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Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products

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ABSTRACT

Temperate forests are an important carbon sink, yet there is debate regarding the net effect of forest management practices on carbon storage. Few studies have investigated the effects of different silvicultural systems on forest carbon stocks, and the relative strength of *in situ* forest carbon versus wood products pools remains in question. Our research describes (1) the impact of harvesting frequency and proportion of post-harvest structural retention on carbon storage in northern hardwood-conifer forests, and (2) tests the significance of including harvested wood products in carbon accounting at the stand scale. We stratified Forest Inventory and Analysis (FIA) plots to control for environmental, forest structural and compositional variables, resulting in 32 FIA plots distributed throughout the northeastern U.S. We used the USDA Forest Service's Forest Vegetation Simulator to project stand development over a 160 year period under nine different forest management scenarios. Simulated treatments represented a gradient of increasing structural retention and decreasing harvesting frequencies, including a "no harvest" scenario. The simulations incorporated carbon flux between aboveground forest biomass (dead and live pools) and harvested wood products. Mean carbon storage over the simulation period was calculated for each silvicultural scenario. We investigated tradeoffs among scenarios using a factorial treatment design and two-way ANOVA. Mean carbon sequestration was significantly ($\alpha = 0.05$) greater for "no management" compared to any of the active management scenarios. Of the harvest treatments, those favoring high levels of structural retention and decreased harvesting frequency stored the greatest amounts of carbon. Classification and regression tree analysis showed that management scenario was the strongest predictor of total carbon storage, though site-specific variables were important secondary predictors. In order to isolate the effect of *in situ* forest carbon storage and harvested wood products, we did not include the emissions benefits associated with substituting wood fiber for other construction materials or energy sources. Modeling results from this study show that harvesting frequency and structural retention significantly affect mean carbon storage. Our results illustrate the importance of both post-harvest forest structure and harvesting frequency in carbon storage, and are valuable to land owners interested in managing forests for carbon sequestration.

1. Introduction

While deforestation accounts for about 20% of total global carbon dioxide (CO_2) emissions, due primarily to tropical deforestation (IPCC 2007), forests in United States are currently a carbon (C) sink sequestering approximately 10% of U.S. annual CO_2 emissions (Birdsey et al., 2006). Developing carbon markets have recognized the important role of forests in the terrestrial C cycle and the potential contribution of sustainable forest management to climate change mitigation efforts (Canadell and Raupach, 2008; Ray et al., 2009b). A working hypothesis is that "improved forest management" could achieve higher levels of C storage (termed "additionality") compared to "business as usual" or a baseline condition (Ruddell et al., 2007). While forest management clearly impacts terrestrial C storage (Birdsey et al., 2007), little information is available describing how specific forest management alternatives might affect C storage and sequestration. This understanding is vital, because the dynamics of storage and fluxes among the different sinks impacted by management (e.g., forest C versus wood products pools) are complex, rendering accounting of net effects on C storage challenging (Birdsey et al., 2006; Ray et al., 2009b). The purpose of this study is to inform forest C management practices using empirical data coupled with forest-stand development modeling. We investigate the impacts of harvesting frequency and post-harvest retention on C sequestration in managed forests in the northeastern U.S. We also

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specifically address the importance of accounting for C stored in wood products when determining net effects on sequestration (Seidl et al., 2007).

Some researchers have suggested that sustainably managed forests sequester more C than unmanaged forests, stressing the high tree growth rates achieved in harvested stands (Ruddell et al., 2007), and C stored in wood products (Malmsheimer et al., 2008). However, other studies have demonstrated that unmanaged forests, such as old-growth forests in the U.S. Pacific Northwest (Harmon et al., 1990; Harmon and Marks, 2002) and boreal forests in northwestern Russia (Krankina and Harmon, 1994), sequester greater amounts of C than managed forests. These authors have argued that intensified forest management actually leads to a net flux of C to the atmosphere due to lower biomass in harvested stands and the often short lifespan of wood products. These conclusions, however, are based primarily on studies involving conversion of old-growth forest to young plantations (Harmon et al., 1990) and the effects of intensive harvesting practices, such as clearcutting (Krankina and Harmon, 1994). Net effects on C dynamics across a range of silvicultural systems, including modified even-aged and less intensive uneven-aged forest management practices, remain poorly explored and thus are a focus of this study.

Recently, interest has developed in the use of reduced harvesting frequency (Curtis, 1997) and post-harvest structural retention (Franklin et al., 1997; Keeton, 2006; Swanson, 2009) as approaches favoring maintenance and development of high levels of *in situ* forest C storage. However, previous analyses of harvesting frequency (also termed "extended rotations") were focused primarily on even-aged forest management (Liski et al., 2001; Harmon and Marks, 2002; Balboa-Murias et al., 2006). Few studies have addressed the coupled effects of variations in harvesting frequency and post-harvest structural retention in mature, even to multi-aged forests, such as those now dominant on the New England landscape. Decreased harvesting frequency increases C storage in managed stands (Liski et al., 2001; Balboa-Murias et al., 2006); however, the resulting sequestration remains less than the total C storage in unmanaged forests, even accounting for fluxes caused by natural disturbances at landscape scales (Krankina and Harmon, 1994). In other studies, accounting for C stored in durable, long-lived wood products increased the estimated net C storage for intensively managed forests in which rotation periods were also increased (Perez-Garcia et al., 2005). Discrepancies among previous studies signal that further research is needed to quantify the coupled effects of harvesting frequency and post-harvest structural retention, informing the on-going debate within the forest management community (Ray et al., 2009b). Moreover, the effects of "harvesting intensity" (used here to refer to the combination of harvesting frequency and structural retention) on C sequestration remains poorly investigated for northern hardwood forests specifically, though some research has been conducted in the U.S. Pacific Northwest (Harmon and Marks, 2002) and the U.S. Central Appalachian region (Davis et al., 2009). The specific C pools considered when defining "sequestration" affect the net accounting result (Harmon, 2001). In this study we are particularly interested in aboveground C storage, and thus use the term "sequestration" to refer to total C stocks (aboveground forest biomass + wood products), rather than uptake rates. We explicitly describe "forest carbon uptake rates" as such whenever they are discussed.

Quantifying mean C sequestration under a given forest management scenario requires a temporal scale spanning at least one complete harvesting cycle. For this reason, simulation modeling is often used to quantify C sequestration in forests. Numerous process-based, empirical, and hybrid models have been developed to project forest C dynamics in response to management activities. These models have been used in a variety of forest types in Europe (Seidl et al., 2007), northwest Russia (Krankina and Harmon, 1994), the U.S. Pacific Northwest (Harmon and Marks, 2002), Chile (Swanson, 2009), and the U.S. Central Appalachian region (Davis et al., 2009). While absolute predictions generated by models carry uncertainty, they are useful for comparing relative differences among alternate management and forest development scenarios (Eriksson et al., 2007; Seidl et al., 2007).

This study uses a widely accepted forest growth model to examine C sequestration tradeoffs among harvesting frequency and post-harvest structural retention under even- and uneven-aged forest management, while incorporating fluxes to wood products. We address a fundamental research question facing forest managers, namely: what is the most effective way to store C through forest management? Is C sequestration greater under more intensive approaches favoring high rates of uptake and C transfer to wood products? Or are less intensive approaches, favoring *in situ* forest C storage, more effective at maximizing C storage? We test two key variables with the potential to affect forest C sequestration: (1) harvesting frequency (rotation length or entry cycle), and (2) post-harvest structural retention (residual biomass following a harvest). Our first hypothesis is that unmanaged forests sequester greater amounts of C than actively managed forests, even accounting for C storage in durable wood products. The second hypothesis focuses on the effects of management intensity. We hypothesize that silvicultural prescriptions with increased structural retention coupled with decreased harvesting frequency will sequester the greatest amount of C relative to other active management scenarios.

2. Methods

2.1. Study area and selection of study sites

The geographic focus of this study is the northern hardwood region of the northeastern U.S., encompassing portions of upstate New York, Vermont, New Hampshire, and Maine (Fig. 1). The study area is dominated by northern hardwood-conifer forests, in which *Acer saccharum* (sugar maple), *Fagus grandifolia* (American beech), *Tsuga canadensis* (eastern hemlock), and *Betula alleghaniensis* (yellow birch) form the major late-successional species. We used Mapmaker 2.1 (*accessed* 7/22/2008, *available at*: www.fia.fs.fed.us/tools-data/other/) to stratify the study area by eco-subregions (Bailey, 2004) and then selected Forest Inventory and Analysis (FIA) plots (or sites) from within these to ensure that our sample was representative and well-distributed (Fig. 1). We used the most recent FIA inventory data (Maine: 2003, New York: 2004, New Hampshire: 2005, Vermont: 2005) to avoid potential discrepancies among survey periods. We further stratified FIA plots using US Forest Service defined site-specific variables to select only financially mature stands ready for harvest at the beginning of the simulation period. Variables included stand age (80–100 years old), slope (0–50%), forest type (maple-beech-birch), stand origin (natural), site productivity (site class 1–5 out of 7), physiographic class (mesic classes 21–25), basal area (BA > 23 m^2 ha^{-1}), and total merchantable cubic volume (>141 m^3 ha^{-1}). To obtain a sufficient sample size, our selection criteria encompassed a degree of heterogeneity in initial stand conditions. The stratification process, applied to the entire FIA database for the selected subregions, resulted in a total of 32 FIA plots meeting these criteria (14 sites in the White Mountain Region and western Maine, 3 sites in the Green Mountain Region, and 15 sites in the Adirondack Mountain Region); these are hereafter referred to as our study sites (Table 1).

2.2. Model description

FVS was chosen for its ability to simulate forest management activities, the availability of a model variant calibrated for northern

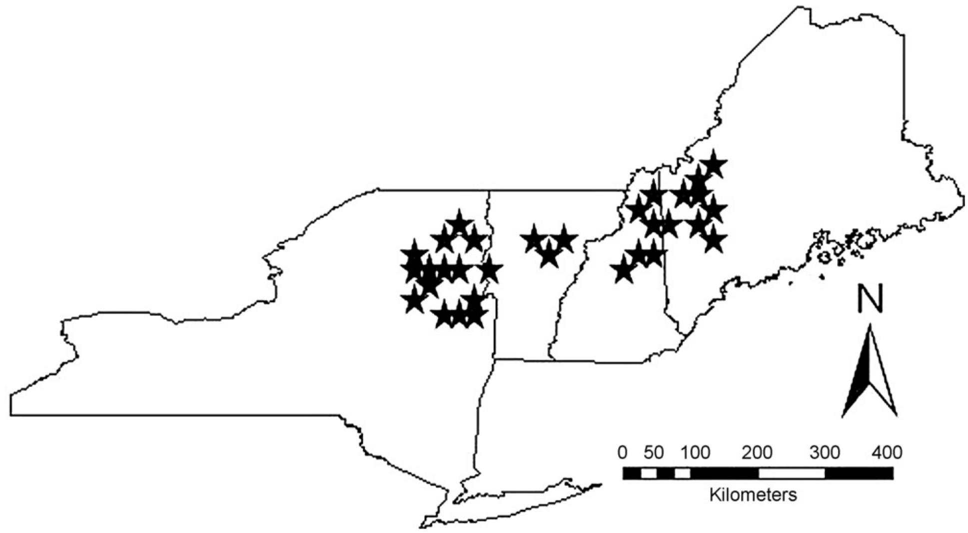

Fig. 1. Map of approximate locations of FIA plots used in simulation modeling. In total, we selected 32 stands spanning 10 eco-subregions and 4 states.

hardwoods, its accessibility to the general public, and its compatibility with FIA data (Ray et al., 2009a). In addition, FVS is one of several simulation models identified by voluntary C markets for estimating C sequestration in managed forests as part of climate change mitigation projects. Site specific stand structure and composition data were input into FVS to project stand development under alternate management scenarios. The FVS model has been used by North American forest managers for over 30 years in a variety of applications, and can be used in multiple biomes (Teck et al., 1996; Crookston and Dixon, 2005). FVS is a distance-independent, individual tree-based forest growth model, specifically designed for even- and uneven-aged stands with simple to mixed species composition (Crookston and Dixon, 2005). Aboveground biomass estimates are based on species group-specific allometric equations (Jenkins et al., 2003). The temporal scope of model projections ranges from five to several hundred years, with five-to-ten-year resolution. FVS calculates carbon sequestration in a variety of aboveground and belowground carbon pools at each time step; however, this study examined only the aboveground live and dead tree biomass model outputs. FVS also tracks C fluxes among wood products pools throughout their life cycles, from production to landfill or incineration, following methodologies developed by the USDA Forest Service (Smith et al., 2006). To simulate C fluxes in wood products, FVS identifies pulp and sawlogs (Dixon, 2002), and applies product-specific (i.e., paper, durable wood product, etc.) life span curves based on recent data specific to North American forest types (Smith et al., 2006).

Component models (variants) are used to adjust model behavior to reflect regional climatic conditions and growth rates. We used the Northeast Variant (NE-FVS), which uses growth and yield equations from NE-TWIGS (Hilt and Teck, 1989) and embedded height equations and bark ratios specific to northeastern species. A comprehensive validation study is not available for all sub-routines within NE-FVS. However, regional validation studies of NE-FVS have shown adequate predictions of forest growth in northern hardwood forests, with modeled volume predictions within 10–15% of actual volumes (Yaussy, 2000). FVS is effective at simulating forest growth under different management scenarios (Crookston and Dixon, 2005; Ray et al., 2009a). Modeling efficiencies of 77–99% were found in short term projections, however, regionally calibrated regeneration inputs are necessary to increase model accuracy in projections greater than 20 years (Bankowski et al., 1996). Furthermore, FVS is not an appropriate model for simulating impacts of climate change on forest growth (Yaussy, 2000).

Our stand development simulations assumed: (1) no natural disturbances; (2) constant climate; and (3) stable soil C storage. Excluding these sources of variability allowed us to isolate forest management effects on aboveground C and explore the relative differences between scenarios. Intensive forest management practices leading to heavy soil scarification can significantly increase soil carbon flux rates (Lal, 2005). While we recognize the uncertainty inherent to this approach, it is consistent with previous modeling work that also focused on relative differences among forest management trajectories (Eriksson et al., 2007; Seidl et al., 2007).

2.3. Silvicultural simulations

To test our two hypotheses, we evaluated a variety of even-aged (Table 2) and uneven-aged (Table 3) silvicultural prescriptions. In total, we simulated nine different management scenarios, including one passive (i.e., a reserve-based) "no management" scenario and eight active management scenarios. The latter were representative of silvicultural systems used commonly in the Northeast, but were modified to encompass a range of harvesting intensities. Specific prescription parameters were derived from silvicultural guides and studies in the Northeast (Leak et al., 1986; Nyland, 1996; Keeton, 2006). The silvicultural prescriptions included four even-aged scenarios and four uneven-aged scenarios. Within these broad groups, individual treatments were derived by factoring two levels for each of two categories: harvesting frequency and degree of structural retention (Tables 2 and 3), for a total of 8 active management scenarios.

To test the effect of harvesting frequency on C sequestration, stand development simulations for the four active management scenarios were run under two different harvesting intervals, long (120 years for even-aged scenarios; 30 years for uneven-aged scenarios) and short (80 years for even-aged scenarios; 15 years for uneven-aged scenarios) (Tables 2 and 3).

To evaluate the effect of structural retention, we developed two different even-aged management scenarios representing different levels of structural retention. A clearcut represented low structural retention and the most intensive management practice, with a complete removal of all trees greater than 5 cm diameter at breast height (DBH). A shelterwood (Nyland, 1996) represented greater structural retention, with the retention of six legacy trees (canopy

Table 1
Environmental, structural, and compositional attributes for the 32 Forest Inventory and Analysis (FIA) plots used in simulation modeling.

FIA plot code	Starting stand age	Eco-subregion[a]	Site index	Slope (%)	Elevation (meters)	Aspect (degrees)	Percent conifer (%BA)	Basal area (m^2/ha)	SDI	Trees per hectare	QMD (cm)	MAI ($m^3 ha^{-1} yr^{-1}$)	Number of strata [b]	Canopy height (m)	Percent canopy cover
2320030702501505	94	M211Af	44	14	518	195	13	37.6	510	10,843	6.6	2.6	1	18.6	80
2320030702502686	97	M211Af	42	12	427	235	21	31.5	444	11,125	6.1	1.6	1	19.5	82
2320030900702261	86	M211Af	34	8	549	215	34	33.1	506	17,423	4.8	1.8	1	19.2	76
2320030900703046	80	M211Ae	42	9	701	100	18	30.5	480	18,318	4.6	2.2	1	17.4	73
2320030900703313	87	M211Ag	51	12	183	2	50	35.1	430	5997	8.6	2.5	1	17.1	80
2320030900703677	89	M211Af	81	10	488	140	1	26.2	384	11,191	5.3	1.6	1	19.5	79
2320030901700110	84	M211Ag	37	14	366	22	62	42.2	604	16,032	5.8	3.2	2	21.3	72
2320030901700852	81	M211Af	37	13	823	248	42	29.4	372	6005	7.9	1.9	1	16.2	59
2320030901701013	96	M211Ae	41	14	610	124	17	34.7	450	8058	7.4	2.4	1	18.6	69
2320030901702963	85	M211Ag	65	27	274	65	0	24.6	334	7117	6.6	1.8	2	21.3	78
3320050200300163	82	M211Ad	81	17	274	250	0	30.5	398	7122	7.4	2.9	1	24.4	78
3320050200700781	80	M211Af	62	5	549	60	22	28.7	355	5300	8.4	2.3	1	21.9	71
3320050200900018	85	M211Ba	83	12	579	343	0	26.6	395	11,826	5.3	2.8	1	26.8	73
3320050200900904	97	M211Ad	49	3	427	0	34	32.6	454	10,939	6.1	2.1	1	23.5	82
3620040303506767	81	M211Db	62	0	335	0	44	47.8	477	2894	14.5	4.6	1	23.2	86
3620040304303762	80	M211Dd	60	12	457	179	3	38.1	465	6440	8.6	3.5	1	24.4	82
3620040304303966	80	M211Dd	43	6	549	256	27	33.1	403	5545	8.6	2.4	1	21.3	85
3620040403101088	95	M211Df	46	16	640	85	18	29.8	437	12,639	5.6	2.1	1	24.4	71
3620040403102007	92	M211Df	88	20	549	81	4	30.5	354	4040	9.9	2.5	1	25.9	76
3620040403102851	97	M211Df	35	18	335	148	37	35.1	413	4982	9.4	2.4	1	20.1	79
3620040403105127	100	M211Df	50	13	701	287	7	24.6	330	6808	6.9	1.5	1	20.1	66
3620040403105218	90	M211Df	57	33	305	137	57	33.5	443	8599	7.1	2.1	1	21.0	75
3620040404102413	82	M211Dd	47	0	640	0	15	48.0	525	4663	11.4	4.8	1	25.3	75
3620040404102456	86	M211Dd	60	12	671	12	15	29.6	362	5115	8.6	2.3	1	25.0	73
3620040404102703	90	M211Dd	62	18	579	327	57	26.2	345	6588	7.1	2.0	2	21.9	57
3620040404104669	91	M211Dd	41	22	732	306	20	29.2	363	5488	8.1	2.1	1	20.1	72
3620040404106138	86	M211Dd	60	12	579	12	27	38.3	480	7480	8.1	3.2	1	22.6	80
3620040411302486	80	M211De	88	12	488	166	0	44.3	506	5382	10.2	5.0	1	33.8	90
3620040411305029	100	M211De	48	14	518	169	51	25.5	357	8819	6.1	1.8	1	23.5	59
5020050200900479	91	M211Ae	37	11	396	276	44	38.8	507	9160	7.4	3.0	2	21.3	81
5020050201701120	85	M211Ba	64	27	671	235	0	29.6	400	828	6.9	2.4	1	22.9	80
5020050202300275	81	M211Ca	89	47	183	10	0	23.0	261	2743	10.4	2.9	2	27.4	59
Mean	88	–	56	14	503	146	23	33	423	7985	7.6	2.6	1	22.2	75
Standard deviation	7	–	17	9	162	109	20	6	72	4121	2.0	0.9	0.4	3.5	8

Note: All values were measured by USDA Forest Service Forest Inventory and Analysis Program, and retrieved through the stand list file in FVS.
[a] As defined in Cleland et al. (1997).
[b] As defined in Crookston and Stage (1999).

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Table 2
Description of the four even-aged silvicultural prescriptions used as management scenarios. We used a factorial design to test the independent effects of and interactions among two levels each for harvesting frequency and structural retention.

Structural retention	Harvesting frequency	
	High (80 years)	Low (120 years)
	Clearcut_High	*Clearcut_Low*
Low	(1) Commercial thin: implement when stand reaches stocking density above fully stocked (2) Clearcut: 2005 and 2085 Number of permanently retained trees/ha: 0 Slash removed from site	(1) Commercial thin: implement when stand reaches stocking density above fully stocked (2) Clearcut: 2005 and 2125 Number of permanently retained trees/ha: 0 Slash removed from site
Structural retention	Harvesting frequency	
	High (80 years)	Low (120 years)
	Shelterwood_High	*Shelterwood_Low*
High	(1) Commercial thin: implement when stand reaches stocking density above fully stocked (2) Shelterwood harvest: 2005 and 2085 Residual basal area: 14 m^2/ha Number of permanently retained trees/ha: 6 Smallest diameter in removal cut: 15 cm Slash left on site	(1) Commercial thin: implement when stand reaches stocking density above fully stocked (2) Shelterwood harvest: 2005 and 2125 Residual basal area: 14 m^2/ha Number of permanently retained trees/ha: 6 Smallest diameter in removal cut: 15 cm Slash left on site

trees never harvested) per hectare (Table 2). In uneven-aged scenarios, two individual tree selection (ITS) systems were used. For ITS, harvesting was based on a pre-defined diameter distribution (q factor) that directed harvesting towards diameter classes with stem densities above target levels (Table 3). Slash was not included in the aboveground dead wood carbon calculations when removed from the site as part of management prescriptions.

We ran all the management scenarios over 160 year simulation periods in order to capture a minimum of two complete harvesting cycles in the high frequency even-aged management scenarios. Estimates of average C sequestration under lower frequency harvesting were thus lower than if these scenarios had been simulated through two complete cycles. This resulted in conservative evaluations of the relative differences among scenarios, while minimizing uncertainty associated with projections run over longer timeframes. Model calculations (e.g., predicted growth and mortality) were performed on 5 year time steps (Dixon, 2002).

2.4. Regeneration inputs in model simulations

Because NE-FVS includes only a vegetative regeneration submodel (i.e., limited stump sprouting only), user-defined parameters (including species, spatial distribution, total number per acre, and seedling size) must be defined in order to simulate regeneration. We acquired information on natural regeneration rates in northern hardwood forests from the literature (Graber and Leak, 1992) and from field data in the northeastern U.S. for similar silvicultural treatments and site/stand conditions (Vermont Forest Ecosystem Management Demonstration Project, unpublished data) (Table 4). We used these data to develop background regeneration rates based on site-specific average overstory species proportions. Background regeneration rates (intermediate to shade tolerant species only), input at 10 year intervals, emulated natural regeneration within stands, independent of forest management activities.

Table 3
Description of the four different uneven-aged silvicultural prescriptions used as management scenarios. We used a factorial design to test the independent effects of and interactions among two levels each for harvesting frequency and structural retention. ITS = individual tree selection.

Structural retention	Harvesting frequency	
	High (15 years)	Low (30 years)
	ITS_LowHigh	*ITS_LowLow*
Low	*q*-factor[a]: 1.3 Residual basal area: 15 m^2/ha Min DBH class: 5 cm Max DBH class: 50 cm DBH class width: 5 cm Number of legacy trees/ha[b]: 0 Slash left on site	*q*-factor[a]: 1.3 Residual basal area: 15 m^2/ha Min DBH class: 5 cm Max DBH class: 50 cm DBH class width: 5 cm Number of legacy trees/ha[b]: 0 Slash left on site
Structural retention	Harvesting frequency	
	High (15 years)	Low (30 years)
	ITS_HighHigh	*ITS_HighLow*
High	*q*-factor[a]: 1.3 Residual basal area: 19 m^2/ha Min DBH class: 5 cm Max DBH class: 61 cm DBH class width: 5 cm Number of legacy trees/ha[b]: 12 Average diameter of legacy tree: 41 cm Slash left on site	*q*-factor[a]: 1.3 Residual basal area: 19 m^2/ha Min DBH class: 5 cm Max DBH class: 61 cm DBH class width: 5 cm Number of legacy trees/ha: 12[b] Average diameter of legacy tree: 41 cm Slash left on site

[a] *q*-Factor is defined as the ratio of the number of stems to those in each successively larger diameter class.
[b] Legacy tree is defined as a permanently retained tree larger than the maximum diameter used to define the target diameter distribution.

Table 4
Regeneration inputs used in model simulations. The numbers represent seedlings per hectare.

Management scenario	*Acer saccharum*	*Fagus grandifolia*	*Tsuga canadensis*	*Picea rubens*	*Fraxinus americana*	*Betula alleghaniensis*	*Acer rubrum*	*Populus tremuloides*	*Betula papyrifera*
Clearcut	4448	1730	432	432	8154	8093	8093	15,320	15,320
Shelterwood	4448	4695	62	62	618	556	1174	–	–
ITS_Low Retention	2471	1730	309	309	62	62	185	–	62
ITS_High Retention	1977	2224	309	309	62	57	185	–	62
Background	494	247	62	62	–	62	62	–	–

For active management scenarios, we adapted regeneration data specific to northern hardwood even-aged (Leak, 1987, 2005) and uneven-aged management (Mader and Nyland, 1984; Leak, 1987; Donoso et al., 2000). We correlated input regeneration values (Table 4) with percent canopy cover (e.g., decreased percent canopy cover following harvests corresponded with increased total seedling inputs). We also adjusted the relative proportions of shade intolerant, intermediate, and tolerant species based on post-harvest canopy cover (Nunery, 2009). We employed user-defined model rules to initiate management scenario-specific regeneration inputs at the time step immediately following all simulated regeneration harvests. A full description of adjustments to regeneration inputs, based on modeled biomass accumulation sensitivity to stand density, is presented in Nunery (2009).

2.5. Data analysis

Simulation output from the 32 different sites were averaged to produce mean values for each scenario. All values, unless stated otherwise, are presented as mean C sequestration over the 160 year simulation period. We calculated the mean C stock in aboveground biomass (live and dead) and wood products during the simulation period, as a way to compare C sequestration between management scenarios (Eriksson et al., 2007). In order to examine the tradeoffs in C sequestration between active and passive management, our first hypothesis, we used SPSS 16.0 (2008) statistical software to run single-factor ANOVA and post hoc Bonferroni multiple comparisons testing significant differences ($\alpha = 0.05$) between scenarios. To evaluate our second hypothesis, examining the effect of management intensity on C sequestration, we used two-way ANOVA to test for significant effects of harvesting frequency, structural retention, and their interaction on mean C sequestration.

We also conducted a sensitivity analysis to help identify subtle differences in the effects of harvesting frequency on C sequestration. We did this by adjusting the low and high harvesting frequency scenarios applied to each of the four original silvicultural prescriptions. The original high harvesting frequency (80 years in even-aged and 15 years in uneven-aged scenarios) was decreased by 25% to create two additional harvesting frequencies (60 years for even-aged and 11 years for uneven-aged). The original low harvesting frequency (120 years in even-aged and 30 years in uneven-aged) was increased by 25% to create two additional harvesting frequencies (150 years for even-aged and 38 years for uneven-aged scenarios). Due to data storage limitations in the model, we were unable to simulate extremely high harvest frequencies (harvesting frequency < 15) for uneven-aged scenarios over the entire 160 year simulation period. For this reason, the 25% below original high frequency scenarios (11 year entry cycles) for uneven-aged management are computed in FVS the same as the original high frequency (15 year harvesting frequency), and the sensitivity analysis in uneven-aged scenarios is restricted to three different harvesting frequencies (15, 30, and 38 years). Adjusted model outputs were tested using two-way ANOVA.

A logical criticism of attributing predicted C sequestration effects solely to management scenario is that site characteristics, such as productivity, pre-harvest stand volume, and species composition (e.g., percent conifer), might also affect forest growth rates and C sequestration potential. To evaluate this, we used a classification and regression tree (CART) to test the predictive strength of management scenarios relative to other site-specific environmental, structural, and compositional attributes, modeled as independent variables. CART analysis is a powerful tool for analyzing complex ecological data (De'ath and Fabricius, 2000). It is a robust, nonparametric, binary method that partitions variance in a dependent variable through a series of repeated splits (branches) based on values of multiple independent variables (Breiman et al., 1984; Keeton et al., 2007b, p. 857). CART was chosen for its ability to explain variation within a single response variable (in this case, mean C sequestration) based on both categorical and continuous independent variables generated from FIA plot measurements (Table 5). In the case of independent

Table 5
Description of independent variables used in CART analysis. The character of variables is denoted by A = silvicultural scenario, S = spatial, E = environmental, C = stand composition, T = stand structure; and the type by N = numeric, O = ordinal, or C = categorical.

Variable	Character	Type	Values	Description
Scenario code	A	C	A–I	A (Background), B (ITS_HighLow), C (ITS_HighHigh), D (ITS_LowLow), E (ITS_LowHigh), F (Clearcut_Low), G (Clearcut_High), H (Shelterwood_Low), I (Shelterwood_High)
Eco-subregion	S	C	10	No of ecological subregions included, as defined by the USDA, 2005, Forest Service ECOMAP team, Washington, DC
Site index	E	N	$30 < x < 90$	Site index for sugar maple at tree age 50
Aspect	E	N	$0 < x < 359$	Aspect in degrees for individual stands
Percent conifer	C	N	$0 < x < 63$	Starting percent conifer, calculated as a percentage of basal area
Basal area	T	N	$24 < x < 49$	Starting basal area (m^2/ha),
Quadratic mean diameter	T	N	$4.6 \leq x \leq 11.4$	Starting QMD. QMD is the diameter of the tree of average basal area.
Structure class	T	O	0–6	0 (bare ground), 1 (stand initiation), 2 (stem exclusion), 3 (understory reinitiating), 4 (young forest, multi-strata), 5 (old forest, single stratum), 6 (old forest, multi-strata) (Crookston and Stage, 1999)
Number of strata	T	O	1–3	Strata differentiated by 30% differentiation in tree height, with minimum threshold of 5% cover to qualify as a strata (Crookston and Stage, 1999)
Slope	E	N	0–30	Percent slope steepness for individual stands
Stand age	T	N	$80 \leq x \leq 100$	Starting stand age in years

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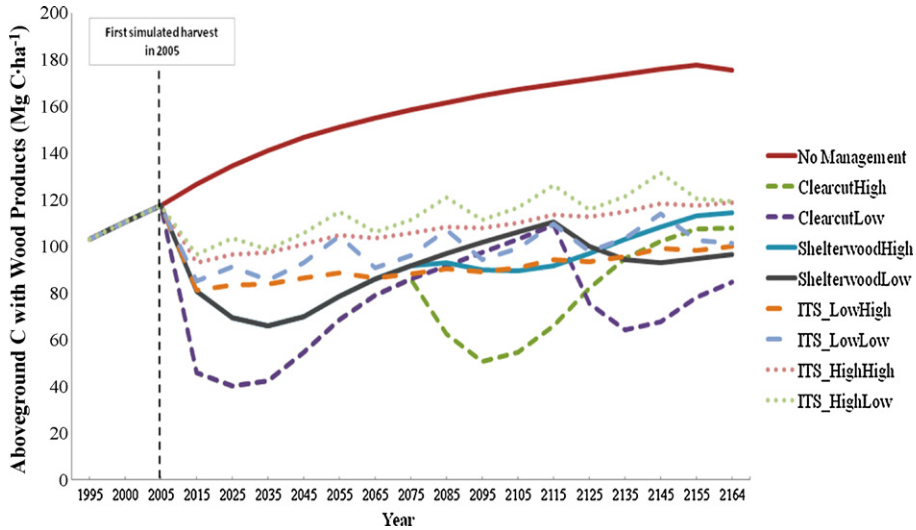

Fig. 2. Simulation output time series for the 9 different management scenarios (values represent 10 year mean of 32 stands C storage in aboveground live/dead biomass and wood products). Ten year means of C sequestration were used to create chronosequences to illustrate the temporal dynamics for each management scenario, however these values were not used in the overall statistical analyses and are presented here for illustrative purposes. Average forest growth was estimated for 1995 using 20 year mean predicted growth rates of all stands. Chronosequences starts from the estimated mean averages in 1995, all harvest cycles began at 2005 (noted with vertical dotted line). For management scenario descriptions refer to Tables 2 and 3.

variables exhibiting strong collineatity ($r^2 > 60$), the variable having greater correlation with the dependent variable was used in analyses to avoid redundancy. CART analysis was performed using S-Plus software (Statistical S-Plus, 2002). Cost-complexity pruning was used to eliminate non-significant nodes. Pruning was dictated by $\alpha = 0.05$, in this case a measure of how much additional accuracy an individual split must add to the entire tree to warrant additional complexity.

3. Results

3.1. Mean C sequestration under alternate forest management scenarios

3.1.1. Simulation model predictions

The simulation results show a clear gradient of increasing C sequestration as forest management intensity ranges from high (clearcut) to low (ITS_HighLow and No Management) (Fig. 2). Sharp declines in C within active management scenarios are caused by the removal of C from the forest following a scheduled harvest. The amplitude of these declines is muted by the flux of C into storage pools in wood products as well as the averaged 10-year C sequestration values. Generally, scenarios with decreased harvesting frequency show greater accrual of C as a result of accretion of C in dead wood pools and increased live biomass (Fig. 2). Clearcut scenarios sequestered less C than all other management scenarios (Table 6). Shelterwood scenarios sequestered similar amounts of C as ITS scenarios emphasizing low structural retention. Of the active management scenarios, ITS scenarios incorporating high structural retention sequestered the greatest amount of C (Table 6). Mean C sequestration in the no management scenario was significantly higher ($p < 0.01$) than all other scenarios as indicated by ANOVA and multiple comparison tests (Fig. 3).

3.1.2. Effects of harvesting frequency and post-harvest structural retention

Model predictions showed that post-harvest structural retention significantly affects C sequestration ($p < 0.01$), based on the results of the two-way ANOVA. In our initial analysis, harvesting frequency did not have a statistically significant effect ($p = 0.081$, Table 7). The interactive effect of harvesting frequency and retention also was not statistically significant ($p = 0.584$). In order to investigate more subtle differences among silvicultural prescriptions, we re-ran the two-way ANOVAs, separating treatments into two groups: even-aged and uneven-aged treatments (Table 7). In this second iteration, harvesting frequency significantly affected C sequestration for uneven-aged treatments ($p = 0.01$). Conversely, for even-aged scenarios our initial set of harvesting frequencies did not significantly affect C sequestration ($p = 0.658$). In both uneven and even-aged scenarios, structural retention significantly affected

Table 6
Mean C storage over the 160 year simulation period for several different pools ($n = 32$).

Management scenario	Value (mean ± 95% CI)					
	Total C with wood products (Mg C/ha)	Aboveground live (Mg C/ha)	Standing dead (Mg C/ha)	Down dead wood (Mg C/ha)	Wood products (Mg C/ha)	Landfill (Mg C/ha)
No Management	157 ± 9	140 ± 8	7 ± 0.5	13 ± 1	0 ± 0	0 ± 0
ITS_HighLow	113 ± 5	83 ± 3	0.6 ± 0.2	9 ± 1	9 ± 1	12 ± 2
ITS_HighHigh	107 ± 5	75 ± 3	0.3 ± 0.1	9 ± 1	10 ± 1	13 ± 2
ITS_LowLow	98 ± 5	63 ± 2	0.3 ± 0.1	8 ± 1	11 ± 1	16 ± 2
ITS_LowHigh	91 ± 4	54 ± 2	0.2 ± 0.04	9 ± 1	12 ± 1	16 ± 3
Shelterwood_Low	90 ± 5	64 ± 5	0.2 ± 0.1	7 ± 0.4	9 ± 1	10 ± 1
Shelterwood_High	90 ± 5	65 ± 4	0.2 ± 0.1	7 ± 0.4	8 ± 1	10 ± 1
Clearcut_Low	74 ± 5	31 ± 3	0.1 ± 0.03	9 ± 1	17 ± 1	8 ± 1
Clearcut_High	72 ± 5	29 ± 3	0.1 ± 0.04	10 ± 1	15 ± 1	18 ± 2

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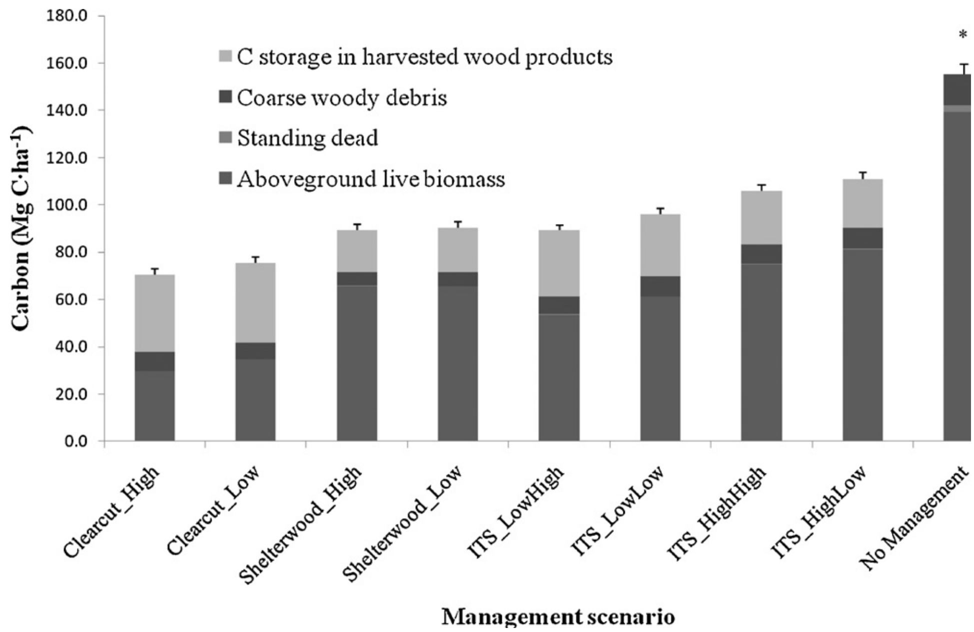

Fig. 3. Comparison of mean C stocks in nine different management scenarios. Error bars show + one standard error of the mean. For management scenario descriptions refer to Tables 2 and 3. Asterisk notes significant difference ($p < 0.01$) between active and passive management scenarios. Significant differences between active management treatment effects are described in Table 7.

C sequestration ($p < 0.01$). Furthermore, the interaction of harvesting frequency and retention was not significant in either uneven-aged ($p = 0.716$) or even-aged ($p = 0.554$) management scenarios.

To test model sensitivity to harvesting frequency, we performed a secondary analysis in which we adjusted harvesting frequency in all active management scenarios (Table 8). When the difference between low and high frequencies was increased by 25% or more, C sequestration for all scenarios was significantly affected ($p \leq 0.01$). The interaction of harvesting frequency and structural retention was not significant ($p > 0.01$), except when scenarios were compared against even-aged prescriptions with harvesting frequency set to 60 years ($p < 0.01$). In this case, the strong interaction was driven by a combination of extremely high harvesting frequencies (relative to typical silvicultural practices in the northern hardwood region), and very low structural retention.

3.1.3. Effects of forest management scenario versus site-specific factors

The CART results ($n = 288$) strongly supported our second hypothesis that harvesting intensity significantly affects C sequestration, but showed that site-specific variables, in some cases, can also be important secondary predictors. Of the eleven independent variables included in the initial model, four variables were incorporated in the final CART model: management scenario, site index, percent conifer, and basal area. Of these variables, management scenario was the strongest predictor of mean C sequestration, explaining variance at both primary, and in some cases, lower splits on the tree (Fig. 4). The primary split at the root node, or top of the tree, was divided between active and passive management techniques (Fig. 4). The left side of the tree was further divided at the next node between high intensity (higher harvesting frequency and lower retention) and low intensity (lower harvesting frequency and higher retention) active management scenarios. However, after the general range of C sequestration potential was established by management scenario, CART showed that some sub-groupings of sites with higher site index (i.e., more productive), greater initial basal area (e.g., >36.4 m^2/ha), and lower percent conifer (e.g., <15%) had significantly greater mean C sequestration. Together these results indicate the potential for interaction between management scenario and site-specific conditions.

3.2. Effects of forest management scenarios on C uptake rates

To clarify the relative importance of uptake rates versus storage in our estimates of total predicted sequestration, we calculated average annual C uptake rates three different ways (Table 9): (1) C uptake rate per harvest cycle with the inclusion of wood products (U_1); (2) C uptake rate for 160 simulation period without the

Table 7
Treatment effects on the mean C sequestration over the 160 year simulation period, based on two-way ANOVA. Italicized p values are statistically significant.

Treatment	Silviculture type	Mean square error	*F*	Significance (*p*)
Harvesting frequency × structural retention (interaction)	Total	92.1	0.300	0.584
	Even-age	71.1	0.352	0.554
	Uneven-age	26.4	0.133	0.716
Harvesting frequency	Total	940.2	3.07	0.081
	Even-age	39.8	0.197	0.658
	Uneven-age	1373.4	6.91	*0.010*
Structural retention	Total	17,575.9	57.3	*0.000*
	Even-age	9674.5	48.0	*0.000*
	Uneven-age	7944.0	40.0	*0.000*

Table 8
Two-way ANOVA results from sensitivity analysis. Results are divided by harvesting frequency and structural retention. Harvesting frequency adjustments are shown as percent above (+) or below (−) the original high and low harvesting frequencies used in simulation modeling. Four harvesting frequencies were used: (1) 25% below the original high frequency (60 years even-age; 11 years uneven-age); (2) the original high frequency (80 years even-age; 15 years uneven-age); (3) the original low frequency (120 years even-age; 30 years uneven-age); (4) 25% above original low frequency (150 years even-age; 38 years uneven-age). Italicized *p* values are statistically significant.

Treatment	Silviculture type	Harvesting frequency adjustment	Mean square error	*F*	Significance (*p*)
Harvesting frequency × structural retention (interaction)	Even-age	−25%	14,955.3	94.7	*0.000*
		+/−25%	17,339.0	103.4	*0.000*
		No change	71.1	0.4	0.554
		+25%	317.4	1.5	0.223
	Uneven-age	−25%[a]	67.8	0.3	0.569
		+/−25%[a]	67.8	0.3	0.569
		No change	26.4	0.1	0.716
		+25%	67.8	0.3	0.569
Harvesting frequency	Even-age	−25%	17,935.0	113.6	*0.000*
		+/−25%	29,779.8	177.6	*0.000*
		No change	40.0	0.2	0.658
		+25%	2020.6	9.6	*0.002*
	Uneven-age	−25%[a]	3811.7	18.4	*0.000*
		+/−25%[a]	3811.7	18.4	*0.000*
		No change	1373.4	6.9	*0.010*
		+25%	3811.7	18.4	*0.000*
Structural retention	Even-age	−25%	45,037.8	285.2	*0.000*
		+/−25%	41,142.1	245.4	*0.000*
		No change	9674.5	48.0	*0.000*
		+25%	7916.2	37.4	*0.000*
	Uneven-age	−25%[a]	7402.1	35.6	*0.000*
		+/−25%[a]	7402.1	35.6	*0.000*
		No change	7944.0	40.0	*0.000*
		+25%	7402.1	35.6	*0.000*

[a] As a result of model limitations, 11 year harvesting frequencies in uneven-aged scenarios are simulated the same as 15 year entry cycles and values are identical.

inclusion of C stored in wood products (U_2); and (3) C uptake rate for 160 simulation period with the inclusion of wood products (U_3). Annual uptake rates were calculated by averaging the delta values between time steps over the specified period of time. Greater temporal variation in uptake rates (Table 9) highlights C flux changes over time as a result of management activities. When C uptake rates were averaged by harvest cycle (U_1), clearcut scenarios had greater C uptake rates than all other scenarios (Table 9). In this same calculation (U_1), C uptake rates in the no management scenario were the third highest overall. When averaged over the 160 year simulation period without the inclusion of C stored in wood products (U_2), C uptake rates in three scenarios were negative. However, the inclusion of C stored in wood products (U_3) resulted in positive uptake rates for all scenarios. It should be noted that mean C uptake rates for the 160 year simulation period (U_2 and U_3) include at least one harvest in

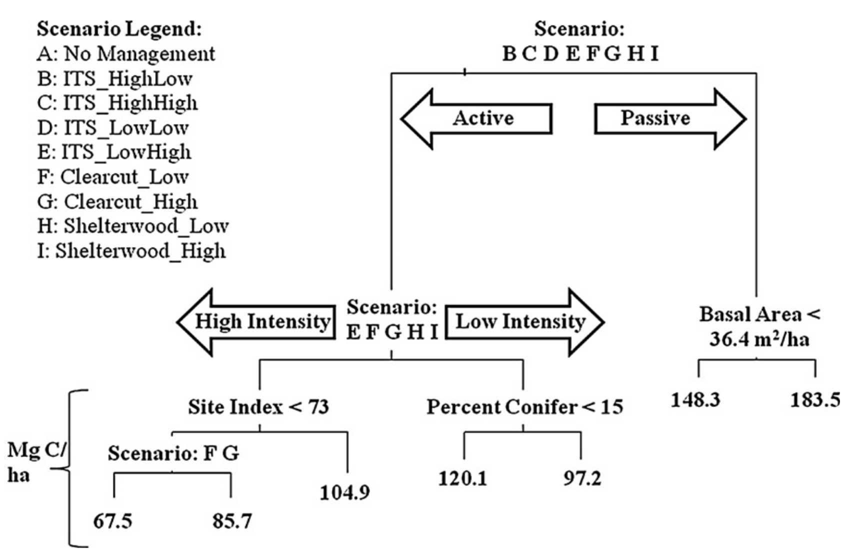

Fig. 4. Classification and regression tree (CART) showing independent variables selected, split values, and partitioned mean values (bottom) of the dependent variable (mean C sequestration). The figure ranks independent variables by predictive strength (top to bottom); the length of each vertical line is proportional to the amount of deviance explained by each variable. Independent variables were selected from an initial set of 11 variables. Minimum observations required for each split = 5; minimum deviance = 0.05; n = 288. The n value in CART is determined by the multiplication of the total number of inventory plots (n = 32) and the total number of management scenarios (n = 9).

Table 9
Comparison of three different calculated mean C uptake rates by management scenario.

Management scenario	Values (mean ± 95% CI)			
	Harvesting frequency (years)	U_1 Forest C uptake rate per harvesting cycle (Mg C ha^{-1} yr^{-1})	U_2 Forest C uptake rate for 160 year simulation period (Mg C ha^{-1} yr^{-1})	U_3 Forest and harvested wood products C uptake rate for 160 year simulation period (Mg C ha^{-1} yr^{-1})
Clearcut_High	80	0.55 ± 0.05	0.23 ± 0.03	0.23 ± 0.05
Clearcut_Low	120	0.44 ± 0.05	0.02 ± 0.03	0.08 ± 0.05
Shelterwood_High	80	0.18 ± 0.05	0.13 ± 0.02	0.13 ± 0.03
Shelterwood_Low	120	0.17 ± 0.04	−0.02 ± 0.02	0.02 ± 0.03
ITS_LowHigh	15	−0.02 ± 0.02	−0.04 ± 0.01	0.07 ± 0.03
ITS_LowLow	30	−0.01 ± 0.02	−0.04 ± 0.01	0.08 ± 0.03
ITS_HighHigh	15	0.04 ± 0.03	0.02 ± 0.02	0.14 ± 0.09
ITS_HighLow	30	0.05 ± 0.02	0.02 ± 0.02	0.14 ± 0.09
No Management	NA	0.36 ± 0.04	0.36 ± 0.04	NA

the active management scenarios, wherein significant amounts of C are lost from forest pools following the treatment.

4. Discussion

Our modeling results indicate that forest management intensity strongly affects C sequestration. While our findings tell a novel story, they build on previous studies in temperate forest regions (Eriksson et al., 2007; Seidl et al., 2007; Swanson, 2009). Research in North America has shown that actively managed forests sequester substantial amounts of C and should be considered when developing terrestrial C management options (Davis et al., 2009). Furthermore, research in European forests has highlighted the importance of considering wood products in C accounting (Eriksson et al., 2007; Seidl et al., 2007). Unlike previous studies, our results show there can be important, and sometimes interactive, effects of both post-harvest structural retention and harvesting frequency. These findings are relevant to ongoing debates regarding forest management and C sequestration, as addressed by our two hypotheses. The results supported both our first hypothesis that passive management sequesters more C than active management, as well as our second hypothesis that management practices favoring lower harvesting frequencies and higher structural retention sequester more C than intensive forest management.

Currently, the incorporation of active forest management in climate change mitigation is widely debated. At issue is whether this can achieve real (or net) C storage benefits, as opposed to simply increasing flux rates between different pools (Ray et al., 2009b). On one hand, intensively managed forests with high harvesting frequencies that produce wood products and biofuels are recognized as a viable option for reducing C emissions by avoiding substitution of more C intensive products or energy (Eriksson et al., 2007; Malmsheimer et al., 2008). On the other hand, numerous studies have concluded that the replacement of older forests with younger forests results in a net release of C to the atmosphere (Harmon et al., 1990; Schulze et al., 2000). Our results support these latter findings, and show that a shift towards intensively managed forests does not increase C sequestration when accounting is restricted to aboveground forest biomass and harvested wood products.

4.1. Effects of forest management on carbon sequestration

Our study is among the first to explore the combination of both harvesting frequency and post-harvest structural retention in the northern hardwood region. The results show that management practices favoring lower harvesting frequencies and higher structural retention sequester more C than more intensive practices. There are also more subtle effects of structural retention and harvesting frequency. In our first iteration of management scenario projections, structural retention had a greater effect on C sequestration than harvesting frequency. However, our sensitivity analysis showed that harvesting frequency can significantly affect C sequestration when rotation periods are sufficiently extended (or differentiated in the case of our methodology). This finding is supported by prior research (Krankina and Harmon, 1994; Liski et al., 2001; Balboa-Murias et al., 2006). Unlike previous studies focused on even-aged management (Harmon et al., 1990; Liski et al., 2001; Balboa-Murias et al., 2006) or *in situ* forest C without consideration of wood products (Krankina and Harmon, 1994), our analysis demonstrated the importance of retention and harvesting frequency for both even- and uneven-aged silvicultural practices and included wood products. Furthermore, we expect the differences between intensive and less intensive management to be even greater with the inclusion of greenhouse gas emissions from energy inputs (i.e., diesel fuel, gasoline, and electricity generation) associated with timber harvesting, trucking, and processing.

Accounting for emissions offsets from the substitution of wood products for non-wood products, such as steel and concrete, can significantly change the net C effect of forest management (Hennigar et al., 2008). This is especially true when considering the potential for reduced availability of wood products associated with decreased harvesting (Ray et al., 2009b). Comprehensive life-cycle analyses show that substituting wood products for steel and concrete decreases emissions of CO_2 to the atmosphere, due to the energy inputs required to manufacture the latter (Lippke et al., 2004). However, incorporation of substitutive effects within life-cycle analyses is challenging and potentially unreliable due to uncertainties in quantifying emissions from wood products transportation and methane emissions attributable to decomposition of forest products in landfills (Miner and Perez-Garcia, 2007). Moreover, C markets currently only award credits for C stored in the forest and in wood products due to the complexities involved with broader energy accounting (Ruddell et al., 2007). It is critical to understand the individual impacts of fluxes between pools in order to inform broader studies addressing substitutive benefits of forest products, which is why this study focused on C fluxes between a restricted set of identified pools.

Few studies have investigated the effects of harvesting frequency on C sequestration in uneven-aged silviculture specifically. Our study showed that for uneven-aged management scenarios common to the northern hardwood region, decreased harvesting frequency significantly increased C sequestration, independent of post-harvest structural retention in all scenarios. However, for even-aged management scenarios, we found that decreasing harvesting frequency alone does not always result in a statistically significant increase in C sequestration. Thus, consideration of both structural retention and harvesting frequency is necessary to optimize forest C sequestration in northern hardwood ecosystems.

4.2. Carbon uptake rates versus storage

Another important issue is the relative importance of C uptake rates versus *in situ* storage (or biomass) in terms of effects on total ecosystem sequestration. Our results showed that increased management intensity was positively correlated with increased C uptake rates. Younger forests have high C uptake rates, though they store significantly less C than older forests (Harmon et al., 1990; Luyssaert et al., 2008). However, C uptake rates vary depending on the scale (spatial, temporal, and process resolution) at which they are measured or assessed (Harmon, 2001). Our results showed that when the temporal scope was restricted to one harvesting cycle, the greatest C uptake rates were in clearcut scenarios (0.55 and 0.44 Mg C ha^{-1} yr^{-1}), representing the highest management intensity. These findings are consistent with previous research (Hoover and Stout, 2007).

With the exception of the two clearcut scenarios, "no management" had greater C uptake rates than all other management scenarios. We believe this is a result of two factors: (1) model sensitivity to regeneration inputs; (2) C sequestered in dead wood pools. We examined the first factor by testing model sensitivity to varying regeneration inputs, confirming the model's high sensitivity to user-defined regeneration inputs. Model sensitivity to regeneration was tested by re-running all 32 stands in two randomly selected management scenarios with no regeneration inputs. These simulations showed large increases in C uptake rates (up to 12.5 times greater). Mortality and stand developmental dynamics within FVS are largely a function of stand density; hence, accurate regeneration inputs are critical. NE-FVS simulations lacking well researched, user-defined regeneration inputs may not realistically reflect stand developmental processes for northern hardwood forests.

To address the influence of dead wood accumulation on uptake rates, we analyzed model partitioning of C within forest pools (Table 6). In the "no management" scenario, dead wood recruited and accumulated for longer and at faster rates compared to the other scenarios, with C additions to dead wood pools exceeding losses from decomposition. Allocation of C to dead wood pools increases with forest stand development and, in some cases, compensates for declining growth rates in older trees in terms of total ecosystem biomass accumulations (Harmon, 2001). For this reason, in our results "no management" had C accrual rates similar to the highest rates seen in intensive active management scenarios, where rapid biomass accretion was closely related to increased growth rates. Excepting the most intensive management scenarios (i.e., clearcutting), our results did not show that intensively managed forests have greater total C accumulation rates than older, slower growing forests. We attribute this to a combination of model sensitivity to regeneration, projected net positive C additions in live trees (Keeton et al., 2007b; Luyssaert et al., 2008), and the significantly greater dead wood C pool that develops over time under less intensive management scenarios. Furthermore, recent research has shown that older temperate forests maintain net positive C uptake rates longer than previously recognized (Luyssaert et al., 2008). Predicted C sequestration uptake rate declined over time for the unmanaged forest, largely as a result of the embedded equations in FVS describing forest growth patterns. This would mean that FVS may be under-estimating C uptake under the passive and less intensive management scenarios, as the model predicts reduced growth rates with increasing age (e.g., rotation period) and stand density. Thus, our conclusions comparing more intensive with less intensive scenarios are likely to be conservative. Our results were similar to those found by Davis et al. (2009), who found similar average annual C uptake rates between unmanaged and even-aged managed forests.

4.3. Uncertainty in projections

We recognize the uncertainties within model predictions related to underlying assumptions, such as those pertaining to disturbance and climate change. Changes in climate and natural disturbance regimes are highly likely to impact northeastern forests over the next 160 years. Natural disturbances impact C sequestration through rapid flux of C from living biomass to dead wood pools following large-scale disturbance, or more gradual flux of C between pools as a result of small to intermediate-scale disturbances. Climate change is likely to cause individual species range shifts (Beckage et al., 2008), community compositional changes (Xu et al., 2009), and increased mortality from drought, disease, and spread of exotic organisms (van Mantgem et al., 2009). Previous research has incorporated climate change and other anthropogenic stressors into model projections of forest ecosystem processes (Aber et al., 2001), however, this was not within the scope of our project.

In some cases, forestry practices have the potential to increase susceptibility to disturbances, such as windthrow. In temperate deciduous forests sensitivity to direct climate impacts also can be increased by canopy removals (Beckage et al., 2008). These effects are likely to accentuate the C sequestration differences between harvesting practices that maintain continuous forest canopy and below-canopy microclimate, and those that remove greater proportions of the canopy cover. The latter increase susceptibility to the direct effects of climate on plant physiology (Beckage et al., 2008), such as summer drought effects on seedlings (Franklin et al., 1991). The potential for CO_2 fertilization effects on plant growth is also major source of uncertainty (Hyvonen et al., 2007). Managing the risks associated with climate change and natural disturbances will require an adaptive approach regardless of carbon management scenario (Keeton et al., 2007a).

4.4. Integrating carbon sequestration into forest management systems

There is significant potential for enhanced C sequestration by modifying harvesting frequencies and retention levels, applied both to conventional silvicultural systems as well as innovative systems, such as disturbance-based forestry (North and Keeton, 2008). Some silvicultural tools have already been developed that utilize these concepts and would be applicable for land managers interested in managing for increased C sequestration. In the U.S. Pacific Northwest, for example, the variable retention harvest system (Franklin et al., 1997) retains post-harvest biomass and better approximates natural disturbance effects, including persistence of biological legacies (Franklin et al., 2002). In the U.S. Northeast, silvicultural approaches that emulate the frequency and scale of natural disturbances (Seymour et al., 2002), and increase post-harvest structural retention (Keeton, 2006) represent options for managing for high biomass forests. In temperate European forests, conversion from short rotation, even-aged forestry to uneven-aged management has been shown to increase net C sequestration, even under multiple climate change scenarios (Seidl et al., 2008). Less intensive management strategies may provide co-varying ecosystem services, such as enhanced habitat for late successional wildlife biodiversity (McKenny et al., 2006), hydrologic regulation (Jackson et al., 2005), and riparian functionality (Keeton et al., 2007b).

4.5. Conclusions: implications for carbon market participation

Sustainably managed forests sequester considerable amounts of C and thus have a role to play in climate change mitigation projects. However, it is essential to recognize that forestry is only one of many necessary abatement options (Tavoni et al., 2007). Standardized protocols for both managing and measuring C in forests are necessary to achieve demonstrable C sequestration benefits (Lindner and Karjalainen, 2007), while maintaining socially and ecologically responsible mitigation projects. The methodologies used in this study provide a simple framework, with broad geographic applicability, for assessing C sequestration effectiveness in managed forests. With nationally available FIA data, and a widely accessible simulation model, our general methodology can be replicated in other regions. Findings from this study together with further research will help policy makers evaluate the potential for forest management to contribute to climate mitigation programs.

Emerging cap and trade C markets may provide a potential source of revenue for forest landowners interested in practicing sustainable forest management (Ray et al., 2009b). To participate, landowners will have to demonstrate a change in management leading to enhanced C sequestration or "additionality." Our findings suggest that passive or less intensive management are the most effective management techniques for achieving additionality, assuming no inclusion of substitution effects and market mechanisms to minimize displacement of timber harvesting to other properties or regions. We showed that even with consideration of C sequestered in harvested wood products, unmanaged northern hardwood forests will sequester 39 to 118% more C than any of the active management options evaluated. This finding suggests that reserve-based approaches will have significant C storage value.

However, this does not mean that additionality cannot also be achieved through specific choice of active forest management approach. For example, we showed that a shift from high frequency management with low structural retention to low frequency management with high structural retention can sequester up to 57% more C. This difference is largely a result of the significant initial loss of C incurred from removal of large quantities of C stored in live and dead aboveground tree biomass, slow post-harvest accretion of C in dead wood pools, and the transient nature of C in the wood products stream (Smith et al., 2006). Collectively, our findings suggest that a shift to less intensive forest management alternatives will result in a net increase in C sequestration in northern hardwood ecosystems, so long as the accounting is restricted to forest and wood products C pools.

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