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REVIEW

Mineral soil carbon fluxes in forests and implications for carbon balance assessments

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Abstract

Forest carbon cycles play an important role in efforts to understand and mitigate climate change. Large amounts of carbon (C) are stored in deep mineral forest soils, but are often not considered in accounting for global C fluxes because mineral soil C is commonly thought to be relatively stable. We explore C fluxes associated with forest management practices by examining existing data on forest C fluxes in the northeastern US. Our findings demonstrate that mineral soil C can play an important role in C emissions, especially when considering intensive forest management practices. Such practices are known to cause a high aboveground C flux to the atmosphere, but there is evidence that they can also promote comparably high and long-term belowground C fluxes. If these additional fluxes are widespread in forests, recommendations for increased reliance on forest biomass may need to be reevaluated. Furthermore, existing protocols for the monitoring of forest C often ignore mineral soil C due to lack of data. Forest C analyses will be incomplete until this problem is resolved.

Keywords: carbon accounting, deep soil mineral carbon, Forest carbon pool assessments, forest soil, stand level carbon dynamics

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Introduction

Analysis of forest carbon (C) cycles is central to understanding and mitigating climate change (IPCC, 2007). Globally, forests store an estimated 861 gigatons of C (Lal, 2008), representing 25%–27% of the total terrestrial C pool of ~3,300 gigatons C, and have a sink capacity of around 2.4 gigatons C per year (Pan *et al.*, 2011). Forests also account for 16%–20% of total annual anthropogenic Carbon dioxide (CO_2) emissions (Lal, 2005, 2008), mainly due to ongoing net deforestation.

Understanding forest C cycles requires an in-depth analysis of the storage in and fluxes among different forest C pools. These pools include aboveground live and dead biomass, as well as the belowground organic soil horizon, mineral soil horizon and roots. Accurate accounting of these pools is a precondition for national forest C statistics reported to the United Nations Framework Convention on Climate Change (UNFCCC, 2005), quantifying the CO_2 emissions associated with harvesting and processing forest products (Werner *et al.*, 2010) and forest management practices (Nunery & Keeton, 2010), bioenergy C accounting frameworks (European Commission, 2010; EPA, 2011), calculating C emissions from bioenergy systems (Zanchi *et al.*, 2012), or forest-based C offset markets.

Forest soils are a critical part of any forest C accounting effort (Fig. 1). Forest soils are the largest active terrestrial C pool (2,500 gigatons to a 1 m depth, Lal, 2008) and account for 34% of the global soil C pool (Pan *et al.*, 2011). Soil characteristics, climate, and land use change affect the rate of biological and chemical processes that, in turn, impact soil C content on timescales ranging from hours to thousands of years (Fontaine *et al.*, 2007; Trumbore 2009). C input to the soil comes from roots, dead trees, and litterfall, and is released through root and heterotrophic respiration (Dixon 1994; Fahey *et al.*, 2005). In the case of soil organic C in the forest floor, the relationships between forest harvest practices and soil C responses are increasingly well understood (Lal, 2005): the loss of aboveground biomass results in increased solar radiation to the soil and decreased evapotranspiration from the soil (Lal, 2005; Mariani *et al.*, 2006), and soils are often compacted and may experience mechanical mixing, although this is typically confined to the organic horizon (Yanai *et al.*, 2003). These changes impact decomposition rates and soil microbial communities, potentially increasing soil C respiration rates (Diochon *et al.*, 2009).

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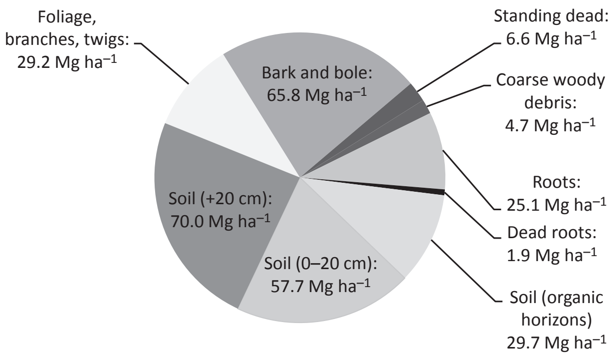

Fig. 1 Major forest carbon (C) pools for a 100-year old hardwood forest in New Hampshire (Fahey *et al.*, 2005). The depicted size of the pools is in proportion to their relative C content.

The mineral component of forest soils stores more than 50% of the C in forest soils (Jobbagy & Jackson, 2000; Fig. 1). However, due to limited understanding of mineral soil C fluxes in response to forest harvesting (e.g. Zummo & Friedland, 2011), and because mineral soil C pools are commonly assumed to be stable (e.g. Smith *et al.*, 2006), mineral soil C fluxes are not considered in empirical simulation models commonly used to project forest C dynamics over time (e.g. the U.S. Forest Service's Forest Vegetation Simulator (FVS), Hoover & Rebain, 2011). In the policy realm, the lack of sound scientific data on mineral soil C in forests often leads to exemptions for reporting mineral soil C storage capacity and C stock changes. For example, under C market accounting protocol soil C is often optional or excluded in forestry projects (e.g. VCS, 2012).

In this article, we review data from the northern temperate forest in eastern North America as well as anecdotal evidence from a growing body of literature around the globe to (i) review the current knowledge, practice, and requirements for including and quantifying mineral soil C balances in forest C accounting systems, (ii) elucidate how recent insights into mineral soil C fluxes challenge conventional wisdom in forest C accounting, (iii) describe the current limitations to quantifying and tracking mineral soil C, and (iv) suggest steps to incorporate mineral soil C fluxes in forest C accounting, policy, and management.

Current views on soil C

Conventional wisdom

Contemporary practice-oriented forest C accounting models and literature on soil C fluxes regularly exhibit two assumptions: (i) only C fluxes to and from the upper organic soil horizons (<40 cm) and root compartment respond to forest management practices and (ii) a post-harvest soil C equilibrium is reached in the short-term within 20 years, even under intense harvest practices (e.g. Johnson & Curtis, 2001 on a global scale; Jones *et al.*, 2011 for bioenergy applications in New Zealand). Deeper soil C pools are considered stable. For instance, several recent review papers on landscape C analysis provide an in-depth overview of C accounting, but avoid any reference to mineral soil C (e.g. Ryan *et al.*, 2010; McKinley *et al.*, 2011; or Fahey *et al.*, 2010 for forestry, Conant *et al.*, 2011 for agriculture). Likewise, the US-wide lookup tables for soil C fluxes in conjunction with clearcutting regimes provided by Smith *et al.* (2006) assume that the mineral soil C pool remains constant throughout the 125 years postharvest. Meanwhile, many studies analyzing soil C changes focus on examples such as converting agricultural land to forest or vice versa (e.g. Cowie *et al.*, 2006; Searchinger *et al.*, 2009) rather than soil C change on land continuously categorized as forested.

As a result of these assumptions, forest C accounting frameworks frequently consider upper soil horizon C fluxes only (e.g. IPCC, 2006). Partly due to this exclusion of soil C, study results then find rapid net C-emission benefits from intensified forestry (e.g. Perez-Garcia *et al.*, 2005; Cowie *et al.*, 2006) and support the substitution of forest-based products and fuels for energy-intensive products and fossil fuels, respectively.

Such outcomes reinforce the prevailing wisdom that "research suggests that harvest operations have no effect on soil carbon" (Perschel *et al.*, 2007 pg 25, for the Northeastern US), and have led some researchers to exclude soil C from their analyses until further evidence of harvest impacts on this C pool is found (e.g. Lippke *et al.*, 2011). In other cases, the change in mineral soil C as a response to forest management is acknowledged, but omitted due to data uncertainty (e.g. Holtsmark, 2012), or the change is declared marginal in comparison to potential greenhouse gas mitigation gains (e.g. Cowie *et al.*, 2006). Sometimes it is discussed as a potential additional and marketable C sink rather than a potential source (e.g. Lorenz *et al.*, 2011).

These approaches are not unreasonable given the many articles that have indicated that mineral soil C in managed forests is stable. However, additional evidence points to changes in mineral soil C brought on by harvesting, and its potentially large impact makes it especially worthy of consideration. We present this evidence in the following section.

Challenges to the conventional wisdom

Further research suggests that mineral soil C responses can be highly variable depending on harvesting intensity, surface disturbance, and soil type (e.g. Nave *et al.*, 2011). However, several recent studies suggest that certain forest harvesting practices might cause significant and long-term C losses in the mineral soil. Pregitzer & Euskirchen (2004) observed a decrease in mineral soil C with decreasing age class in a study encompassing tropical, temperate and boreal forest biomes. Johnson (1995) noticed that "the decline in mineral soil C was significant" over 8 years following whole tree harvest clear-cuts in the temperate US northern hardwood forest (pg 1349). For the same region, Zummo & Friedland (2011) found, in Spodosols, a significantly lower total C amount in the 10–45 cm depth soil horizons of forests 55 years after clear-cuts. In a global meta-analysis encompassing 432 sites, Nave *et al.* (2011) detected "a significant decline in deep mineral soil Carbon" (pg 860), also for Spodosols, by 9% following harvest, although no significant mineral soil C loss was detected when other soil types were included in the analysis. Diochon *et al.* (2009) observed a 50% loss in mineral soil C 30 years following harvest in the boreal forest of Nova Scotia. In temperate forests in the Great Lakes region, Tang *et al.* (2009) discovered that "total soil C at 0–60 cm initially decreased after harvest, and increased after stands established" (pg 153). There is no consensus on what processes cause the decrease in mineral soil C (Jandl *et al.*, 2007; Diochon *et al.*, 2009; Zummo & Friedland, 2011).

Including forest soil C fluxes in forest management analysis could have significant impacts on modeling results. For instance, Zanchi *et al.* (2012) included volatile soil C fluxes in their analysis of increasing fellings in an Austrian forest from 60% to 80% of net annual increment. Their model assumed only moderate forest C losses with the loss rate peaking at around 0.03 Mg/ha after ~60 years. In this work, we assessed that the accumulated soil C losses constituted 12% of total forest C losses or 3.6 Mg/ha (Fig. 2a) once a C payback period was reached after 175 years compared to a coal substitution scenario (Fig. 2b). Excluding even these presumably minor changes in soil C would lead to a significantly shorter (by about 25 years) C payback period. Including forest soil C fluxes is especially important in bioenergy C accounting because residues are often the primary fuel considered and residue decomposition patterns have a significant impact on litter and soil C stock changes (Repo *et al.*, 2011).

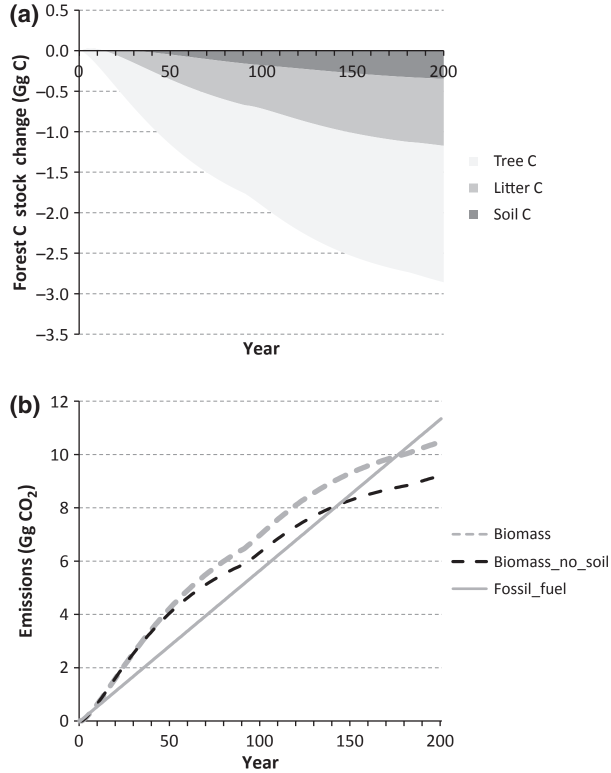

Fig. 2 Forest Carbon (C) stock change (a) and effects of excluding forest soil C (b) in a bioenergy substitution scenario modeling C fluxes in a 90 ha Austrian forest when increasing fellings from 60% to 80% of net annual increment (Zanchi *et al.* in press).

Limitations to forest soil C analysis

Forest mineral soil datasets

Collecting robust data on mineral soil C has proven difficult due to the labor necessary to make the required measurements. As a result, regional, national, and global soil C datasets are often restricted to the upper soil strata, utilize only short-term observations, and are incapable of associating forest management regimes to belowground C fluxes. Examples include the periodic nationwide U.S. Forest Inventory and Analysis National Program, which samples several aboveground forest C attributes, but has not been designed to provide sufficient data to analyze upper-strata soil (Fahey *et al.*, 2010) or deep soil characteristics (Harrison *et al.*, 2010) in response to different forest management regimes.

The soil-specific datasets that do exist are extensive, but often are not robust enough to provide stand- or treatment-specific analysis of mineral soil C. Examples include the USDA Natural Resources Conservation Service STATSGO database or the Harmonized World Soils Database, which contain estimates of mineral soil C up to 1 m depth, but without any connection to aboveground C data. One of the largest available soil C databases, the ISRIC_WISE World Inventory of Soil Emissions Potentials, has ~10,250 ISRIC_WISE plots, but most of these include soil C measurements only to a depth of 30 cm (Batjes, 2011). The spatially explicit design for large-scale analysis prohibits the use of these datasets for analysis in smaller scales where "the use of local data is preferable" (Smith *et al.*, 2012 pg 2091).

Inclusion of mineral soil C in standard forest C accounting tools

Although reliable soil C data are a precondition for full forest C accounting, another requirement for successful integration of soil C fluxes is the availability of C accounting tools that are capable of accounting for all above- and belowground C fluxes. A range of existing forest C accounting models have this capacity. One example is FORCARB (Birdsey, 2006). Another, the ecosystem process model Biome-BGC, is able to include forest mineral soil C fluxes (e.g. Peckham & Gower, 2011 using mineral soil data from the STATSGO database). Models that use forest growth models for data input, such as the GORCAM model, are among the most flexible ones. It calculates C fluxes to and from the atmosphere for different forest management strategies, incorporates C pools in wood products and fuels (Schlamadinger & Marland, 1996), and allows independent integration of soil C (Zanchi *et al.*, 2012).

However, such models acknowledge limitations by available data. For example, the fact that "empirical evidence is lacking for consistent changes in average organic C stocks in the mineral soil following harvesting and immediate regeneration" (pg 376) forced Heath *et al.* (2002) to use soil C constants in FORCARB instead of a dynamic soil C model for cases of continuous forest cover. Furthermore, many forest and soil C modeling tools offer no link to the mineral soil C pool. Examples include the FVS and the Carbon OnLine Estimation tool (COLE). Mineral soil C fluxes can be modeled in standard soil C models such as CENTURY and Yasso07 based on land management. However, both models are focusing on soil organic C and the mineral soil C component is less established (Hilinski, 2001; Tuomi *et al.*, 2011).

Soil C in regulatory forest C accounting frameworks

Periodic national and international forest C inventories provide a snapshot in time of different forest C pools (e. g. IPCC, 2006 or EIA, 2011 for an international or national level, respectively). A range of voluntary as well as mandatory frameworks also specify forest C accounting standards. Many require tracking and identifying causal relationships between C fluxes and forest management practices. Key questions are which forest C pools to include and which downstream emissions should be accounted for [e.g. C stored in wood products or emissions avoided by substituting wood products for other materials (Law & Harmon, 2011)].

In contrast to the inventory and monitoring frameworks mentioned above, frameworks or protocols developed for marketing forest C storage and sequestration are based on modeling future trends. Most of these C market protocols acknowledge the role of mineral soil C in forest ecosystems, especially when land use change occurs. However, the complex relationship between below- and aboveground C pools makes the inclusion of mineral soil C in these market protocols difficult and therefore rare when no land use change is assumed (Table 1, see also Fahey *et al.*, 2010) – as is the case in projects focusing on improving forest management or reducing emissions from deforestation. The reasoning is that such projects will increase aboveground C through reduced harvest intensity such as extended rotation periods, and therefore will not reduce soil C (e.g. Gershenson & Barsimantov, 2011). For instance, the Verified Carbon Standard (VCS) has soil C monitoring only as an option in its protocol. Even if soil C is included, VCS limits measurements of soil C to the top 30 cm, therefore excluding part of the mineral soil C. Meanwhile, the Climate Action Reserve (CAR) acknowledges the potential of soil C fluxes triggered by harvest practices and long recovery times (Gershenson & Barsimantov, 2011) and requires soil C inclusion in any registered project but it also restricts soil monitoring to the top 30 cm (CAR, 2012). Given that the California Compliance Offset Program, a recently approved regulatory protocol administered by the California Air Resources Board, used a previous version of the CAR forestry protocol for its offset protocol (ARB, 2011) and the extensive changes made between the two versions, it is not clear if this new version will be endorsed by ARB. Mineral soil C losses are therefore not completely considered in these programs. Similarly, the Regional Greenhouse Gas Initiative (RGGI), a framework specific to large electric utilities in the Northeastern US, does stress the monitoring of soil C prior to project start but fails to specify a sampling protocol.

An additional, nonmarket protocol, the IPCC C inventory standards for managed forests, takes a similar approach to the market-based protocols. As the default for Tier 1 applications, it assumes no soil C change if land remains forest and applies a constant mineral soil C factor and the assumption that SOC stabilizes within 20 years for land use change scenarios (Table 1). Tier 2 and 3 applications consider temporal dynamics in soil C and allow the use of soil C model estimates and national inventories (Ortiz *et al.*, 2011), but are rarely applied (e.g. Batjes, 2011) due to inherent uncertainties. Although fluxes in forest mineral soil C are recognized, forest management is not considered a potential high-impact factor on mineral soil C fluxes (IPCC, 2006, chapter 3.2).

Table 1 Carbon protocol requirements on monitoring soil Carbon (C)

Protocol	Soil C requirements	Source
American Carbon Registry (ACR)	Soil C not specified	ACR, 2011;
Verified Carbon Standard (VCS)	Soil C not included or optional in improved forest management or reduced emissions from deforestation projects Assessments usually to a depth of 30 cm only	VCS, 2012;
Climate Action Reserve (CAR)	Soil C included in all forest projects Assessments usually to a depth of 30 cm only.	CAR, 2012;
Regional Greenhouse Gas Initiative (RGGI)	Soil C inclusion mandatory No specification of assessment and monitoring methods	RGGI, 2008;
IPCC inventory standard for managed forests	Impact of forest management regime on mineral soil C considered marginal Range of C assessment methods offered: Tier 1 assumes constant mineral soil C if land remains forest Tier 2 and 3 allow the use of soil C model estimates and national inventories if preferred by contender	IPCC, 2006

Protocols of potential global significance are still under development, including a potential UN-REDD (Reducing Emissions from Deforestation and Forest Degradation, Goetz *et al.*, 2010) instrument as well as an effort by the EU to account for C in international biomass trade (European Commission, 2010). Both documents acknowledge the potential impact of forest management practices on and the significance of the mineral soil C pool, but fall short of outlining methods on how to account for mineral soil C fluxes. Without a clear accounting procedure for mineral soil C fluxes, it is not clear how future voluntary or regulatory frameworks will accurately account for total forest C flux.

Conclusions

Mitigating climate change through forest management strategies is a major component of forest policy, but the technical and organizational difficulties of long-term and mineral soil C research have led current practice to assume stable or replenished forest soil C pools 20 years postharvest (e.g. IPCC, 2006). Recent forest mineral soil C research (e.g. Diochon *et al.*, 2009; Zummo & Friedland, 2011) and forest C accounting studies (e.g. Zanchi *et al.*, 2012) suggest that the exclusion of mineral soil C in forest C flux analysis can result in not fully accounting for the C flux under specific forest management or site conditions. These results also emphasize the importance of considering sufficiently long temporal scales in forest C flux analysis (Marland, 2011). Forest management alternatives that result in a delayed or avoided release of GHGs might be more effective in mitigating climate change relative to a scenario characterized by high, although short-term, CO_2 emissions.

The potentially significant and long-term release of mineral soil C by practices such as a clearcutting (Zummo & Friedland, 2011) might have profound impacts on the forest use vs. preservation debate. Although some studies stress the beneficial impact of intensified forest management for biomass on atmospheric CO_2 reduction targets by replacing fossil-fuel intensive products (Werner *et al.*, 2010), other studies suggest that less intensive forest management strategies might be more beneficial from a climate change perspective (Nunery & Keeton, 2010). While such contradictory results can be largely explained by differences in boundary settings (e.g. the inclusion or exclusion of product substitution), our research indicates that a more nuanced debate regarding forest management strategies is appropriate. This debate must include mineral soil C. Including even a moderate forest soil C loss can have significant impacts on calculating a C payback time when assessing bioenergy substitution scenarios for fossil fuel use comparing forest-based bioenergy with fossil fuel scenarios (Fig. 2). Likewise, the timing of emissions is of considerable concern when aiming for climate change mitigating strategies even if the CO_2 is re-sequestered at a later stage (Kendall *et al.*, 2009; Cherubini *et al.*, 2011; Sathre & Gustavsson, 2011).

Regarding forest C credit markets, forestry projects generally realize climate benefits through reducing management impacts (e.g. through retention harvesting systems and extended rotation periods). Avoiding intensive harvesting practices might justify the exclusion of the mineral soil C in forest C accounting in this case where a stable or enlarged forest C pool is the goal.

There is a need to bridge knowledge gaps in mineral soil C fluxes and to accurately, cost-effectively and transparently monitor all major forest C pools, including soil. 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 (Harrison *et al*., 2010). New technologies, such as inelastic neutron scattering, laser-induced breakdown spectroscopy or ground-penetrating radar, might allow cost-effective *in situ*, nondestructive analysis of deeper soil strata (Johnston *et al*., 2004). This increased production of data is essential to meaningfully couple land cover management methods with soil structure which in turn can be built into larger soil datasets. Only then can regional datasets be justifiably applied in smaller spatial scales as well (Smith *et al*., 2012) and soil C pools can be widely included in forest C flux analysis.

As of now, ecosystem process models or forest product C accounting models offer increasingly sophisticated analytical capacities. A combination of available models could more fully account for above- and belowground C fluxes within a given project than any single model existing today. Using several models or the extended use of sensitivity analysis would provide a helpful step toward improved C monitoring and the communication of C flux uncertainties to researchers in other fields as well as practitioners. However, until the production of robust science describing the relationship of forest management practices to mineral soil C matures, we recommend a precautionary approach by avoiding intensified forest management practices such as an increased harvest frequency and intensity if the primary forest management objective is to increase forest C storage (Jandl *et al*., 2007).

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References

ACR (2011) The ACR Forest Carbon Project Standard v 2.1.American Carbon Registry, Arlington, VA, 62pp. Available at: http://www.americancarbonregistry.org/carbon-accounting/ACR%20Forest%20Carbon%20Project%20Standard%20v2.1.pdf (accessed 4 September 2012).

ARB (2011). Compliance Offset Protocol U.S. Forest Projects. California Environmental Protection Agency, Air Resources Board, Sacramento, CA, 113 p. Available at: http://www.arb.ca.gov/regact/2010/capandtrade10/copusforest.pdf (accessed 4 September 2012).

Batjes NH (2011) Soil organic carbon stocks under native vegetation – Revised estimates for use with the simple assessment option of the Carbon Benefits Project system. *Agriculture, Ecosystems and Environment*, **142**, 365–373.

Birdsey RA (2006) Carbon accounting rules and guidelines for the United States forest sector. *Journal of Environmental Quality*, **35**, 1518–1524.

CAR (2012) Quantification Guidance for Use with Forest Carbon Projects. Climate Action Reserve, Los Angeles, CA, 31 pp. Available at: http://www.climateaction-reserve.org/wp-content/uploads/2012/08/FPP_Quantification_Guidance.pdf (accessed 19 November 2012).

Cherubini F, Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *Global Change Biology Bioenergy*, **3**, 413–426.

Conant RT, Ogle SM, Paul EA, Paustian K (2011) Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Frontiers in Ecology and the Environment*, **9**, 169–173.

Cowie A, Smith P, Johnson D (2006) Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitigation and Adaptation Strategies for Global Change*, **11**, 979–1002.

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.

Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994) Carbon pools and flux of Global Forest Ecosystems. *Science*, **263**, 185–190.

EIA (2011) Voluntary Reporting of Greenhouse Gases Program, Reporting Guidelines, Technical Guidelines, Part I Appendix: Forestry. Energy Information Administration, Washington DC, 280 pp. Available at: http://www.eia.doe.gov/oiaf/1605/Forestryappendix%5B1%5D.pdf (accessed 4 September 2012).

EPA (2011) Accounting Framework for Biogenic CO_2 Emissions from Stationary Sources. Environmental Protection Agency, Washington DC, 141 pp. Available at: http://www.epa.gov/climatechange/emissions/biogenic_emissions/study.html (accessed 4 September 2012).

European Commission (2010) Commission staff working document - Impact Assessment Accompanying document to the Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling COM (2010) 11 final SEC(2010) 66 final, European Commission, Brussels, Belgium, 91 pp. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2010:0065:FIN:EN:PDF (accessed 4 September 2012).

Fahey TJ, Siccama TG, Driscoll CT *et al*. (2005) The biogeochemistry of carbon at Hubbard Brook. *Biogeochemistry*, **75**, 109–176.

Fahey TJ, Woodbury PB, Battles JJ, Goodale CL, Hamburg SP, Ollinger SV, Woodall CW (2010) Forest carbon storage: ecology, management, and policy. *Frontiers in Ecology and the Environment*, **8**, 245–252.

Fontaine S, Barot S, Barre P, Bdioui N, Mary B, Rumpet C (2007) Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, **450**, 277–281.

Gershenson A, Barsimantov J (2011) Accounting for Carbon in Soils. White Paper for the Climate Action Reserve, Arlington, VA, 46 pp. Available at: http://www.climateactionreserve.org/wp-content/uploads/2010/12/Accounting_for_Carbon_in_Soils-Forest_White_Paper.pdf (accessed 4 September 2012).

Goetz S, Achard F, Joosten H *et al*. (2010) Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. CEE protocol 09-016 (SR77).Collaboration for Environmental Evidence, 34 pp. Available at: http://www.environmentalevidence.org/Documents/Final_protocols/Protocol77.pdf (accessed 4 September 2012).

Harrison RB, Footen PW, Strahm BD (2010) Deep soil horizons: contribution and importance to soil carbon pools and in assessing whole-ecosystem response to management and global change. *For. Sci*., **57**, 67–76.

Heath LS, Birdsey RA, Williams W (2002) Methodology for estimating soil carbon for the forest carbon budget model of the United States. *Environmental Pollution*, **1**, 373–380.

Hilinski TE (2001) Implementation of Exponential Depth Distribution of Organic Carbon in the CENTURY Model. Available at: http://www.nrel.colostate.edu/projects/century5/reference/html/Century/exp-c-distrib.htm (accessed 4 September 2012).

Holtsmark B (2012) Harvesting in boreal forests and the biofuel carbon debt. *Climate Change*, **112**, 415–428.

Hoover CM, Rebain SA (2011) Forest carbon estimation using the Forest Vegetation Simulator: Seven things you need to know. Gen. Tech. Rep. NRS-77. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA. 16 pp.

IPCC (2006) 2006 IPCC Guidelines forNational Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed 4 September 2012).

IPCC (2007) Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jandl R, Lindner M, Vesterdal L *et al*. (2007) How strongly can forest management influence soil carbon sequestration? *Geoderma*, **137**, 253–268.

Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, **10**, 423–436.

Johnson CE (1995) Soil nitrogen status 8 years after whole-tree clear-cutting. *Canadian Journal of Forest Research*, **25**, 1346–1355.

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

Johnston CA, Groffman P, Breshears DD *et al*. (2004) Carbon cycling in soil. *Frontiers in Ecology and the Environment*, **2**, 522–528.

Jones HS, Beets PN, Kimberley MO, Garrett LA (2011) Harvest residue management and fertilisation effects on soil carbon and nitrogen in a 15-year-old Pinusradiata plantation forest. *Forest Ecology and Management*, **262**, 339–347.

Kendall A, Chang B, Sharpe B (2009) Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science and Technology*, **43**, 7142–7147.

Lal R (2005) Forest soils and carbon sequestration. *Forest Ecology and Management*, **220**, 242–258.

Lal R (2008) Sequestration of atmospheric CO_2 in global carbon pools. *Energy & Environmental Science*, **1**, 86–100.

Law BE, Harmon ME (2011) Forest sector carbon management, measurement and verification, and discussion of policy related to mitigation and adaptation of forests to climate change. *Carbon Management*, **2**, 73–84.

Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Management*, **2**, 303–333.

Lorenz K, Lal R, Shipitalo MJ (2011) Stabilized soil organic carbon pools in subsoils under forest are potential sinks for atmospheric CO_2. *Forest Science*, **57**, 19–25.

Mariani L, Chang SX, Kabzems R (2006) Effects of tree harvesting, forest floor removal, and compaction on soil microbial biomass, microbial respiration, and N availability in a boreal aspen forest in British Columbia. *Soil Biology and Biochemistry*, **38**, 1734–1744.

Marland G (2011) Accounting for carbon dioxide emissions from bioenergy systems. *Journal of Industrial Ecology*, **14**, 866–869.

McKinley DC, Ryan MG, Birdsey RA *et al*. (2011) A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications*, **21**, 1902–1924.

Nave LE, Vance ED, Swanston CW, Curtis PS (2011) Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management*, **259**, 857–866.

Nunery JS, Keeton WS (2010) Forest carbon storage in the northeastern United Sates: net effects of harvesting frequency, post-harvest retention, and wood products. *Forest Ecology and Management*, **259**, 1363–1375.

Ortiz CA, Karltun E, Stendahl J, Gärdenäs AI, Ågren GI (2011) Modelling soil carbon development in Swedish coniferous forest soils - an uncertainty analysis of parameters and model estimates using the GLUE method. *Ecological Modelling*, **17**, 3020–3032.

Pan Y, Birdsey RA, Fang J *et al*. (2011) A large and persistent carbon sink in the world's forests. *Science*, **333**, 988–993.

Peckham SD, Gower ST (2011) Simulated long-term effects of harvest and biomass residue removal on soil carbon and nitrogen content and productivity for two Upper Great Lakes forest ecosystems. *Global Change Biology Bioenergy*, **3**, 135–147.

Perez-Garcia J, Lippke B, Comnick J, Manriquez C (2005) An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood and Fiber Science*, **37**, 140–148.

Perschel RT, Evans AM, Summers MJ (2007) Climate change, carbon, and the forests of the Northeast. The Forest Guild, Santa Fe, NM, 51 pp. Available at: http://www.forestguild.org/publications/research/2007/ForestGuild_climate_carbon_forests.pdf (accessed 4 September 2012).

Pregitzer KS, Euskirchen EN (2004) Carbon cycling and storage in world forests: biome patterns related to forest age. *Global Change Biology*, **10**, 2052–2077.

Repo A, Tuomi M, Liski J (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *Global Change Biology Bioenergy*, **3**, 107–115.

RGGI (2008) Regional Greenhouse Gas Initiative Model Rule 12/31/08, New York, NY, 135 pp. Available at: http://www.rggi.org/docs/Model%20Rule%20Revised%2012.31.08.pdf (accessed 4 September 2012).

Ryan MG, Harmon ME, Birdsey RA *et al*. (2010) A synthesis of the science on forests and carbon for U.S. forests. *Issues in Ecology*, **13**, 1–30.

Sathre R, Gustavsson L (2011) Time-dependent climate benefits of using forest residues to substitute fossil fuels. *Biomass and Bioenergy*, **35**, 2506–2516.

Schlamadinger B, Marland G (1996) The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy*, **10**, 275–300.

Searchinger TD, Hamburg SP, Melillo J *et al*. (2009) Fixing a critical climate accounting error. *Science*, **326**, 527–528.

Smith JE, Heath LS, Skog KE (2006) Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. Gen. Tech. Rep. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, NE-343.Newtown Square, PA, 216 pp.

Smith P, Davies CA, Ogle S *et al*. (2012) Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology*, **18**, 2089–2101.

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

Trumbore S (2009) Radio carbon and soil carbon dynamics. *Annual Reviews of Earth and Planetary Science*, **37**, 47–66.

Tuomi M, Rasinmäki J, Repo A, Vanhala P, Liski J (2011) Soil carbon model Yasso07 graphical user interface. *Environmental Modelling & Software*, **26**, 1358–1362.

UNFCCC (2005) Land use, land-use change and forestry. Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its first session, held at Montreal from 28 November to 10 December 2005. Montreal, QC, Canada, 103 pp. Available at: http://unfccc.int/resource/docs/2005/cmp1/eng/08a03.pdf#page=3 (accessed 4 September 2012).

VCS (2012) Agriculture, Forestry and Other Land Use (AFOLU) Requirements. VCS Version 3 Requirements Document 1 February 2012, v3.2. Verified Carbon Standard, Washington DC 56 pp. Available at: http://v-c-s.org/sites/v-c-s.org/files/AFOLU%20Requirements%20v3.2.pdf (accessed 4 September 2012).

Werner F, Taverna R, Hofer P, Thürig E, Kaufmann E (2010) National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environmental Science and Policy*, **13**, 72–85.

Yanai RD, Currie WS, Goodale CL (2003) Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. *Ecosystems*, **6**, 197–212.

Zanchi G, Pena N, Bird N (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Global Change Biology Bioenergy*, **4**, 761–772.

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.