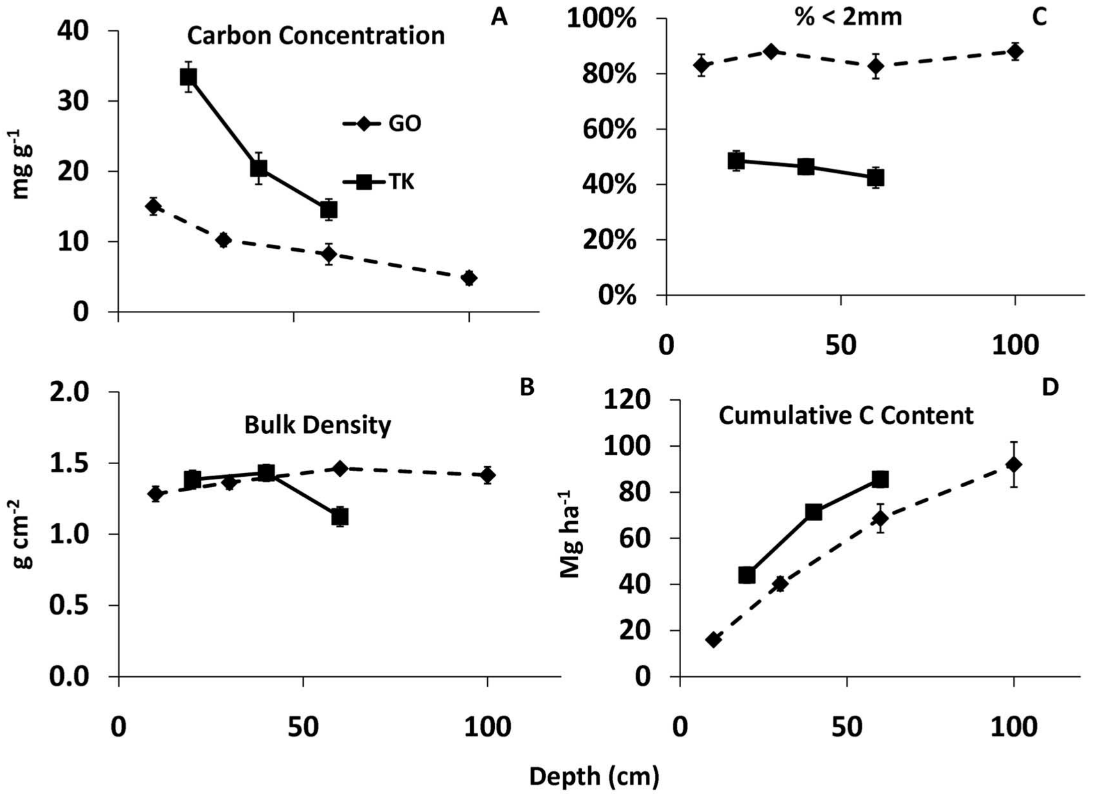

Figure 5. (A) Carbon concentration, (B) bulk density, (C) % <2 mm, and (D) cumulative soil C content for the Gondola and Truckee sites. Means and standard errors are shown (data from Murphy et al. 2006 and Johnson et al. 2007, 2008).

(Table 4). Coefficients of variation for cumulative C contents were similar to those for C concentrations (8–19% for GO soil and 4–8% for TK soil). Coefficients of variation for C concentration were greater in deeper horizons at both sites, but there were no consistent patterns for bulk density or % <2 mm with depth.

Negative correlations between bulk density and C concentration are to be expected, because organic matter is less dense than mineral soil (Federer et al. 1993), and this fact should offset the positive effect of C concentration on C content to some extent. However, we found no significant correlations between whole-soil bulk density and C concentration for any horizon in either soil, nor did we find any correlation between % <2 mm and C concentration. We considered that this lack of correlation may have been due in part to the fact that we used whole-soil bulk density (which includes large rocks) rather than the typical soil core bulk density as a correlate. Consequently, we tried regressing core bulk densities against C concentration as well and still found no significant correlations.

Table 4. Coefficients of variation (SE divided by the mean × 100) for bulk density, % <2 mm, percent carbon, and cumulative carbon contents in the Gondola and Truckee sites

Depth (cm)	C concentration	% <2 mm	Bulk density	Cumulative C content
	. . . .	(%)	. . . .	
Gondola				
0–10	8	5	4	8
10–30	9	1	3	9
30–60	18	5	2	18
60–100	19	4	4	19
Truckee				
0–20	6	7	5	8
20–40	11	6	4	4
40–60	10	9	6	4

n = 7 pits.

Conclusions

1. This review and analysis suggest that the only meaningful categorization for evaluating the importance of soil C in deeper horizons of non-Spodosols is the shape of the soil C content profile: the greater the convexity, the less important deeper horizons are as a fraction of total soil C content.
2. In the data we compared, the convex asymptotic soils contained a significantly lower fraction of their total C (36 ± 8%) below 20 cm than the nonasymptotic soils (51 ± 2%), even though the asymptotic soils were 12 cm (23%) deeper on average than the nonasymptotic soils. Spodosols contained the most total C below 20 cm (66 ± 3%) partly because of the presence of spodic horizons.
3. The simple empirical models used here seem to predict C contents of deeper horizons fairly well for most non-Spodosol soils, where C content declines systematically with depth. The equations predict poorly for Spodosols, however, because of the increases in soil C with depth that often occur with spodic horizons.

4. The two case studies from the Sierra Nevada mountains suggest that C concentration varies to a greater degree than does bulk density or % <2-mm-size fraction; analyses of data sets from other regions are needed to see whether this result generally holds true.
5. The case studies show the importance of getting good estimates of the large stone content, which can offset differences in C concentration when the standard protocol of ignoring the C content of the stone fraction is applied.
6. The case studies do not support the idea of estimating bulk density from C concentration, and, in addition, C concentration will not predict large stone content.

Literature Cited

Arrouays, D., and Pelissier, P. 1994. Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. *Plant Soil* 160:215–223.

Bashkin, M.A., and D. Binkley. 1998. Changes in soil carbon following afforestation in Hawaii. *Ecology* 79:828–833.

Bernaux, M., C.C. Cerri, C. Neill, and J.F.L. de Moraes. 1998. The use of stable carbon isotopes for estimation soil organic matter turnover rates, *Geoderma* 82:43–58.

Blake, G.R., and K.H. Hartge. 1986. Peterson, R.G., and L.D. Calvin. 1986. Bulk density. Pp. 363–376 in *Methods of soil analysis. Part 1. Physical and mineralogical methods*, Klute, A. (ed.). 2nd ed. No. 9 in the series Agronomy. Soil Science Society of America, Madison, WI.

Burton, A.J., and K. Pregitzer. 2008. Measuring forest floor, mineral soil, and root carbon stocks. Pp. 129–142 in *Field measurements for forest carbon monitoring*, Hoover, C.M. (ed.). Springer Science + Business Media, New York, NY.

Carmer, S.G., and M.R. Swanson. 1973. An evaluation of ten pairwise multiple comparison procedures by Monte Carlo methods. *J. Am. Stat. Assoc.* 68:66–74.

Federer, C.A., D.E. Turcotte, and C.T. Smith. 1993. The organic fraction-bulk density relationship and the expression of nutrient content in forest soils. *Can. J. For. Res.* 23: 1026–1032.

Fisher, M.J., I.M. Rao, M.A. Ayarza, D.E. Lascano, J.I.L. Sanz, R.J. Thomas, and R.R. Vera. 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. *Nature* 371:236–238.

Hamburg S. P. 1984. Effects of forest growth on soil nitrogen and organic matter pools following release from subsistence agriculture. Pp 145–148 in *Forest soils and treatment impacts: Proceedings of the North American forest soils conference*. Knoxville, TN.

Harrison, R.B., A.B. Adams, C. Licata, B. Flaming, G.L. Wagoner, P. Carpenter, and E.D. Vance. 2003. Quantifying deep-soil and coarse-soil fractions: Avoiding sampling bias. *Soil Sci. Soc. Am. J.* 67:1602–1606.

Hooker, T.D., and J.A. Compton. 2003. Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecol. Appl.* 13:299–313.

Jobbágy, E.G., and Jackson, R.B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* 10:423–436.

Johnson, C.E. 1995. Soil nitrogen status eight years after whole-tree clear-cutting. *Can. J. For. Res.* 25:1346–1355.

Johnson, D.W., and S.E. Lindberg. 1991. *Atmospheric deposition and forest nutrient cycling: A synthesis of the integrated forest study.* Ecological Series 91. Springer-Verlag, New York. 707 p.

Johnson, D.W., J.D. Murphy, R.F. Walker, D. Glass, and W.W. Miller. 2007. Wildfire effects on forest carbon and nutrient budgets. *Ecol. Eng.* 31:183–192.

Johnson, D.W., J.D. Murphy, R.F. Walker, W.W. Miller, and D.E. Todd. 2008. The combined effects of thinning and prescribed fire on carbon and nutrient budgets in a Jeffrey pine forest. *Ann. For. Sci.* 65:601–612.

Johnson, D.W., R.B. Susfalk, and R.A. Dahlgren. 1997. Nutrient fluxes in forests of the eastern Sierra Nevada Mountains, USA. *Global Biogeochem. Cy.* 11:673–681.

Kern, J.S. 1994. Spatial patterns of soil organic carbon in the contiguous United States. *Soil Sci. Soc. Am. J.* 58:439–455.

Lündstrom, U.S., N. Van Breemen, and D. Bain. 2000. The podzolization process. A review. *Geoderma* 94:91–107.

Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carroll, and R.R. Blank. 2006. Wildfire effects on soil nutrients and leaching in a Tahoe basin watershed. *J. Environ. Qual.* 35:479–489.

Nepstad, D.C., C.R. de Carvalho, E.A. Davidson, P.H. Jipp, P.A. Lefebvre, G.H. Negeiros, E.A. da Silva, T.A. Stone, S.E. Trumbore, and S. Viera. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372:666–669.

O'Neill, K.P., M.C. Amacher, and C.J. Palmer. 2005. Developing a national indicator of soil quality on U.S. forestlands: methods and initial results. *Environ. Monitor. Assess.* 107:59–80.

Peterson, R.G., and L.D. Calvin. 1986. Sampling. Pp. 33–52 in *Methods of soil analysis. Part 1. Physical and mineralogical methods*, Klute, A. (ed.). 2nd ed. No. 9 in the series Agronomy. Soil Science Society of America, Madison. WI.

Ponder, F., and D.E. Alley. 1997. Soil sampler for rocky soils. US For. Serv. Res. Note NC-371. 5 p.

Post, W.M., W.R. Emanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. *Nature* 298:156–159.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: process and potential. *Global Change Biol.* 6:317–327.

Rau, B.M., D.W. Johnson., R.R. Blank, and J.C. Chambers. 2009. Soil carbon and nitrogen in a Great Basin pinyon–juniper woodland: Influence of vegetation, burning, and time. *J. Arid Environ.* 73:472–479.

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.

Turner, J., and M. Lambert. 2000. Change in organic carbon in forest plantation soil in eastern Australia. *For. Ecol. Manag.* 133:231–247.