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EDITORIAL COMMENTARY

A commentary on 'Mineral soil carbon fluxes in forests and implications for carbon balance assessments': a deeper look at the data

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Abstract

Forestry practitioners contacted us with their concerns about a recent review article by Buchholz T, Friedland AJ, Hornig CE, Keeton WS, Zanchi G, Nunery J (2013) *GCB Bioenergy* who questioned the way soil carbon is treated in many models and protocols, and indicated that an increasing number of research studies showed meaningful soil organic carbon (SOC) loss as a result of forest management. We revisit the major studies cited in the review and present a more complete look at the results, consistently treat forest floor carbon as a separate pool, discuss differences in interpretation, and suggest opportunities to advance the state of knowledge regarding SOC and forest carbon accounting. Overall, we conclude that the literature continues to support the current default assumption of little or no change in mineral SOC when sound forest management practices are followed.

Keywords: carbon accounting, carbon assessments, forest soil, management impacts, soil organic carbon, forest soil

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Forestry practitioners contacted us recently after reading the review by Buchholz *et al.* (2013). Managers and decision makers expressed concern that the review indicated an increasing number of scientific studies showed meaningful soil organic carbon (SOC) loss in mineral soils from forest management. We understand their concern, and in our reading of the review, we see a lack of clarity in the main messages and would like to make the following points:

1. Although not explicitly listed in the objectives, the conclusions focus on intensive forest management, specifically management for bioenergy production. The few experimental studies cited by Buchholz *et al.*, however, were not conducted in such systems, and do not provide substantial evidence for large or continuing SOC losses in mineral soils due to forest management activities.
2. It is appropriate to continue to treat SOC in mineral soils (as distinct from organic soils, which are not addressed in the review) as stable under forest management following best management practices in the absence of site-specific evidence to the contrary.

We revisit the original publications discussed in Buchholz *et al.* in light of the review, discuss differences in interpretation, and suggest research opportunities.

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Revisiting studies from the literature as discussed in Buchholz et al.

As Buchholz *et al.* note, the 'conventional wisdom' is that losses of SOC (distinct from the forest floor, or O horizon) are generally small and transient (see review papers including Johnson, 1992; Rollinger *et al.*, 1998; Heath & Smith, 2000; Hoover, 2003), although some sites do show a significant response, which is occasionally positive. To quantitatively test for patterns in SOC response to harvesting across diverse experimental and sampling designs, Johnson & Curtis (2001) conducted a global meta-analysis of results from 26 studies that included 73 observations. They reported no significant effect on A horizon carbon (C) concentrations overall; when whole-tree harvest and sawlog-only harvest were considered separately, they found a slight decrease from whole-tree harvest and a significant increase from sawlog harvest. Nave *et al.* (2010) built on this work in an expanded meta-analysis that included 432 response ratios from 75 studies in temperate forests around the world. Additional elements included considering the forest floor, surface and deep mineral soils separately, as well as separate analyses of C concentration and C content (tC ha^{-1}). Overall, Nave *et al.* (2010) found no significant effects of harvest on the C content of surface or deep mineral soil or the total soil profile (Fig. 1a).

In terms of C concentration, no significant effect was reported for surface soil or the total profile; however,

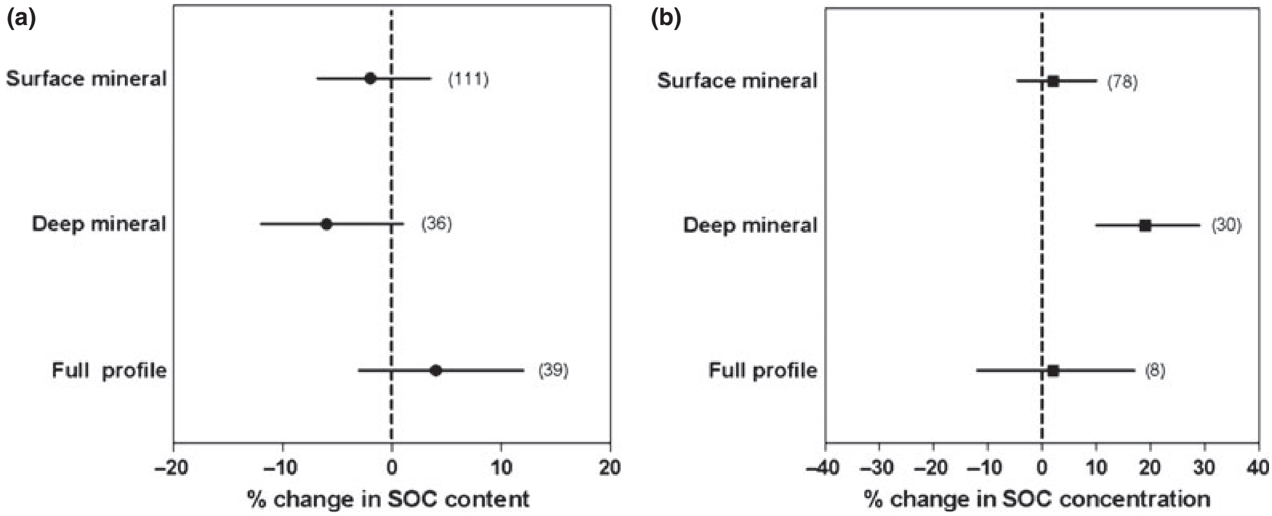

Fig. 1 SOC changes from harvesting by soil layer. Points are mean effect sizes ±95% confidence intervals. Confidence intervals intersecting the 0% change reference line indicate no significant difference. Numbers in parentheses specify the number of studies. (a) Soil C content (tC ha^{-1}), (b) Soil C concentration (%C). After Fig. 1 in Nave *et al.* (2010); data used with permission of author. Note: scales differ between panels a and b.

deep soils showed a significant increase in the C concentration at harvested sites (Fig. 1b), which may warrant further attention. When soil orders were considered separately, differing responses were noted. While Buchholz *et al.* cite the result of a 9% decline in C content in the deeper layers of Spodosols as evidence for the potential for 'significant and long-term C losses in the mineral soil' (p. 3), the results are more complex: Spodosols, while exhibiting a decline in C content in deeper portions of the mineral soil, had a significant increase in C concentration in the same portion of the profile and no change in C content was detected over the whole profile or in surface soil (pp. 862–863). Ultisols and Inceptisols showed significant decreases in SOC due to harvesting, but as with Alfisols the responses varied according to multiple factors, suggesting that much more work is needed to develop predictive understanding of management impacts on SOC. That said, the overarching result of quantitative review by Nave *et al.* (2010) was that mineral SOC showed no overall, significant change in response to harvest (Fig. 4; Conclusions on p. 863), a result that lends no support to the conclusions of the Buchholz *et al.* narrative.

Tang *et al.* (2009) presented a complex picture of soil responses, as opposed to a straightforward decrease after harvest followed by an increase after stand establishment as interpreted and summarized by Buchholz *et al.* The total sampled depth (0–60 cm) showed a decrease in SOC after harvest followed by a large increase in the intermediate stands, slightly higher values in mature stands, and highest values in the old-growth site. However, in the 30–60 cm depth, SOC was higher in the intermediate vs. mature sites. The young stands had the lowest values in the 10–30 cm layer but there was little difference between the other sites at this depth. Interpreting the role of harvest effects is complicated by the fact that the endpoints of the chronosequence (regenerated clear-cut and old-growth forest) consist of a single stand, while the young, intermediate, and mature classes are each represented by four stands. An additional complication is the possible confounding of harvest effects with species effects: the regenerated clearcut, young, and intermediate sites are aspen, although the mature and old-growth categories are northern hardwoods.

Diochon *et al.* (2009) is cited as observing a 50% loss in mineral soil C 30 years following harvest in a boreal red spruce forest; as with Tang *et al.* (2009) above, results from this unreplicated chronosequence are complex and variable (no error values are reported for several depths in one of the age classes, complicating interpretation of the data).

Zummo & Friedland's (2011) investigation of a site harvested with patch cuts is presented as evidence of significant declines in deep SOC after harvesting, because SOC was lower in 55-year-old patch cut plots compared to 3-year-old patch cut plots and plots in a mature forest. Little information is provided about the 55-year-old stand; the focus of the study is a gradient of surface disturbance levels in the 3-year-old patches. The plots in the high disturbance class did have the lowest total profile SOC (0–60 cm) and the lowest values in the middle depths (10–30 cm), as noted on p. 1024 in Zummo & Friedland (2011), 'Highly disturbed sites

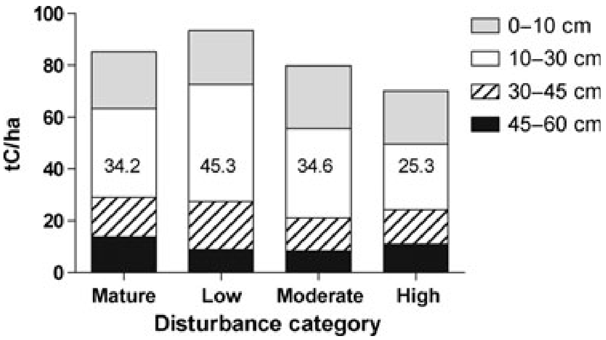

Fig. 2 Data from Table 3 in Zummo & Friedland (2011). The 10–20 and 20–30 cm depth increments in Table 3 have been combined to produce the 10–30 cm depth discussed in Buchholz *et al.*

have been shown to store at least 20 ± 2.5 Mg C ha^{-1} less than moderately and lightly disturbed sites at 10–30 cm below the forest floor (Table 3, Zummo & Friedland, 2011). Overall, highly disturbed soils store 25% less C than lightly disturbed soils.' Plotting the data in Table 3 reveals that SOC in the mature site was 11 tC ha^{-1} less than in the lightly disturbed plots for the 10–30 cm increment, and about 9% less overall (Fig. 2).

While the possibility of differing responses of the deep and surface soil layers to harvesting merits further investigation on multiple soil types, it seems likely that given the relatively small sample size (an unfortunate and common constraint), the outcome is as likely to be a result of the high inherent variability of soil properties (and small sample size) as it is the result of harvesting.

It is apparent that far more research needs to be conducted on the effects of forest management on SOC, particularly in deeper soil layers. Much available literature comes from chronosequences and paired-plot investigations often not originally designed to investigate SOC. Replication is limited or nonexistent, and sample size low due to the cost of obtaining and analyzing large numbers of samples. Sampling to depth is highly labor intensive, further limiting sample size. Given these constraints, the majority of the literature supports the current assumptions of limited or no changes in SOC when conventional forest management techniques are practiced.

Considerations on incorporating SOC in carbon accounting models

The conclusions of Buchholz *et al.* indicate more information is needed before SOC can be widely included in forest C analysis. ('There is a need to bridge knowledge gaps in mineral soil requirements…Only then can regional datasets be justifiably applied…and soil C pools can be widely included in forest C flux analysis.') Indeed, the same conclusion was reached 7–10 years ago, and adopted in developing standard C accounting tools [see the 1605(b) updated technical guidelines (available at Carbon Trading (2013)) which adopted tables from Smith *et al.*, 2006]. Additional reasons for not including soil changes include the high heterogeneity of soil, high cost of measuring SOC, long temporal scale required to detect change, and small changes expected when conventional practices are followed, as supported by the large majority of peer-reviewed publications even at that time. Thus, change in mineral SOC, not to be confused or mixed with the forest floor, has been omitted or assumed to be zero for forest management in some tools (Smith *et al.*, 2006; Heath *et al.*, 2010; Hoover & Rebain, 2011; Van Deusen & Heath, 2013). (Forest floor C is included in these tools following Smith & Heath (2002)). Tools that incorporate soil include SOC differences by forest type, or for land use change. The same thinking probably led to C protocol requirements with SOC optional or not specified.

However, an improvement that could be considered in tools is a coherent, comprehensive accounting approach across forest and nonforest landscapes. One practical reason for this is that sites intensively managed for wood for bioenergy are likely to be defined as agriculture, not forest land. The effects on mineral soil of land use change from forest to nonforest, especially change to cropland involving tillage, are widely recognized and reported by many studies (e.g. Guo & Gifford, 2002). Smith *et al.* (2006) have mineral SOC increasing in response to afforestation; deforestation is counted in the land use which the forest land becomes and is therefore not listed in protocols for forests. The SOC in the converted land use may be derived independently of the SOC in the forest land, and this can produce false SOC differences across a landscape of changing land uses. A coherent approach would permit thoughtful decisions between the economics of sustainable forest management and conversion to other land uses, and the effects on C and other benefits. Landowners may be managing for an economic return on their forest lands, and the choices may be more intensive forest management or conversion to another land use with almost certain mineral SOC and forest floor C losses. Waiting for conclusive research results before making these decisions is not always an option.

Looking ahead

We conclude that, for the default situation, consensus remains for C accounting and tools to continue to treat mineral SOC as optional or not changing due to forest management unless a majority of reasonably site-specific quantitative studies demonstrate otherwise. We agree with Buchholz *et al.* that more well-designed studies are needed, including increased sampling effort of deeper soil layers. Because soil properties are highly variable, an important question to consider is what level of change should be regarded as meaningful; an equivalence testing framework (Wellek, 2003) may provide a more useful approach to assessing management effects on soil properties than conventional significance testing. While we agree with Buchholz *et al.* that, 'Techniques for increasing the frequency and efficiency of mineral soil sampling may be a major first step toward better understanding of mineral soil C fluxes', we maintain that the preponderance of scientific evidence continues to support the current and widely held conclusion (based on multiple reviews and meta-analyses) that little or no loss of SOC occurs as a result of conventional forest management practices.

Looking to the future, we believe a coherent approach to study SOC across a comprehensive range of land uses and lands undergoing land use change is needed to advance the science and to improve operational management. A reasonable hypothesis is that the more a management action disturbs the soil, the more likely it is that mineral SOC will be lost. Comparable studies across a soil disturbance gradient, from forest management to agricultural tillage, would be useful. We are concerned that climate variability or a changing climate may cause increased emissions from mineral soil that will go unnoticed using traditional C accounting frameworks. Establishing a few thoughtfully located intensively monitored sites to test whether changes in mineral soil may be occurring due to climate would help ensure that forest C projects are not losing SOC due to climate.

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References

Buchholz T, Friedland AJ, Hornig CE, Keeton WS, Zanchi G, Nunery J (2013) Mineral soil carbon fluxes in forests and implications for carbon balance assessments. *GCB Bioenergy*. doi:10.1111/gcbb.12044.

Carbon Trading (2013) *Technical Guidelines for Voluntary Reporting of Greenhouse Gas Program Chapter 1, Emission Inventories, Part I Appendix: Forestry*. U.S. Department of Energy, Office of Policy and International Affairs, Washington, DC. Available at: http://carbon.sref.info/registering/partiforestryappendix.pdf (accessed 20 August 2013).

Diochon A, Kellman L, Beltrami H (2009) Looking deeper: an investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens Sarg*.) forest chronosequence. *Forest Ecology and Management*, **257**, 413–420.

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, **8**, 345–360.

Heath LS, Smith JE (2000) Soil carbon accounting and assumptions for forestry and forest-related land use changes. In: *The Impact of Climate Change on America's Forests* (eds Joyce LA, Birdsey R), pp. 89–101. RMRS-GTR-59. U.S. Department of Agriculture, Forest Service, Fort Collins, CO.

Heath LS, Nichols MC, Smith JE, Mills JR (2010) *FORCARB2: An Updated Version of the U.S. Forest Carbon Budget Model*. NRS-GTR-67. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. [CD-ROM].

Hoover CM (2003) Soil carbon sequestration and forest management: challenges and opportunities. In: *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* (eds Kimble JM, Heath LS, Birdsey RA, Lal R), pp. 211–238. CRC Press, Boca Raton.

Hoover CM, Rebain SA (2011) *Forest Carbon Estimation Using the Forest Vegetation Simulator: Seven Things You Need to Know*. NRS-GTR-77. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Johnson DW (1992) Effects of forest management on soil carbon storage. *Water, Air, and Soil Pollution*, **64**, 83–120.

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management*, **140**, 227–238.

Nave LE, Vance ED, Swanston CW, Curtis PS (2010) Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management*, **259**, 857–866.

Rollinger JL, Strong TF, Grigal DF (1998) Forest soil carbon storage in landscapes of the northern Great Lakes region. In: *Management of Carbon Sequestration in Soil* (eds Lal R, Kimble JM, Follett RF, Stewart BA), pp. 335–350. CRC Press, Boca Raton.

Smith JE, Heath LS (2002) *A Model of Forest Floor Carbon Mass for United States Forest Types*. NE-RP-722. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Delaware, OH.

Smith JE, Heath LS, Skog KE, Birdsey R (2006) *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States*. NE-GTR-343. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA.

Tang J, Bolstad PV, Martin JG (2009) Soil carbon fluxes and stocks in a Great Lakes forest chronosequence. *Global Change Biology*, **15**, 145–155.

Van Deusen P, Heath LS (2013) *COLE Web Applications Suite*. NCASI and U.S. Department of Agriculture, Forest Service, Northern Research Station. Available at: http://www.ncasi2.org/COLE/ (accessed 5 July 2013).

Wellek S (2003) *Testing Statistical Hypotheses of Equivalence*. Chapman and Hall/CRC, Boca Raton.

Zummo LM, Friedland AJ (2011) Soil carbon release along a gradient of physical disturbance in a harvested northern hardwood forest. *Forest Ecology and Management*, **261**, 1016–1026.