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Long-term management impacts on carbon storage in Lake States forests

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ABSTRACT

We examined carbon storage following 50+ years of forest management in two long-term silvicultural studies in red pine and northern hardwood ecosystems of North America's Great Lakes region. The studies contrasted various thinning intensities (red pine) or selection cuttings, shelterwoods, and diameter-limit cuttings (northern hardwoods) to unmanaged controls of similar ages, providing a unique opportunity to evaluate long-term management impacts on carbon pools in two major North American forest types. Management resulted in total ecosystem carbon pools of 130–137 Mg ha^{-1} in thinned red pine and 96–177 Mg ha^{-1} in managed northern hardwoods compared to 195 Mg ha^{-1} in unmanaged red pine and 224 Mg ha^{-1} in unmanaged northern hardwoods. Managed stands had smaller tree and deadwood pools than unmanaged stands in both ecosystems, but management had limited impacts on understory, forest floor, and soil carbon pools. Total carbon storage and storage in individual pools varied little across thinning intensities in red pine. In northern hardwoods, selection cuttings stored more carbon than the diameter-limit treatment, and selection cuttings generally had larger tree carbon pools than the shelterwood or diameter-limit treatments. The proportion of total ecosystem carbon stored in mineral soil tended to increase with increasing treatment intensity in both ecosystems, while the proportion of total ecosystem carbon stored in the tree layer typically decreased with increasing treatment intensity. When carbon storage in harvested wood products was added to total ecosystem carbon, selection cuttings and unmanaged stands stored similar levels of carbon in northern hardwoods, but carbon storage in unmanaged stands was higher than that of thinned stands for red pine even after adding harvested wood product carbon to total ecosystem carbon. Our results indicate long-term management decreased on-site carbon storage in red pine and northern hardwood ecosystems, but thinning intensity had little impact on carbon storage in red pine while increasing management intensity greatly reduced carbon storage in northern hardwoods. These findings suggest thinning to produce different stand structures would have limited impacts on carbon storage in red pine, but selection cuttings likely offer the best carbon management options in northern hardwoods.

1. Introduction

Concerns over rising atmospheric CO_2 concentrations, and the recognition that forests represent a major global carbon sink have sparked increased interest in developing forest management strategies to maximize carbon storage. Silvicultural research has traditionally focused on timber production rather than broader ecosystem services, leaving a knowledge gap in current efforts to develop carbon management strategies (Birdsey et al., 2006). While we have a well-developed understanding of changes in carbon storage during stand development following stand-replacing disturbances (Pregitzer and Euskirchen, 2004), many managed forests experience periodic partial disturbances associated with thinning (i.e., an intermediate treatment intended to reduce stand density, improve growth and health of the remaining trees, or recover potential mortality) or selection cutting (i.e., the periodic removal of trees to establish a new age class in an uneven-aged silvicultural system). Although researchers are beginning to consider the carbon consequences of partial harvests (e.g., Skovsgaard et al., 2006; Hoover and Stout, 2007; Finkral and Evans, 2008; Blanc et al., 2009; Davis et al., 2009; North et al., 2009), few experimental studies have directly examined the long-term carbon consequences of repeated thinning or selection cutting. Studies that quantify carbon pools in forests that have been managed for many decades using various silvicultural treatments are needed to fill this knowledge gap and identify the management practices most likely to increase carbon storage in managed forests.

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A growing number of studies examining the short-term effects of thinning and selection cutting indicate a number of potential influences on carbon storage in managed forests. Harvesting directly removes aboveground biomass, so these treatments can decrease live biomass or aboveground carbon pools (Skovsgaard et al., 2006; Finkral and Evans, 2008; Chatterjee et al., 2009; North et al., 2009). Further, treatments that periodically reduce stocking (i.e., basal area density) to lower levels might be expected to have smaller live biomass carbon pools than treatments that maintain higher stocking levels. Managed forests typically have less deadwood than unmanaged forests (Duvall and Grigal, 1999; Gibb et al., 2005), so we might also expect long-term forest management to reduce deadwood carbon pool sizes relative to unmanaged stands. Harvesting often reduces forest floor C storage substantially, but harvest impacts on mineral soil C are more variable and highly influenced by soil chemistry and physical soil characteristics (Nave et al., 2010). While these results provide a useful basis for predicting how different forest management practices may influence carbon storage in the short-term, modeling studies provide most of the current framework for evaluating the carbon consequences of silvicultural treatments over an entire rotation.

Modeling efforts suggest long-term forest management practices that involve repeated partial harvesting should decrease total ecosystem carbon storage relative to unmanaged stands of similar ages (Seidl et al., 2007; Swanson, 2009; Nunery and Keeton, 2010). These studies also suggest that rotation length and management intensity influence carbon storage, such that longer rotations and uneven-aged regeneration methods or even-aged systems with partial overstory retention may store more carbon than clearcutting (Seidl et al., 2007; Davis et al., 2009; Swanson, 2009; Nunery and Keeton, 2010). These results underscore the importance of understanding carbon storage patterns following repeated thinning (during an extended rotation) and different levels of overstory retention in both even-aged and uneven-aged systems.

Forest management activities can also produce wood products from harvested material, and these products can store significant amounts of carbon for many years after harvesting as both end-use products and landfill material (Eriksson et al., 2007; Seidl et al., 2007; Chen et al., 2008). Although the residence time of these products may be shorter than the residence time of live and dead wood in the forest (Profft et al. 2009), life cycle analyses indicate that products derived from different wood types (e.g., softwoods vs. hardwoods) or log sizes (e.g., pulpwood vs. sawlogs) have highly variable mean residence times (Smith et al., 2006; Profft et al., 2009). This suggests the potential for silvicultural practices that produce different stand structures and remove different tree sizes to promote different patterns of carbon storage in harvested wood products (Garcia-Gonzalo et al., 2007; Profft et al., 2009).

While studies of one-time treatment impacts on individual carbon pools and models of long-term management impacts on C storage in both forests and harvested wood products provide valuable insights, there is still a shortage of studies that have quantified total ecosystem carbon storage and wood product carbon storage following several decades of management to use in judging the transience of short-term effects or for validating model predictions. In this study, we examined carbon storage after 50+ years of forest management in two long-term silvicultural experiments that encompass a range of intermediate (i.e., thinning), uneven-aged, and even-aged treatments in red pine (*Pinus resinosa* Ait.) and northern hardwood forests of North America's Great Lakes region. We compared carbon pools among silvicultural treatments within each forest type, and analyzed differences in the proportion of total ecosystem carbon within each pool to evaluate how repeated thinning, selection cutting, shelterwood cutting, and diameter-limit cutting influence the quantity and distribution of carbon stored within managed stands compared to unmanaged control stands. The thinning and selection cutting treatments encompass a range of target basal area densities that can be used along with the shelterwood and diameter-limit treatments to evaluate the long-term influence of harvest intensity on carbon storage in managed forests.

2. Materials and methods

2.1. Study sites and experimental design

Our study used data from two long-term silvicultural experiments in the North America's Great Lakes region. The Cutfoot Growing Stock Level Study incorporates thinning treatments to various basal area densities in red pine (*Pinus resinosa* Ait.) stands on the Cutfoot Experimental Forest in northern Minnesota, USA (47°32′ N, 94°05′ W). The stands are composed of a nearly pure red pine overstory that established following a wildfire in 1867, and have a woody understory community dominated by beaked hazel (*Corylus cornuta* Marsh.) and balsam fir (*Abies balsamea* (L.) P. Mill.). Soils are outwash origin, excessively-drained loamy sands. The Cutfoot study has a randomized complete block design, with five thinning treatments replicated across three blocks of five 1–2 ha stands. Stands were thinned to 14, 18, 23, 28, or 32 $m^2\ ha^{-1}$ beginning in the winter of 1948–1949 and repeated at 5–10 year intervals, except for the 14 and 18 $m^2\ ha^{-1}$ treatments, which were not thinned after 1974. Our study uses data collected during the 2003 measurement of these stands, with the most recent thinning occurring eight years earlier in 1995. Measurements from three nearby unmanaged stands that were not in the original study design, but established after the same wildfire were used as unharvested controls.

The Argonne Cutting Methods Study incorporates five harvest treatments applied to second-growth northern hardwood stands on the Argonne Experimental Forest in northern Wisconsin, USA (45°45′ N, 89°03′ W). The overstory of these stands is composed primarily of sugar maple (*Acer saccharum* Marsh.), with minor components of white ash (*Fraxinus Americana* L.), basswood (*Tilia americana* L.), yellow birch (*Betula allegheniensis* Britt.), and eastern hemlock (*Tsuga canadensis* (L.) Carr.). The Argonne stands have a woody understory community dominated by sugar maple regeneration and raspberries (*Rubus spp.*). The stands regenerated after clearcutting in approximately 1902. Soils are moderately well-drained sandy loams with a high rock content formed on a glacial till plain. The Argonne study has a randomized block design with three blocks divided into 1 ha stands, each randomly assigned one of six treatments. Treatments included single tree selection to one of three residual basal area densities (14, 17, or 21 $m^2\ ha^{-1}$), a 20 cm diameter-limit treatment, a shelterwood treatment, and an unharvested control. The diameter-limit treatment removed all stems with a stump diameter (diameter at 30 cm in height) greater than 20 cm resulting in a basal area density of 4–5 $m^2\ ha^{-1}$ in 1952 and was harvested again in 1992. The shelterwood treatment was initially cut to 60% crown cover (about 9 $m^2\ ha^{-1}$) in 1958, with removal of the shelterwood overstory in 1966 for one treatment block, and in 1975 for the remaining blocks. Selection treatments were first implemented in 1951, and have been repeated at 10 year intervals since. Our study uses data collected in 2004, with the most recent harvest occurring in 2001. Both the Cutfoot and Argonne stands were bole-only harvested, with limbs retained on-site.

2.2. Data collection and summarization

Diameters of all trees $\geqslant$10 cm diameter at 1.4 m height (dbh) were sampled at three randomly located 0.08 ha plots in each stand at the Cutfoot study, and in five randomly located 0.04 ha plots in each stand at the Argonne sites. Live tree biomass was calculated for each species using equations from Pastor and Bockheim (1981), Perala and Alban (1994), and Ter-Mikaelian and Korzukhin (1997). Belowground biomass was estimated from aboveground volume measurements using equations by Smith et al. (2003) or from dbh using equations from Perala and Alban (1994). Aboveground and root biomass was converted to carbon mass by assuming a carbon concentration of 50%.

Saplings (woody stems < 10 cm dbh and ⩾2.5 cm dbh) were inventoried on a 30 m^2 plot at 10 points in each stand. Shrubs and tree regeneration (woody stems < 2.5 cm dbh and >15 cm tall) were inventoried on a 10 m^2 plot at the same 10 points. Sapling dbh and shrub diameter at 15 cm in height were used to estimate biomass (Perala and Alban, 1994), and biomass was converted to carbon mass by assuming a carbon concentration of 50%.

Soil and forest floor data were collected at 20 sample points on a 20 m × 20 m square grid in each stand. At each point, forest floor samples were collected in a 15.2 cm diameter plastic cylinder, and a 30 cm deep mineral soil core was collected with a 5 cm diameter soil corer. The forest floor and mineral soil samples were dried to a constant mass, weighed, ground, and analyzed for carbon content with a Thermo Elemental Iris Intrepid (model 14410300) elemental analyzer.

Herbaceous and woody vegetation <15 cm tall were sampled at the same 20 points used for soil and forest floor carbon pools. All herbaceous vegetation and woody vegetation <15 cm tall in a 0.18 m^2 plot was clipped and collected at each point. Sampling was timed in mid-July to correspond to peak standing biomass. Samples were dried to a constant mass, weighed, ground, and analyzed for carbon content with a Thermo Elemental Iris Intrepid (model 14410300) elemental analyzer.

Down deadwood was sampled using a line-intersect method (Brown, 1974) along three 9 m transects at five randomly chosen points in each stand. The diameter of all woody residue >0.64 cm (0.25 in) diameter was measured across the entire length of the transect. Woody biomass was calculated using the formulas:

$$\mathrm{CWD} = \sum[(f\,\mathrm{dia}^2 p_\mathrm{d})/L]$$

from Chojnacky et al. (2004), where CWD = coarse woody debris in Mg/ha, f is a unit conversion factor (f = 26.09266), dia is woody debris diameter at the point of transect intersection (in inches), p_d is wood density, and L is the total length of transects at a plot (in feet). For the red pine stands, we used locally-derived wood density values specific to this forest type based on four decay classes and four species groups (Duvall and Grigal, 1999), rather than the generic estimates from Chojnacky et al. (2004). Standing dead stems (snags) were sampled at the same five points used for down deadwood sampling using a variable radius plot with a 10 BAF prism (2.3 m^2 ha^{-1}). Deadwood biomass was converted to carbon mass by assuming a carbon concentration of 50%.

After calculating the sizes of each individual pool, we added them together to estimate total ecosystem C storage. We used these data to calculate the percentage of total ecosystem C represented by each pool in each stand as

$$\mathrm{POOLX}_\mathrm{prop} = 100 * (\mathrm{POOLX}/\mathrm{TEC})$$

where POOLX represents the percentage of total ecosystem carbon stored in any given individual carbon pool and TEC is the estimate of total ecosystem carbon for that stand.

We calculated carbon storage in wood products and landfills using a production approach based on methods described by Smith et al. (2006). We used estimates of bole minus bark carbon derived from our tree layer measurements and the allometric relationships described above as a starting point for dividing harvested carbon into industrial roundwood categories (hardwood sawlogs, softwood sawlogs, hardwood pulpwood, and softwood pulpwood), calculated the total carbon pool for each industrial roundwood category that was removed during each harvest over the lifetime of our long-term studies, and determined current carbon storage in wood products and landfills based on the fraction of industrial roundwood carbon estimated to remain in each pool at the time of our measurements using residence time data from Smith et al. (2006). We then added our estimates of carbon stored in wood products and landfills to estimates of on-site carbon pools in our study areas to determine the combined C storage in on-site pools, wood products, and landfills. We did not consider emissions during harvesting, transport, milling, or combustion for energy and other uses in our calculations as we were primarily interested in quantifying pools of stored carbon rather than estimating sequestration rates over the lifetime of the study.

2.3. Data analysis

We used analysis of variance to examine treatment-related differences in carbon storage of six individual pools (overstory trees including roots; understory including saplings, shrubs, tree regeneration, and herbaceous vegetation; deadwood including down deadwood and snags; forest floor; mineral soil; and harvested wood products including wood stored in end-use products and landfills) in addition to total ecosystem carbon (on-site carbon storage) and total combined carbon (total ecosystem carbon plus harvested wood products carbon). Individual and aggregated carbon pools were used as the dependent variable, with silvicultural treatment as the independent variable, and a fixed block effect. Analysis of variance was also used to examine treatment effects on the proportion of total ecosystem carbon stored in each of the individual on-site pools. Logarithmic and square root transformations were applied when necessary to meet ANOVA assumptions regarding the homogeneity of error variances and distribution of residuals. Differences in carbon storage or the distribution of total ecosystem carbon across pools among silvicultural treatments were analyzed using post hoc Tukey's tests. Since the unharvested stands used as controls in the red pine study were not a part of the original study design, and were not, therefore, randomized or located within the treatment blocks themselves, we analyzed these data using ANOVAs both with and without the inclusion of control stands. All significant differences in the text or figures are based on the ANOVAs without the controls stands for the red pine study, unless otherwise indicated. All ANOVAs using data from the northern hardwoods study were conducted with control stands included in the test. All analyses were performed at an α = 0.05 significance level using SAS version 9.2 (SAS Institute, Cary, NC).

3. Results

3.1. Red pine

Repeated thinning influenced some carbon pools (Table 1), but not all. Total ecosystem carbon was similar among thinning treatments (Fig. 1), but higher in unmanaged stands than in any thinning treatment (P < 0.001 for the ANOVA including control stands). Overstory tree carbon was somewhat higher in the 32 m^2 ha^{-1} treatment than the 14 or 23 m^2 ha^{-1} treatments, and higher in unmanaged stands than in any thinning treatment (P < 0.001 for the ANOVA including control stands). Understory carbon was not significantly different among treatments. Deadwood carbon was similar among thinning treatments, but 6–13 times higher in unmanaged stands than in thinned stands (P = 0.004 for the ANOVA including control stands). Forest floor

Table 1
ANOVA model results for analyses of treatment effects on carbon storage in two long-term silvicultural experiments in the Great lakes region, USA.

	Dependent variable	Model *P*-value	R^2	Block *P*-value	Treatment *P*-value	Minimum significant difference[a]
Red pine	Total ecosystem C	0.034	0.758	0.034	0.057	33.646
	Overstory tree C	0.012	0.819	0.713	0.005	19.256
	Understory C	0.148	0.624	0.075	0.293	2.540
	Deadwood C	0.568	0.389	0.210	0.860	12.516
	Forest floor C	0.049	0.730	0.064	0.065	4.055
	Mineral soil C	0.034	0.757	0.033	0.060	10.897
	Harvested wood C	0.144	0.627	0.13	0.182	13.766
	All pools combined	0.026	0.776	0.005	0.288	33.217
	Tree proportion	0.002	0.888	0.025	0.002	5.349
	Understory proportion	0.159	0.616	0.078	0.311	1.678
	Deadwood proportion	0.565	0.390	0.120	0.879	5.855
	Forest floor proportion	0.221	0.572	0.285	0.199	3.487
	Mineral soil proportion	0.004	0.869	0.322	0.002	4.953
Northern hardwoods	Total ecosystem C	<0.001	0.903	0.381	<0.001	51.173
	Overstory tree C	<0.001	0.900	0.580	<0.001	48.419
	Understory C	0.139	0.595	0.139	0.169	2.126
	Deadwood C	0.015	0.765	0.712	0.007	3.488
	Forest floor C	0.022	0.742	0.005	0.161	3.306
	Mineral soil C	0.023	0.739	0.002	0.510	15.581
	Harvested wood C	0.034	0.758	0.469	0.017	12.847
	All pools combined	0.003	0.833	0.413	0.001	52.779
	Tree proportion	<0.001	0.893	0.849	<0.001	19.722
	Understory proportion	0.094	0.634	0.109	0.117	1.771
	Deadwood proportion	0.072	0.657	0.828	0.036	1.752
	Forest floor proportion	0.001	0.884	<0.001	0.037	1.125
	Mineral soil proportion	<0.001	0.898	0.568	<0.001	19.875

[a] Based on post hoc Tukey tests at an $\alpha = 0.05$ significance level.

carbon was similar among thinning treatments and thinning treatments were similar to the control stands, although there was a nonsignificant trend towards greater forest floor carbon in the 14 and 18 $m^2\ ha^{-1}$ thinning treatments. Mineral soil carbon was similar among thinning treatments, but higher in unmanaged stands than in the 32 $m^2\ ha^{-1}$ treatment ($P < 0.001$ for the ANOVA including control stands).

The percentage of total ecosystem carbon stored in the overstory tree layer was lower in the 14 $m^2\ ha^{-1}$ thinning treatment than in any other treatment, but there were no significant differences among the other thinning treatments, and all other thinning treatments were similar to the control stands (Fig. 2). There were no significant differences among thinning treatments in the percentage of total ecosystem carbon stored in the understory or deadwood layers, but the percentage of total ecosystem carbon stored in deadwood was 4–8 times higher in unmanaged stands than in any thinning treatment ($P = 0.019$ for the ANOVA including control stands. The forest floor represented a similar percentage of total ecosystem carbon among thinning treatments, and was generally similar in thinning treatments compared to control stands. The proportion to total ecosystem carbon stored in the mineral soil was highly variable among treatments. Mineral soil represented a larger proportion of total ecosystem carbon in the 14 $m^2\ ha^{-1}$ thinning treatment than any other treatment except the 23 $m^2\ ha^{-1}$ treatment, and a smaller proportion of total ecosystem carbon in unmanaged stands than in any thinning treatment except the 32 $m^2\ ha^{-1}$ treatment ($P < 0.001$ for the ANOVA including control stands).

Although estimates of carbon stored in harvested wood products varied as much as twofold among treatments, there were no statistically significant differences in harvested wood product carbon due to the high degree of stand-to-stand variability within treatments (Fig. 3). When carbon storage in harvested wood products was added to total ecosystem carbon, the combined carbon storage was similar among thinning treatments, but unmanaged stands stored 30–43% more carbon than thinned stands ($P < 0.001$ for the ANOVA including control stands).

3.2. Northern hardwoods

Like red pine, forest management influenced many, but not all of the carbon pools we quantified in northern hardwoods (Table 1). Total ecosystem carbon was higher in the unharvested treatment than in the 14 $m^2\ ha^{-1}$ selection treatment, 17 $m^2\ ha^{-1}$ selection treatment, shelterwood, and diameter-limit treatment, but there was not a significant difference in carbon storage between unharvested stands and stands that received the 21 $m^2\ ha^{-1}$ selection treatment (Fig. 1). Stands managed using individual tree selection stored more carbon than stands treated with diameter-limit cutting, and the 21 $m^2\ ha^{-1}$ selection treatment stored more carbon than the shelterwood treatment. Overstory tree carbon was greater in unmanaged stands than in any other treatment except the 21 $m^2\ ha^{-1}$ selection treatment, and selection cutting treatments had more carbon in the tree layer than the diameter-limit treatment. There were no significant differences in understory carbon, forest floor carbon, or mineral soil carbon pools among treatments, but unmanaged stands stored 3–12 times more carbon in deadwood than managed stands. There were no significant differences in deadwood carbon pools among managed stands.

The tree layer represented a larger percentage of total ecosystem carbon in unmanaged stands, selection treatments, and the shelterwood treatment than in the diameter-limit treatment, and a greater percentage of total ecosystem carbon in unmanaged stands than in the shelterwood treatment (Fig. 2). There were no significant differences in the percentage of total ecosystem carbon represented by the understory or forest floor pools, but deadwood composed a greater percentage of total carbon in unmanaged stands than in the diameter limit treatment. Mineral soil represented the largest percentage of total ecosystem carbon in the diameter-limit treatment, and a larger percentage of total carbon in shelterwoods than in unmanaged stands.

There were significant differences in estimates of carbon storage in harvested wood products among silvicultural treatments in the Argonne study. The diameter limit treatment stored more

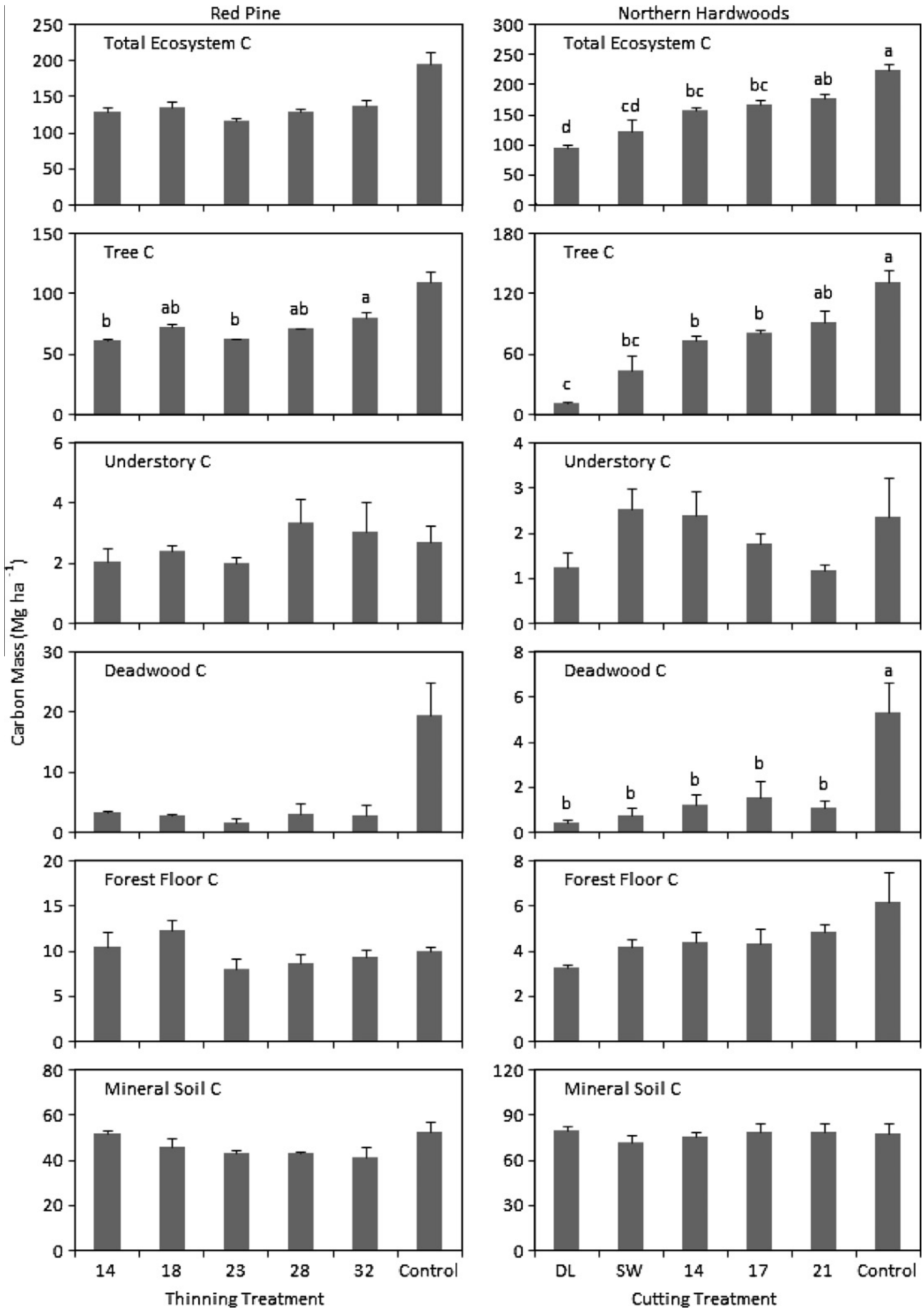

Fig. 1. Carbon storage in various pools in red pine and northern hardwood stands following more than five decades of periodic management. Different letters indicate significantly different means, and error bars represent one standard error. Note that control stands are shown only for reference purposes for red pine and were not included in post hoc multiple comparisons tests.

carbon in harvested wood products than the shelterwood or 21 m^2 ha^{-1} selection treatment (Fig. 3). The sum of harvested wood carbon and total ecosystem carbon in selection treatments was more similar to carbon storage in unmanaged stands than when these treatments were compared based only on total ecosystem carbon. Even when harvested wood carbon and total ecosystem carbon were added together carbon storage in the diameter-limit and shelterwood treatments was lower than the 21 and 17 m^2 ha^{-1} selection treatments and unmanaged stands.

4. Discussion

Five decades of forest management altered carbon pools in both red pine and northern hardwood ecosystems. Although

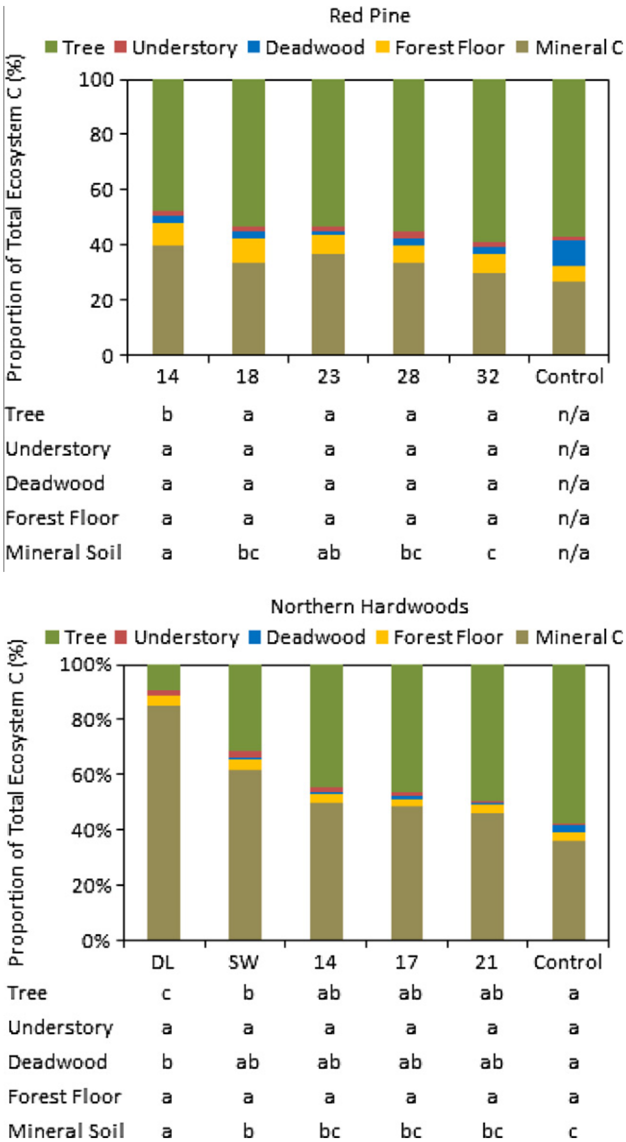

Fig. 2. Carbon storage in major ecosystem pools expressed as a proportion of total ecosystem carbon in red pine and northern hardwood stands following more than five decades of periodic management. Different letters below the graph indicate significant differences among treatments in the proportion of carbon stored in a given pool. Note that control stands are shown only for reference purposes for red pine and were not included in post hoc multiple comparisons tests.

comparisons between thinned and unmanaged control stands must be interpreted cautiously for the red pine study, most of the silvicultural treatments implemented in these two long-term studies appeared to reduce on-site carbon storage compared to unmanaged controls. However, the variability among treatments depended on the ecosystem that was studied. Both total carbon storage and storage in individual pools varied little among thinning treatments in red pine, but tree carbon (and as a result, total ecosystem carbon) was quite variable among silvicultural treatments in the northern hardwood ecosystem. The distribution of total ecosystem carbon among individual pools was also variable, with mineral soil typically representing a smaller percentage of total carbon in less intensive treatments. Our results suggest that, while long-term forest management clearly impacts carbon pools in both systems, carbon pools in red pine forests are relatively stable across a range of stocking levels, while carbon pools in northern hardwood forests appear to be more heavily influenced by management decisions.

Our finding that long-term forest management typically reduced on-site carbon storage compared to unmanaged stands in both ecosystems is consistent with results from modeling studies (Seidl et al., 2007; Swanson, 2009; Nunery and Keeton, 2010). Previous studies suggest this decline in carbon storage could be caused by decreased biomass in live trees, deadwood, and forest floor carbon (Duvall and Grigal, 1999; Gibb et al., 2005; Skovsgaard et al., 2006; Finkral and Evans, 2008; North et al., 2009; Nave et al., 2010). Our data support the argument that reduced carbon storage in tree and deadwood pools should decrease total ecosystem carbon storage in managed forests compared to unmanaged forests, but we did not find strong evidence of management impacts on forest floor carbon. Further, repeated partial harvests had no significant impact on understory carbon storage and limited impacts on mineral soil carbon storage in either system. This suggests that inventories of the relatively easy to sample tree and deadwood layers would likely account for much of the variability in carbon storage among red pine or northern hardwood stands on similar sites, regardless of management history.

The limited variability in total ecosystem carbon among thinning treatments in red pine and among selection cutting treatments in northern hardwoods is surprising since these treatments were designed specifically to manipulate basal area densities. Growing stock manipulation is common in both of our study systems. Red pine typically shows similar levels of stand productivity across the range of residual basal area densities encompassed by the Cutfoot study (Bradford and Palik, 2009; D'Amato et al., 2010), while productivity in northern hardwoods can nearly double across the range of basal area densities in the Argonne selection treatments (Buongiorno et al., 2000; Leak, 2003). Thus, differences in stand-level productivity associated with different stocking levels are an unlikely explanation for the absence of large differences in tree layer carbon storage among treatments in red pine. Higher productivity in treatments with low post-harvest basal area densities could, however help explain the absence of differences in carbon storage among selection cutting treatments in northern hardwoods since the potential for increased productivity could help these stands regain pre-treatment biomass stocks more rapidly than stands cut to higher residual basal area densities. Harvesting in the 14 and 17 $m^2\,ha^{-1}$ red pine thinning treatments did stop after 1975, so these stands may have recovered much of their pretreatment biomass stock. Greater carbon storage in selection cutting treatments than in the diameter-limit treatment in the northern hardwood study appear to be a product of much higher tree carbon storage in the selection cutting treatments since other pools were generally similar among treatments.

Mineral soil represented a highly variable percentage of total ecosystem carbon as a result of differences in the size of other pools among treatments. In general, mineral soil carbon constituted a much larger percentage of total ecosystem carbon in the most intense treatments (e.g., 14 $m^2\,ha^{-1}$ thinning in red pine or diameter limit cutting in northern hardwoods), although this trend was not statistically significant in the red pine study. This pattern is consistent with previous findings (Skovsgaard et al., 2006; North et al., 2009) and appears to be driven by the expected decline in carbon storage among live pools associated with heavy overstory removals (Davis et al., 2009; Swanson, 2009; Nunery and Keeton, 2010) coupled with relatively stable levels of mineral soil carbon among thinning treatments (Skovsgaard et al., 2006; Boerner et al., 2008; North et al., 2009).

Accounting for carbon storage off-site was insufficient to compensate for differences in on-site total ecosystem carbon among thinned and unmanaged stands in red pine, but reduced differences in carbon storage among selection treatments and unmanaged stands in northern hardwoods. This may partially result from the longer residence times attributed to hardwood pulpwood

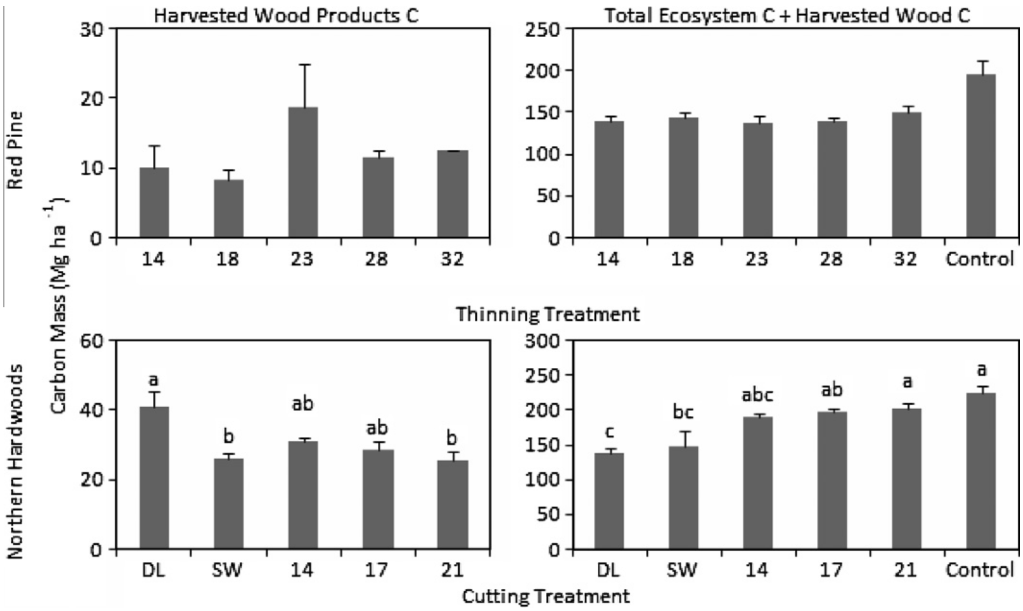

Fig. 3. Carbon storage in harvested wood products and total, on-site ecosystem carbon storage plus harvested wood product carbon. Different Letters indicate significantly different means and error bars represent one standard error. Note that control stands are shown only for reference purposes for red pine and were not included in post hoc multiple comparisons tests.

than to softwood pulpwood in our calculations (Smith et al., 2006). Whatever the cause, selection treatments in northern hardwoods appear to offer a management alternative that can provide similar levels of carbon storage to unmanaged stands when harvested wood products are considered. The low levels of combined on-site and harvested wood products carbon storage associated with more intense silvicultural treatments in northern hardwoods is typical of results from other studies (Skovsgaard et al., 2006; Seidl et al., 2007; Swanson, 2009; Nunery and Keeton, 2010).

The influence of time since harvest and piece size on harvested wood product carbon storage should also be considered when interpreting our results. While all red pine thinning treatments were last harvested eight years before data collection, there was considerable variability in the number of years since the last harvest in the northern hardwoods. The northern hardwood shelterwood and diameter-limit treatment were last harvested 38 years and 12 years prior to our measurements, respectively, while the selection cutting treatments were last harvested just three years before our measurements. The residence time data we used in our calculations indicates about 54% of harvested sawlog carbon and 59% of harvested pulpwood carbon from the last entry was still stored at the time of our measurements as either end-use products or in landfills for the selection treatments, but only around 45% of harvested sawlog and pulpwood carbon was still stored from the last entry in the diameter-limit treatment, and just 35% of harvested sawlog and pulpwood carbon was still stored from the last entry in the shelterwood treatment (Smith et al., 2006).

Different growing stock levels in red pine and different regeneration methods in northern hardwoods also affect tree size and diameter distributions (Leak, 1996; Bradford and Palik, 2009; D'Amato et al., 2010; Gronewold et al., 2010), which impact the products that can be made from harvested wood, and therefore influence mean residence times (Profft et al., 2009). The purpose of this study was to provide point-in-time estimates of carbon storage in the forest (i.e., total ecosystem carbon) and harvested wood products after long-term management with different silvicultural practices so we did not develop detailed life cycle assessments for the wood products themselves and we did not consider carbon emissions from harvesting, fossil fuel burning, or decomposition that would influence rates of sequestration. However, our results should be reflective of the influence different silvicultural practices can have on the mean residence time of harvested wood carbon in so far as our calculation of carbon storage in harvested wood accounts for different residence times in hardwoods vs. softwood and in sawlogs vs. pulpwood (Smith et al., 2006). Thus, while our analyses do not allow us to make any detailed inferences about the mechanisms by which different silvicultural practices influence carbon storage in harvested wood products, or about future trends in carbon storage in our study systems, our results should reflect the cumulative impacts of these influences after a half century of forest management, at least within the range of forest types, silvicultural practices, and site conditions encompassed by our analyses.

5. Conclusions

Long-term management in these systems reduced total ecosystem carbon storage, but the influence of different cutting intensities varied between red pine and northern hardwood ecosystems. Thinning to different basal area densities had little influence on carbon storage in red pine, but carbon storage decreased with increasing treatment intensity in northern hardwoods. Our findings add to existing literature that indicates red pine forests offer a great deal of flexibility for forest managers interested in using different stand structures to balance multiple objectives including wood production, conservation, restoration, and carbon storage (Bradford and Palik, 2009; D'Amato et al., 2010; Powers et al. 2010). A no-harvest approach may maximize carbon storage in red pine when compared to repeatedly-thinned stands under strict stocking control, but when thinning is desired, managers may have great flexibility to choose prescriptions that focus on non-carbon objectives since carbon storage appears relatively invariant across a range of basal area densities in thinned stands.

In northern hardwood systems, selection cuttings may provide greater carbon storage potential than diameter-limit cuts or even-aged treatments, although the 20 cm diameter-limit used in this northern hardwood cutting methods study is relatively small compared to recommendations for maximum wood production and financial returns (Buongiorno et al., 2000). The 21 $m^2\ ha^{-1}$ selection treatment offers a possible compromise between achieving carbon storage levels close to those of unmanaged stands, while producing high quality wood products and some revenue, although merchantable volume production in northern hardwood stands is typically somewhat low at this level of basal area retention compared to 14–18 $m^2\ ha^{-1}$ selection cuttings (Crow et al., 1981; Leak, 2003). Selection cuttings to basal area densities around 17 $m^2\ ha^{-1}$ would provide intermediate levels of on-site carbon storage, while producing greater yields and providing relatively high levels of total carbon storage when carbon in the harvested wood product pool is added to carbon stored on-site.

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