Short- and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest

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ABSTRACT

The long-term response of total soil organic carbon pools ('total SOC', i.e. soil and dead wood) to different harvesting scenarios in even-aged northern hardwood forest stands was evaluated using two soil carbon models, CENTURY and YASSO, that were calibrated with forest plot empirical data in the Green Mountains of Vermont. Overall, 13 different harvesting scenarios that included four levels of aboveground biomass removal (20%, 40%, 60% and 90%) and four different rotation lengths (60 year, 90 year, 120 year, and No Rotation (NR)) were simulated for a 360 year period. Simulations indicate that following an initial post-harvest increase, total SOC decreases for several decades until carbon inputs into the soil pool from the re-growth are greater than losses due to decomposition. At this point total SOC begins to gradually increase until the next harvest. One consequence of this recovery pattern is that between harvests, the size of the SOC pool in a stand may change from −7 to 18% of the pre-harvest pool, depending on the soil pool considered. Over 360 years, the average annual decrease in total SOC depends on the amount of biomass removed, the rotation length, and the soil pool considered. After 360 years a stand undergoing the 90yr-40% scenario will have 15% less total SOC than a non-harvested stand. Long-term declines in total SOC greater than 10% were observed in the 60yr-60%, 60yr-90%, and 90yr-90% scenarios. Long-term declines less than 5% were observed in scenarios with 120 year rotations that remove 60% or less of the aboveground biomass. The long-term decreases simulated here for common management scenarios in this region would require intensive sampling procedures to be detectable.

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1. Introduction

Approximately 50% of the annual terrestrial carbon sink of the United States, or a 16% offset of the total carbon emitted, is from forest re-growth (Pacala et al., 2007). The largest uncertainties regarding long-term forest carbon sequestration are attributed to the soil organic (SOC) and dead wood carbon pools (hereafter referred to collectively as 'total SOC') (Peltoniemi et al., 2006; Lindner and Karjalainen, 2007; Pacala et al., 2007). Yet because they are relatively stable forest carbon pools (especially SOC), their roles are central to long-term carbon sequestration (Jandl et al., 2007). This study used a combination of long-term plot measurements and processed based modeling to evaluate short- and long-term changes in total SOC in response to a variety of tree harvesting scenarios in the northern hardwood forest type in the Green Mountains of Vermont. The principal goal was to quantify the short- and long-term variations in the size of the total SOC pools that can be expected within a stand over time. Temporal changes in total SOC can be detected by intensive sampling or by chronosequence studies (Lindner and Karjalainen, 2007). However, these empirical approaches alone are not always sufficient because the inherent spatial heterogeneity in the soils of northern hardwood forests makes detecting small relevant changes in both mineral soils and forest floor difficult, costly, and time consuming (Johnson et al., 1990; Yanai et al., 2003).

As an alternative to empirical approaches, ecosystem carbon models have been used to model changes over a variety of spatial scales (e.g. local – Bricklemyer et al., 2007; regional – Paustian et al., 1997; national – Peltoniemi et al., 2007). In this study, modeled litter inputs into the soil were calibrated according to edaphic and biomass growth data from 21 forest plots that were established in 1957 and re-measured in 1990 (Johnson, 2008). Additionally, aboveground carbon turnover rates and pool sizes were calibrated from Hubbard Brook data (Fahey et al., 2005). Changes in total SOC over 360 years were then simulated for 13 different harvesting scenarios that included four levels of aboveground biomass removal (20%, 40%, 60% and 90%) and four different rotation lengths (60 year, 90 year, 120 year, and No Rotation (NR)). Biomass removals of current harvesting practices in the Green Mountains probably range from 20% to 60% and clear-

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cutting is rare. Additionally, 90 year to 120 year rotations are common whereas 60 year rotations are rare (R. De Geus, personal communication).

Uncertainties regarding terrestrial carbon sinks (Houghton and Hackler, 2000; Pacala et al., 2007) and increasing demands for biofuels has increased the need for studies in carbon management in forested regions (Liski et al., 2001; Birdsey et al., 2007). While previous studies have modeled changes in SOC in boreal ecosystems in response to prescribed harvest rotations (Jiang et al., 2002; Seely et al., 2002; Wei et al., 2003; Palosuo et al., 2008), to our knowledge no systematic attempt has been made to use ecosystem models to estimate total SOC changes in the northern hardwood forests. Additionally, since management varies widely even within the same region, the approach of this study to include different combinations of rotation lengths and removal intensities may better account for temporal variations in total SOC responses.

2. Methods

2.1. Study area

The Green Mountains are characterized by short cool summers and long cold winters. Average monthly temperatures range from −18 °C in January to 17 °C in July. Mean annual precipitation is distributed evenly throughout the year and ranges from 113 to 147 cm per year. This northern hardwood forest type is dominated by combinations of sugar maple (Acer saccharum), American beech (Fagus americana), yellow birch (Betula alleghaniensis) and paper birch (Betula papyrifera). White ash (Fraxinus americana), red maple (Acer rubrum) and other species are also common. Spodosols and Inceptisols derived from glacial till are the region's most common soils and boulders and other material >2 mm make up a significant portion of the bulk soil (Post and Curtis, 1970; Siccama, 1974).

The northern hardwood forest type currently contributes about 11% of the total C held in U.S. forest soils (Johnson and Kern, 2003). These forests were also some of the most exploited for agriculture during the colonization of New England (Cronon, 1983; Foster et al., 1998). In Vermont it is estimated that in 1880, 37% of the land was forested but by 2000 approximately 80% was forested (as summarized in Klyza and Trombulak, 1999, p. 66). In the Green Mountain region, late 19th and early 20th century logging was the main human disturbance with some land clearing for agriculture. Logging has been documented to influence the vertical distribution SOC and may have some effect on the total SOC content (Johnson et al., 1995; Johnson and Curtis, 2001).

2.2. Modeling approach and calibration

For all simulations, pre-managed forest was defined as the secondary forest that results after clear-cutting of simulated old-growth forest. After 80 years of recovery, managed forest began with the first harvest event of the specified scenario (60, 90, or 120 year rotation under 20, 40, 60 or 90% removal).

2.2.1. Model descriptions

CENTURY (version 4.5) is a process-based ecosystem model that simulates total ecosystem carbon and nitrogen (Parton et al., 1987, 1993). It has been applied to various forest types, including tropical (Sanford et al., 1991; Wang et al., 2002), boreal (Peng et al., 1998; Jiang et al., 2002; Seely et al., 2002; Wei et al., 2003), tundra (Baron et al., 1994; Conley et al., 2000) and hardwoods (Kelly et al., 1997; Smith et al., 1997). The model simulates three soil organic matter pools (active, passive, slow) for the 0–20 cm mineral soil depth and five live biomass pools (leaf, fine root, fine branch, coarse root, large wood). Dead wood carbon moves into the 'slow' organic carbon pool at a rate determined by its lignin:N and C:N and

modified by soil moisture and temperature. Decomposition rates of the 'slow' and 'passive' soil carbon pools are similarly influenced by soil moisture and temperature. Decomposition rate of the active pool is determined by soil texture, in addition to soil moisture and temperature. Other potentially sensitive parameters that are defined by the user are the turnover rates of living biomass pools and the potential site productivity (Liu et al., 2008). For more detailed explanations of the model the reader is referred to Parton et al. (1987, 1993).

YASSO (Yasso07 version) models organic matter decomposition and outputs the total SOC (organic layer plus mineral soil) to a depth of 100 cm (Liski et al., 2005). The model requires inputs of litter amounts and litter chemistry. Woody litter and soil organic matter decompose at empirically defined rates that vary with litter chemical composition, litter diameter, temperature, and precipitation. YASSO output is most sensitive to changes in decomposition rates of organic matter and changes in SOC are most sensitive to model initialization (de Wit et al., 2006; Peltoniemi et al., 2006).

2.2.2. Model input parameters, calibration and performance

Climatic, edaphic, and/or biomass growth data were used as model inputs for the CENTURY and YASSO models (see Johnson, 2008 for details). Precipitation and temperature data were generated from modeled climate data from 1979 to 2003 (Thornton et al., 1997). Total atmospheric N deposition inputs were obtained from Grimm and Lynch (2004) where a constant atmospheric N deposition was applied. Soil texture, soil drainage coefficient and soil pH data were provided from the project files of the Post and Curtis (1970) study. Living biomass chemistry (C and N) was estimated from data for northern hardwood stands in the Northeastern U.S. (Pardo et al., 2005).

Measured stand age and live biomass measurements from 1957 and 1990 were used to constrain simulated live biomass outputs for 21 forest plots by varying live woody biomass turnover rates and potential productivity parameters in CENTURY. The mean rate of live woody biomass turnover used for model calibration was 1.5%. For comparison, the turnover rate of large wood at Hubbard Brook, NH is 1.9% (Fahey et al., 2005). Model outputs for the total woody debris pools (i.e. fine branch, coarse root, and large wood) ranged from 1610 to 3600 gC m^{-2} and were somewhat higher than those estimated at Hubbard Brook, NH (approximately 1313 gC m^{-2} Fahey et al., 2005) and coarse woody debris in the Adirondacks, NY (approximately 790–1240 gC m^{-2} McGee et al., 1999). Simulated live biomass at the plot level agreed well with field measurements (R^2 of 0.72 and 0.92 for 1957 and 1990, respectively) and the slopes of the simulated vs. measured biomass were near 1 (0.92 and 0.96, respectively).

Litter inputs for the YASSO model were simulated by CENTURY. The parameters for chemical composition of litter were adopted from de Wit et al. (2006) and the Yasso07 user-interface manual (Liski et al., 2009). Diameters for litter inputs were assumed to be 0.0 cm for fine roots and leaves, 2.0 cm for fine branches, and 10.0 cm for large wood and coarse roots. These are average sizes and similar to those recorded for northern hardwood forests (McGee et al., 1999).

CENTURY estimates of the 0–20 mineral SOC at individual plots correlated significantly with field measurements (0.56 Spearman's Rho coefficient; $p < 0.01$). Similarly, YASSO outputs were significantly correlated with measured total solum SOC (i.e. forest floor plus mineral soil to top of C horizon) (0.65 Spearman's Rho coefficient; $p < 0.01$). As further validation, CENTURY results indicate that between 1950 and 1990 the total ecosystem carbon (SOC, dead wood, live biomass) in these plots increased at an annual rate of 0.82 MgC ha^{-1} yr^{-1}. These values are similar to those reported in a regional analysis for the Northeastern United States that covered the same period (0.89 MgC ha^{-1} yr^{-1} Houghton

and Hackler, 2000). The simulated living biomass of old growth carbon pools (i.e. 'steady state') were also within the range of estimates for comparable old growth temperate forests (Morrison, 1990; Luyssaert et al., 2008). For additional details on model calibration and performance see Johnson (2008).

3. Results

### 3.1. Between harvest patterns

Simulations from both models indicate that soil carbon pools increase immediately following a harvest event and then decrease before they eventually begin to accumulate again (Fig. 1; Table 1). Changes in dead wood, SOC and total SOC pools are driven by changes in litter inputs (Fig. 1a, b, c) where SOC lags in its response compared to dead wood. The between-harvest patterns in total SOC response are similar for both models except that the organic to 100 cm pool simulated by YASSO recovered at a somewhat slower rate than the CENTURY 0–20 cm pool ($4.7 \, \text{gC m}^{-2} \, \text{yr}^{-1}$ vs. $13.7 \, \text{gC m}^{-2} \, \text{yr}^{-1}$) (Fig. 1c). These within-stand patterns to the soil pool and can result in a -7 to 18% difference in total SOC between the post-harvest highs and the mid-harvest lows. During the initial stages of re-growth, inputs of carbon to the soil pool from forest litter decrease. At the same time the inputs of carbon from the coarse root pool of the harvested trees increases. The net effect of the decreasing large wood litter inputs and increasing root inputs is a short-term increase in SOC. Subsequently, litter input

rates in the recovering forest cannot keep up with SOC decomposition rates and soil carbon decreases until litter inputs from the recovering forest increase. For example in the 90yr-40% scenario, the initial period of increase lasts for approximately 4 years. This is then is followed by a 40 year period before large wood inputs approached their pre-harvest values of $13.6 \, \text{gC m}^{-2} \, \text{yr}^{-1}$ and the total SOC pool begins to accumulate. At this point, total SOC increased at a rate of approximately $4.2 \, \text{gC m}^{-2} \, \text{yr}^{-1}$ over the next 45 years until the next harvest event.

3.2. Long-term trends

Both models also indicate that over 360 years of repeated harvesting, the SOC in a stand will gradually decrease (Fig. 1b and c). The average annual decrease over 360 years depends on the amount of biomass removed, the rotation length and the soil pool considered. In the simulations reported here, this decrease can range from $-11.9 \, \text{gC m}^{-2} \, \text{yr}^{-1}$ for a 60yr-90% rotation to a $-0.85 \, \text{gC m}^{-2} \, \text{yr}^{-1}$ loss for a 90yr-20% rotation (Table 1). Only the No Rotation and 120yr-20% CENTURY scenarios had positive increases in total SOC. These decreases result because even after 120 years of re-growth, the soil carbon pools do not completely recover before the onset of a new harvest event.

The model simulations also indicate that while changes between harvests can be large, after multiple centuries of repeated harvesting and re-growth, the long-term decline in total SOC is less than 10% for the most common land-use scenarios in the region
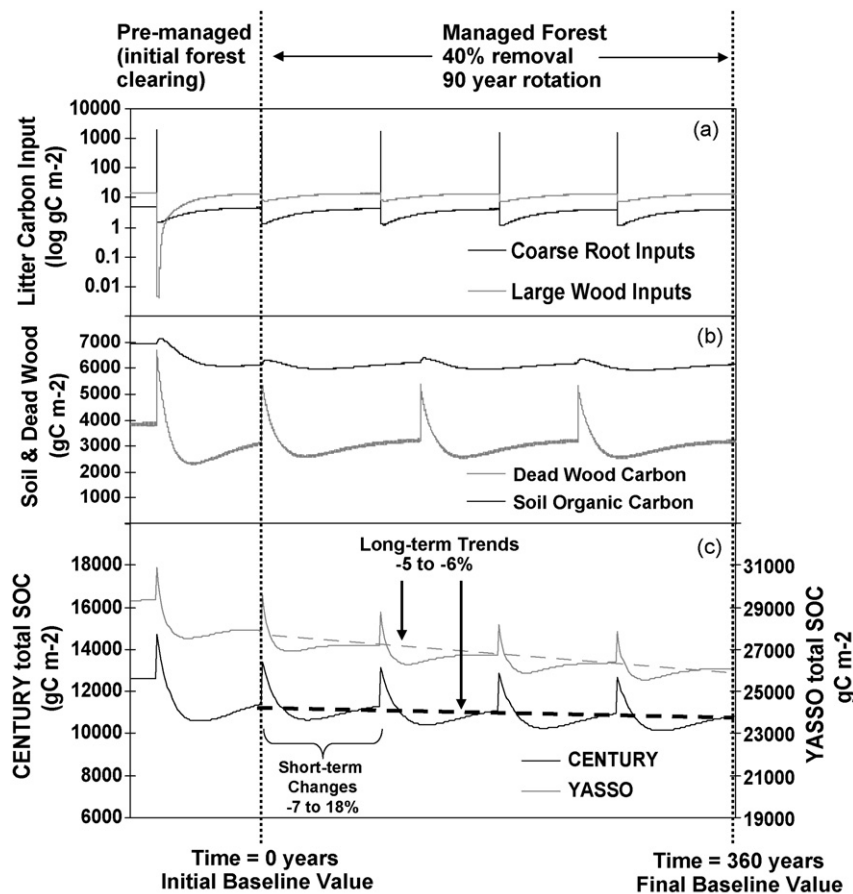

Fig. 1. Short- and long-term changes in carbon pools from CENTURY and YASSO results for a 90 year, 40% removal management scenario. Time = 0 refers to the beginning of management period for a second growth northern hardwood forest. Note the difference in scales for litter amounts and carbon pools (a) large wood and coarse root litter inputs as simulated by CENTURY. (b) Total dead wood carbon (large wood, coarse root, fine branch) and soil organic carbon pools simulated by CENTURY. (c) Total SOC (dead wood carbon plus soil organic carbon) simulated by CENTURY and YASSO. Dashed lines indicate the approximately linear long-term trend in total SOC over 360 years if fitted to the baseline values (i.e. the value just before the next harvest event).

Table 1
Long-term trends (360 years) in total SOC (dead wood carbon plus SOC) in response to continuous management scenarios for CENTURY (0–20 cm mineral) and YASSO (organic layer to 100 cm depth).

Rotation	Model	Change (abs.)	20% removal change (rel.)	Rate	Change (abs.)	40% removal change (rel.)	Rate	Change (abs.)	60% removal change (rel.)	Rate	Change (abs.)	90% removal change (rel.)	Rate
60 year	CENTURY	−966	−8.5%	−2.68	−1381	−12.1%	−3.84	−1792	−15.7%	−4.98	−2385	−20.8%	−6.63
	YASSO	−2045	−7.3%	−5.68	−2732	−9.8%	−7.59	−3366	−12.1%	−9.35	−4287	−15.3%	−11.91
90 year	CENTURY	−307	−2.7%	−0.85	−579	−5.1%	−1.61	−852	−7.5%	−2.37	−1289	−11.3%	−3.58
	YASSO	−1300	−4.7%	−3.61	−1773	−6.3%	−4.92	−2245	−8.1%	−6.24	−2962	−10.6%	−8.23
120 year	CENTURY	81	0.7%	0.23	−107	−0.9%	−0.30	−303	−2.7%	−0.84	−655	−5.7%	−1.82
	YASSO	−883	−3.2%	−2.45	−1238	−4.4%	−3.44	−1577	−5.7%	−4.38	−2172	−7.8%	−6.03
No Rotation	CENTURY	1136	9.9%	3.16									
	YASSO	862	3.1%	2.40									

Change (abs.): the absolute change in carbon from the baseline carbon pool (time = 0) after 360 years of rotations in gC m^{-2}. Change (rel.): the change as a percentage of the baseline carbon pool after 360 years of rotations. Rate: the average yearly decrease in carbon after 360 years of rotations in gC m^{-2} yr^{-1}.
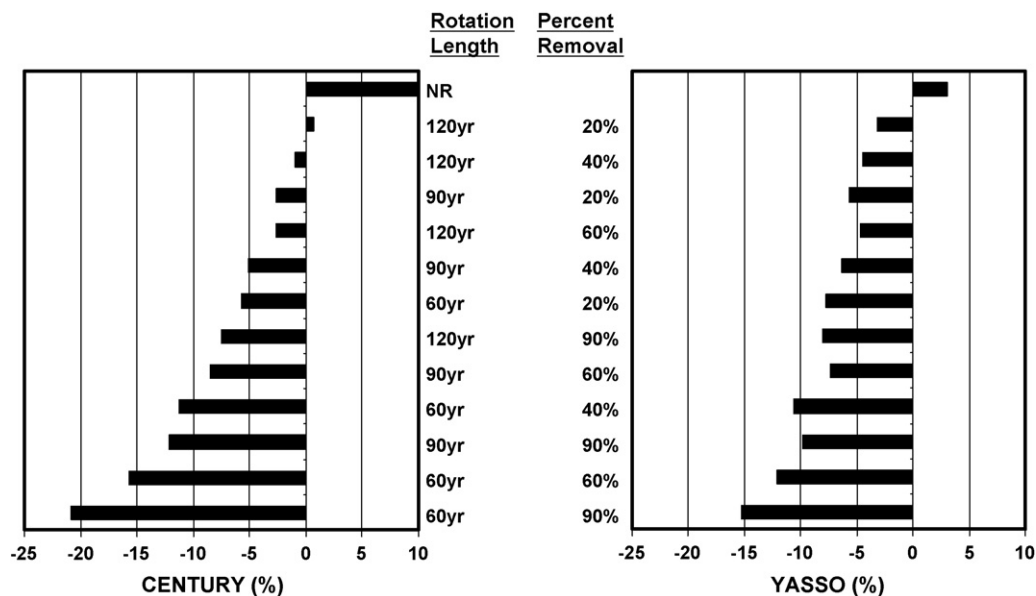
Fig. 2. Comparison table of total SOC changes as a percent of baseline values at time = 0 for both models and under varying management scenarios. The results are ranked top to bottom by least to greatest total SOC decreases for the CENTURY model results.

(e.g. 90yr-40%) (Fig. 2). Furthermore, these changes were well under the level of minimum detectable change (e.g. 10%) using even the most intense sampling procedures (Johnson et al., 1990, 1995). For example, after 360 years of the 90yr-40% scenario, CENTURY simulates that soil organic and dead wood carbon pools decreased by 4.0% (328 gC m^{-2} yr^{-1}) and 8.1% (252 gC m^{-2} yr^{-1}), respectively (Fig. 1b). Similarly, total soil organic carbon decreased by 5.1% (580 gC m^{-2}) and 6.4% (1770 gC m^{-2}) for CENTURY 0–20 cm pools and the YASSO 0–100 cm pools, respectively (Figs. 1c and 2). Decreases larger than 10% only resulted from the 60yr-60%, 60yr-90%, and 90yr-90% scenarios (Table 1 and Fig. 2). Management scenarios which resulted in decreases of less than 5% in both models were the 120 year rotations that did not exceed 60% aboveground carbon removal.

4. Discussion

The 360 year simulations from both models indicate that repeatedly harvesting even-aged northern hardwood stands reduces carbon inputs into the soil pool and eventually results in decreases in total SOC over time. Empirical studies of harvesting have also reported decreases in SOC pools (Johnson et al., 1995; Johnson and Curtis, 2001; Fontaine et al., 2007; Luyssaert et al.,

2008). Empirical studies and model response also suggest that aboveground productivity, nitrogen availability, and tree harvesting are the mechanisms responsible for this negative feedback (Nord-Larsen, 2002; Palosuo et al., 2008). In the CENTURY model this feed back results in part because the model maintains C:N ratios in its soil compartments by mineralization or immobilization. Mineralization of N increases following harvest events because there are lower inputs of high C:N litter (i.e. coarse wood). During the initial stages of re-growth nitrification and nitrogen leaching also increase because of the decreased demand of N from the live biomass. The net result is lower available N and subsequently lower productivity in the following years.

The model simulations and empirical studies discussed above indicate that between harvest cycles the total soil carbon within a stand could vary as much as −7 to 18% of pre-harvest values in response to changes in carbon inputs during forest recovery. However the long-term decline in soil organic matter from typical historic and current northern hardwood harvesting scenarios (e.g. 90yr-40%) is typically less than 10% (Fig. 2). Furthermore, these long-term changes lag behind changes in live biomass carbon on the order of decades, and are not easily detected by field sampling methods. In addition, less intensive but more frequent removals may result in the same loss of organic carbon as more intensive but

less frequent removals (e.g. 60yr-20% vs. 90yr-40%). The simulations also indicate that after 360 years a stand undergoing 90yr-40% rotations will have 15% less soil organic carbon that if it were not harvested at all (e.g. the NR scenario; Table 1).

Acknowledgements

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