Potential Influence of Forest Management on Regional Carbon Stocks: An Assessment of Alternative Scenarios in the Northern Lake States, USA

John B. Bradford

Abstract: Forest management affects stand age. In consideration of the strong link between stand age and carbon cycling, altering harvesting regimes can influence regional carbon stocks and sequestration. Recent research has quantified ecosystem carbon stocks across stand age in upland conifer and aspen–birch forests of the northern Lake States. This study applied those relationships to assess how forest management could influence carbon stocks in these two forest types. US Forest Service Forest Inventory and Analysis data were used to estimate current regional age structure and management intensity and state Gap Analysis Program data were used to assess forest type abundance. Across the region, current carbon stocks in aspen–birch and upland conifer forests are estimated to be 590 and 367 Tg C, respectively. Ceasing timber harvesting over the next century would increase the prevalence of older stands and increase ecosystem carbon stocks by 54% (31% in 50 years) and 30% (19% in 50 years) in aspen–birch and upland conifer forests, respectively. Harvesting aspen–birch stands would change ecosystem carbon stocks by +4% or −13% under annual harvesting of 1 or 2%, respectively. Harvesting upland conifer stands at a rate of 1 or 2% every year would decrease ecosystem carbon by 3 and 18%, respectively. Carbon from harvested material partly compensates for differences in total carbon stocks between no-harvest and harvest scenarios, suggesting a net positive carbon sequestration in all scenarios within 100 years. These results provide insight into the potential maximum impact of forest management on carbon stocks and sequestration in these two forest types. FOR. SCI. 57(6):479–488.

Keywords: carbon cycling, timber harvesting, net ecosystem carbon balance, carbon sequestration, climate change

As the link between changing climatic conditions and elevated atmospheric carbon dioxide concentrations becomes increasingly clear (Intergovernmental Panel on Climate Change 2007), forest management is shifting to include maximization of carbon stocks (Malmsheimer et al. 2008). Globally, forests cover more than 4.1 billion ha and contain more than 80% of aboveground terrestrial carbon, indicating that relatively minor alterations to carbon stocks or cycling in forest ecosystems may have substantial impacts on atmospheric carbon dioxide concentrations (Dixon et al. 1994, Pacala et al. 2001, Bonan 2008). In the United States, forests currently cover approximately 33% of the land area and store roughly 71,000 Tg C (Heath et al. 2003). Net carbon sequestration in US forests is estimated to be approximately 200 Tg C year^{-1} (Smith and Heath 2004), roughly 10% of US emissions from fossil fuels. Abundant evidence indicates that forest management can influence carbon cycling (Vitousek 1991, Nabuurs and Mohren 1995, Winjum and Schroeder 1997, Barford et al. 2001), and the vast majority of the current net carbon sequestration is a result of land use practices (Caspersen et al. 2000). Carbon sequestration from afforestation after agricultural abandonment (e.g., Hooker and Compton 2003), which is gradually declining as forests reach maturity (Heath and Birdsey 1993), is a primary cause of carbon sequestration in US forests. However, other land use practices, particularly reduced harvesting and fire suppression, also play a role (Caspersen et al. 2000). Furthermore, recent syntheses have suggested that altered forest management may not only avoid a decline in net sequestration but enhance sequestration in US forests by 100–300 Tg C year^{-1} (Stavins and Richards 2005, Birdsey et al. 2006).

Manipulation of forest age is one of the most direct and easily predicted consequences of forest management, and forest age is a powerful predictor of many aspects of forest structure and function, including carbon cycling (Pregitzer and Euskirchen 2004, Magnani et al. 2007). Stand age is an especially useful predictor in forests managed using even-aged systems, which is a common silvicultural approach around the globe (Smith et al. 1997). Consequently, alteration of forest age structure over very large areas has been shown to have the potential to influence regional carbon stocks and sequestration (Heath and Birdsey 1993, Turner et al. 1995, Depro et al. 2008, Hudiburg et al. 2009). Ecological modeling efforts have suggested that modifications to management practices, specifically shifting to longer rotations of even-aged stands, could increase carbon stocks through time (Harmon and Marks 2002, Balboa-Murias et

John B. Bradford, US Forest Service, Northern Research Station, 1831 Hwy 169 E., Grand Rapids, MN 55744; Current affiliation: US Geological Survey, Southwest Biological Center, 2255 N. Gemini Dr., Flagstatt, AZ 86001—Phone: (928) 380-4671; jbradford@usgs.gov.

Acknowledgments: I am very grateful to Linda Heath, Anthony D'Amato, and Shawn Fraver for insightful comments on an early version of this manuscript, to Doug Kastendick for fieldwork establishing and measuring the chronosequence sites, and to Samantha Mann for GIS analysis. This research was supported by funding from the US Forest Service Center for Research on Ecosystem Change, the Chippewa National Forest, and NASA Carbon Cycle Science research grants CARBON/04-0225-0191 and CARBON/04-0120-0011.

Manuscript received August 4, 2009, accepted January 5, 2011

al. 2006). In addition, understanding the consequences of altered forest age for total ecosystem carbon stocks requires inclusion of carbon pools not traditionally examined in forest inventories, notably dead woody material, which can be substantial, despite being relatively unexplored (Duvall and Grigal 1999, Kohl et al. 2008, Bradford et al. 2009).

Although previous studies have included regional to national scale assessments of the relationship between timber harvesting practices and carbon cycling, most have relied on modeling frameworks built on forest inventory data to quantify the relationship between age and carbon stocks (e.g., Heath and Birdsey 1993, Depro et al. 2008). This approach has the advantage that the plots are distributed throughout the area of interest and are thus likely to be representative, but it has the disadvantage that inventory data may not provide the best insight into relationships between age and ecosystem carbon stocks because stand age may be related to other factors that influence carbon stocks (Johnson and Miyanishi 2008). For example, if a larger proportion of high productivity stands are managed with shorter rotations, then younger aged inventory plots will have a disproportionately high bias toward these productive conditions and older inventory plots will be skewed toward less productive conditions, potentially biasing age-related patterns inferred from these data. In this study an attempt was made to avoid that potential bias by deriving age-related patterns from carefully selected forest chronosequences and integrating the results with inventory data about regional age structure and remote sensing-derived data about regional forest type abundance. The advantage of the chronosequence approach is that, when it is carefully implemented, differences in carbon stocks between sites are largely a consequence of stand age only.

Recent research has established and measured chronosequences of upland conifer and aspen–birch stands to quantify the relationship between ecosystem carbon stocks and stand age (Bradford and Kastendick 2010) (Figure 1). The goal of this study was to use these results to assess how alternative forest management strategies that alter regional age structure could affect carbon stocks within upland conifer and aspen–birch forests of the northern Lake States. Two specific objectives were to compile data from the state Gap Analysis Programs (GAPs) and the US Forest Inventory and Analysis (FIA) program to characterize the abundance and regional age structure of each forest type and to apply these estimates, along with age-related carbon stocks results, to quantify current and potential future total carbon stocks under divergent management scenarios including no harvest, 1% annual harvest, and 2% annual harvest for a 100-year simulation. These results provide insight into the potential maximum impact that manipulating age class distributions via harvesting could have on regional carbon stocks in these two forest types.

Methods

Study Region

The US northern Lake States region includes the northern parts of Minnesota, Wisconsin, and Michigan (Figure 2). Climate is characterized by short, mild summers and long, cold winters with a north–south gradient in mean annual temperature that ranges from ~2°C in northern Minnesota to 8°C in central Michigan and an east–west gradient in annual precipitation that ranges from 50 cm in central Minnesota to 80 cm in parts of Wisconsin and Michigan (PRISM Climate Group 2010). Soils include a large component of nutrient-poor sands derived from glacial outwash, as well as silt loams from moraines and, occasionally, clays in former lake beds (US Department of Agriculture, Soil Conservation Service 1989). Vegetation in the northern Lake States includes four major forest types: aspen–birch, upland conifer, northern hardwoods, and lowlands (Cleland et al. 2007).

This project examined only upland conifer and aspen–birch forests for two reasons. First, both forest types are very prevalent and intensively managed within the northern Lake States. Second, recent research has established and measured carbon stocks in chronosequences of both forest types from sites carefully selected for similar climate, edaphic conditions, and management history (Bradford and Kastendick 2010), enabling this article to build on those results. Aspen–birch forests consist primarily of quaking and big-toothed aspen (*Populus tremuloides* and *Populus grandidentata*) and paper birch (*Betula papyrifera*), whereas upland conifer forests are dominated by red pine (*Pinus resinosa*), white pine (*Pinus strobus*), or jack pine (*Pinus banksiana*) and contain some white spruce (*Picea glauca*) (Delcourt and Delcourt 2000). Forests of the northern Lake States region have been substantially altered since European settlement. Extensive logging in the late 1800s through early 1900s removed most of the old-growth forests, although scattered remnant stands remain (Frelich 1995). Regionwide logging, followed by slash-fueled fires resulted in large decreases in pine abundance and large increases in aspen abundance throughout the region (e.g., Friedman and Reich 2005). The current landscape includes a mix of managed production forests and preserves and is becoming increasingly more patchy at landscape scales (Mladenoff et al. 1993) yet more regionally homogeneous (Schulte et al. 2007).

Forest Type Abundance.—GAP data from Minnesota, Wisconsin, and Michigan were used to quantify the prevalence of upland conifer and aspen–birch forests. GAP data are based on classification of remotely sensed imagery, which is very effective for differentiating between general forest types over very large areas and provides continuous coverage of forest abundance and distribution across the region. Spatially referenced GAP databases were obtained from the National Gap Analysis Program (US Geological Survey 2009) and reclassified from the detailed, state-specific classifications into general categories that include upland conifers (encompassing all forested cover types dominated by coniferous species on upland soils) and aspen–birch (encompassing all forests dominated by aspen or paper birch) as well as northern hardwood forests and lowland conifer forests, which were not included in this analysis. Areas of upland conifer and aspen–birch forests within this region were estimated from this reclassified GAP data set (Figure 2). Because this study focused on managed forests, the total area of each forest type was

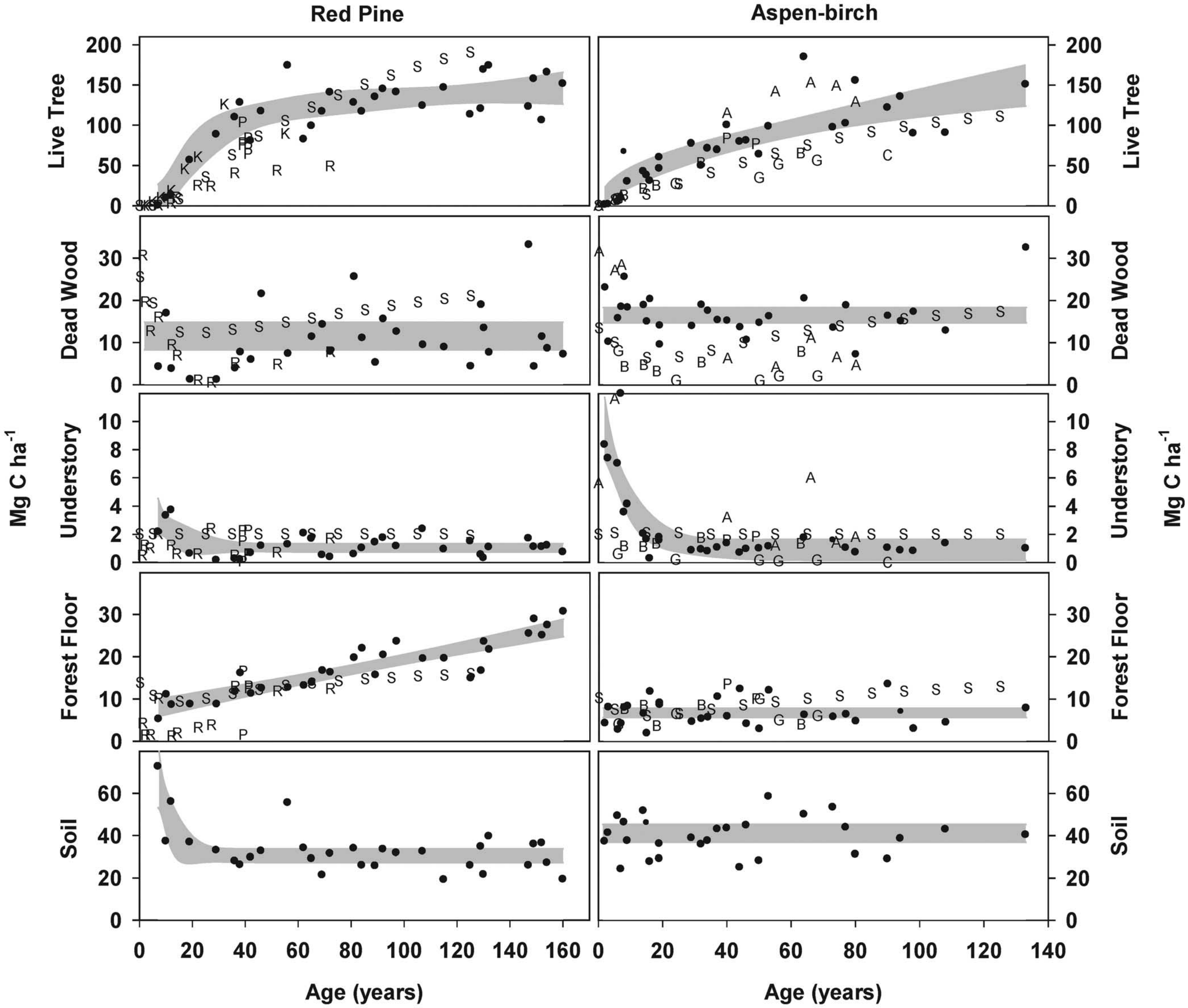

Figure 1. Ecosystem carbon stocks, represented by five carbon pools, as a function of stand age in upland conifer and aspen–birch. Solid symbols are individual stands, and shaded area is the 95% confidence interval around the best fit regression model derived from Bradford and Kastendick (2010). Letters correspond to previous studies (not used in estimating age-related carbon stocks for this analysis). Previous results about mineral soil carbon stocks are not shown because of methodological variability between studies. Units are Mg C ha^{-1}. Sources of previous studies are the following: A, Alban and Perala (1992); B, Ruark and Bockheim (1988); C, Curtis et al. (2002); G, Gough et al. (2007); K, King et al. (2007); P, Perala and Alban (1982); R, Rothstein et al. (2004); S, Smith et al. (2006).

decreased by the proportion of FIA plots that were classified as "timberland" (Bechtold and Patterson 2005), eliminating reserve areas (i.e., national parks, wilderness areas, and so on) from this analysis.

Regional Age Structure

Data from the US Forest Service's FIA program (Bechtold and Patterson 2005) were used to characterize the age distribution of upland conifer and aspen ecosystems in the northern Lake States. FIA data, which include estimates of stand age, provide a statistically based sample about forest age distribution across large geographic areas. The distribution of stand ages in upland conifer forests was characterized from the 2,215 plots classified as timberland in forest type 100 (red, white, and jack pine), whereas the distribution of stand ages in aspen–birch forests was characterized from the 4,987 plots classified as timberland in forest type 190 (aspen–birch). The regional abundance of each forest type was not modified in future scenarios.

Future Scenarios

FIA data from 2004 were used in this study. Simulations of the consequences of future harvesting spanned a 100-year period from 2005 and 2104. Three alternative future management scenarios were examined for each forest type: a scenario in which no harvesting occurs between the years 2005 and 2104 and two harvesting scenarios in which the oldest 1 or 2% of each forest type is harvested each year between 2005 and 2104. All scenarios assumed no stand-replacing natural disturbances in these managed forests.

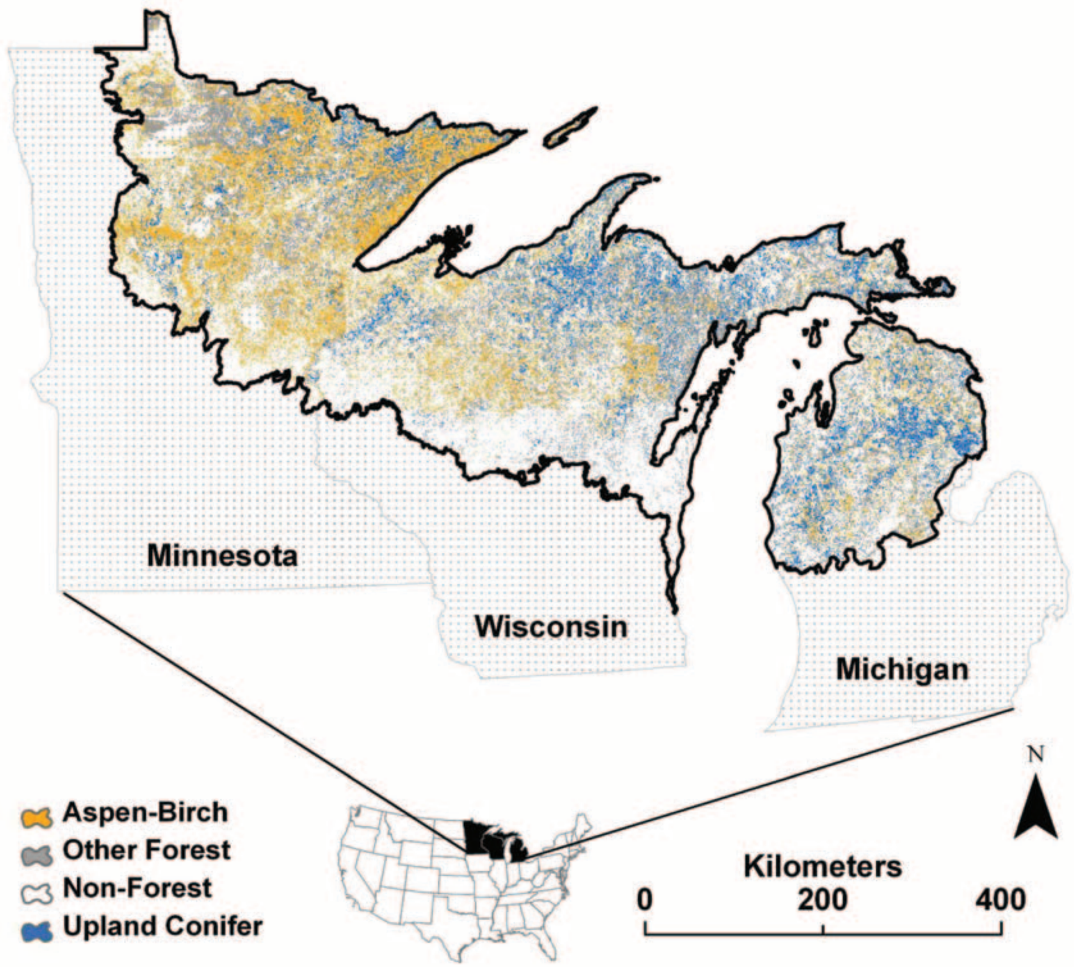

Figure 2. Extent of the northern Lake States region and distribution of upland conifer and aspen–birch forests within the region. Data are derived from state Gap analysis programs and have been reclassified into general forest types.

Future age distributions were estimated for each year from 2005 to 2104 by identifying the oldest 1 or 2% of FIA plots, setting age on those plots to zero, and incrementing the remaining plots by 1 year.

Current and Future Carbon Stocks

Ecosystem carbon stocks were represented by five carbon pools: carbon stored in live tree biomass (above and belowground), carbon stored in dead woody material (standing and down), carbon stored in understory biomass (live and dead, above and belowground), carbon stored in forest floor, and carbon stored in mineral soil (Bradford and Kastendick 2010). Regional ecosystem carbon stocks were estimated by combining the estimates of land area covered by each age and forest type with estimates of carbon stocks in each age class from Bradford and Kastendick (2010), which are comparable to those for other studies in the region (Figure 1). For each forest type, carbon density (stocks per unit land age) was calculated for the following age classes: 0–10, 10–20, 20–30, 30–40, 40–50, 50–70, 70–90, 90–110, 110–130, 130–170, 170–230, and more than 230 years. Carbon density was multiplied by the proportion of plots in each forest type age class combination for each year from 2004 to 2104, yielding annual estimates of ecosystem carbon stocks for both upland conifer and aspen–birch forests. Carbon stored in harvested material was estimated according to Smith et al. (2006), using bole biomass in place of timber volume as an estimate of initial harvested products. In sites examined in this study, the proportion of total live tree carbon stored in boles was very consistent for stand ages greater than 30 years (data not shown). Smith et al. (2006) provided region-specific coefficients for estimating the amount of harvested material converted to sawlogs and pulp for hardwoods and softwoods (Table 1) and coefficients for the proportion of harvested material that remains in wood products and in landfills for up to 100 years after harvest. Material remaining in products transitions from

Table 1. Values for parameters used to estimate carbon in harvested material.

Parameter	Conifer	Aspen
Proportion softwood	0.902	0.157
Sawlog proportion in softwoods	0.646	0.514
Sawlog proportion in hardwoods	0.296	0.336
Roundwood fraction	0.931	0.831
Industrial roundwood fraction for sawlogs	0.985	0.96
Industrial roundwood fraction for pulp	1.285	1.387

Based on Smith et al (2006).

50–70% in year 1 to 0–15% in year 100, whereas material remaining in landfills transitions from 0% in year 1 to 8–27% in year 100 (Smith et al. 2006). With use of these coefficients, the amount of carbon stored in wood products and landfills from harvested material was calculated for each year in each scenario.

Results

Forest Type Abundance and Age Structure

GAP data suggest that upland conifer forests cover 2,664,300 ha in the northern Lake States, spread across the northern parts of Minnesota, Michigan, and Wisconsin, of which roughly 84% is timberland (Figure 2). In contrast, GAP data indicate that aspen–birch-dominated forests cover approximately 4,491,000 ha, with 92% in timberland, occurring in the greatest densities in northern Minnesota, but extending throughout the region. Of the 2,215 FIA plots classified in 2004 as upland conifers in the northern Lake States, average age was 50 years, 35% were less than 40 years old, 81% were less than 70 years old, and 3% were older than 130 years (Figure 3). Of the 4,987 FIA plots within the region that were aspen–birch, average age was 41 years, 46% were less than 40 years old, 88% were less than 70 years old, and only 0.3% were older than 130 years.

All future scenarios created dramatically altered regional age distributions. The no-harvesting scenario simply incremented all stand ages each year, creating upland conifer stands with average age of 100 years in 2054 and 150 years in 2104 and aspen–birch stands with average age of 91 years in 2054 and 141 years in 2104 (Figure 3). The 1% harvesting scenarios decreased ages to a mean of 52 and 48 years in upland conifer and aspen–birch, respectively, by 2054 and to a mean of 50 years in both forest types in 2104. The 2% annual harvesting scenario generated even age distributions from 1 to 50 years (mean 25 years) by 2054 that were maintained in both forest types throughout the remaining 50 years of the scenarios.

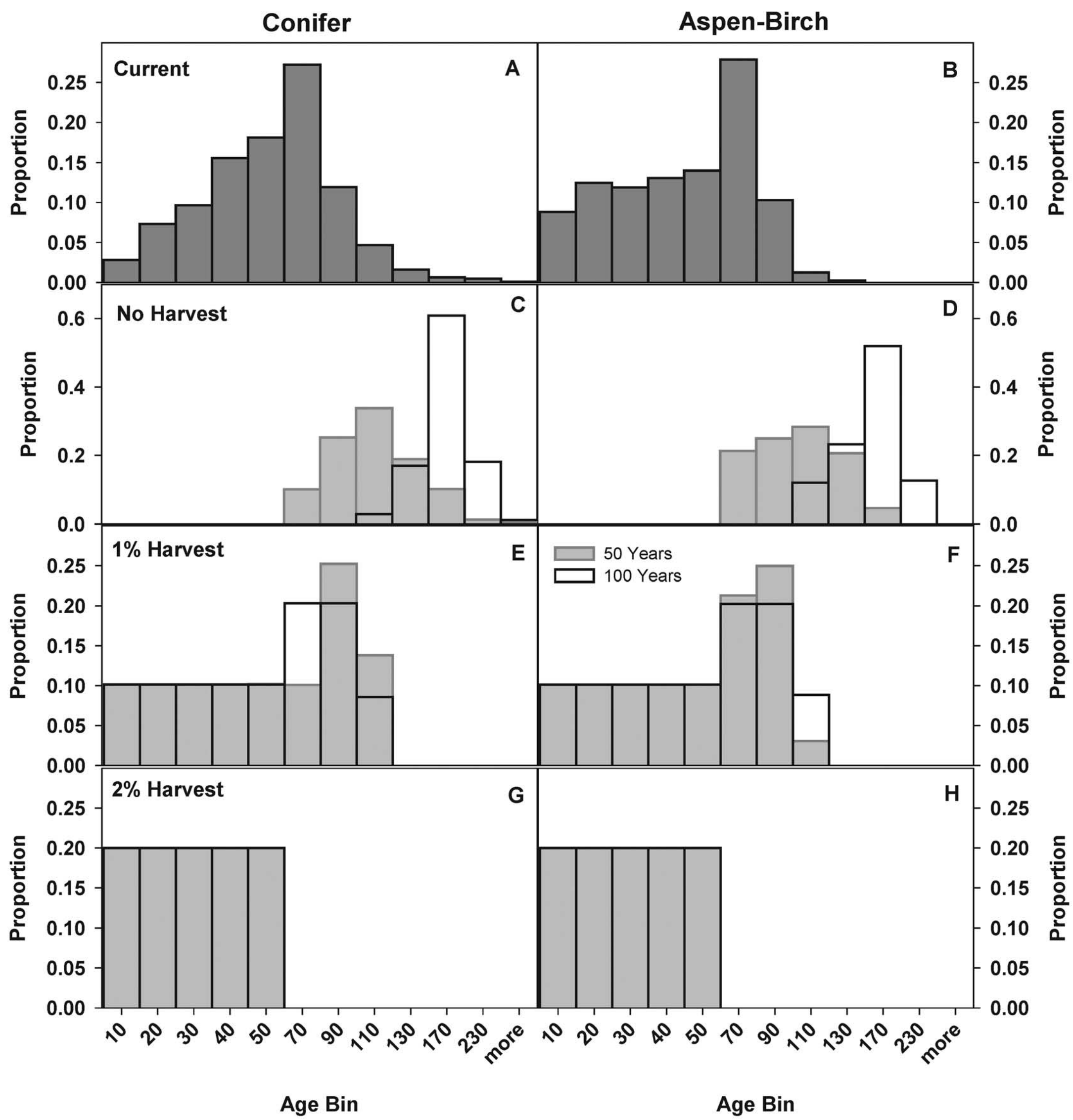

Figure 3. Age class distribution of FIA plots for upland conifer and aspen–birch forests in the northern Lake States in the year 2004 (A and B, dark gray bars) and in the years 2054 (light gray bars) and 2104 (open bars) assuming either no harvesting (C and D), 1% annual harvesting (E and F), or 2% annual harvesting (G and H). See text for description of which FIA forest types were included.

Carbon Stocks

Across the northern Lake States, current (2004) ecosystem carbon stocks of upland conifer forests are estimated to be 367 Tg, with 64% in live trees, 20% in mineral soil, 8% in forest floor, 7% in dead woody debris, and 0.7% in understory vegetation (Table 2). In aspen–birch forests across the region, 590 Tg carbon is currently stored with 53% in live trees, 29% in mineral soil, 12% in dead woody debris, 5% in forest floor, and 1% in understory vegetation.

The older forest age structure predicted by the no-harvesting scenario resulted in increases in ecosystem carbon stocks for both forest types (Figure 4). Ecosystem carbon in upland conifer forests increased 71 Tg (19%) by 2054 and 109 Tg (30%) by 2104, with carbon in live trees and forest floor increasing and carbon in mineral soil decreasing slightly (Table 2). Ecosystem carbon in aspen–birch forests increased 184 Tg (31%) by 2054 and 322 Tg (54%) by 2104 under the no-harvesting scenario, with all of that increase going into live trees and a minor decrease being seen in understory vegetation.

In contrast, the younger regional age structure generated by the harvesting scenarios generally resulted in decreased ecosystem carbon stocks (Figure 4). Harvesting 1% annually deceased upland conifer ecosystem carbon by 6.2 Tg by 2054 and 9.2 Tg (3%) by 2104 and decreased aspen–birch ecosystem carbon by 21 Tg by 2054 and 25 Tg by 2104 (4%). Harvesting 2% annually decreased ecosystem carbon stocks by 2054 by 65 Tg (18%) and 78 Tg (13%) in upland conifer and aspen–birch forests, respectively. Most of these changes are due to a decrease in live tree carbon, with minor decreases in forest floor carbon and increases in mineral soil carbon (Table 2). Harvested material stored in forest products and landfills accumulated in all harvest scenarios, reaching 57 and 104 Tg in 2104 from 1 and 2%, respectively, harvests of upland conifers and a total of 87 and 135 Tg from 1 and 2%, respectively, harvests of aspen–birch. In

Table 2. Carbon storage estimates for upland conifer and aspen-birch ecosystems in the northern Lake States in the year 2004 and the years 2054 and 2104 under three alternative future harvesting scenarios.

Carbon pool	2004 TgC	Year	No harvest TgC	No harvest Δ	No harvest %Δ	1% harvest TgC	1% harvest Δ	1% harvest %Δ	2% harvest TgC	2% harvest Δ	2% harvest %Δ
Upland conifer (2,225,568 ha)											
Live tree	235.0	2054	297.7	62.7	27	217	−17.5	−7	149	−85.5	−36
		2104	322.1	87.2	37	215	−19.7	−8	149	−85.5	−36
Understory	2.7	2054	2.3	−0.4	−15	3.2	0.5	18	4.1	1.4	50
		2104	2.3	−0.4	−15	3.2	0.5	18	4.1	1.4	50
Dead woody material	25.7	2054	25.7	0.0	0	25.7	0.0	0	25.7	0.0	0
		2104	25.7	0.0	0	25.7	0.0	0	25.7	0.0	0
Forest floor	30.1	2054	43.8	13.7	45	30.4	0.3	1	22.8	−7.3	−24
		2104	58.0	27.9	93	29.6	−0.6	−2	22.8	−7.3	−24
Mineral soil	73.3	2054	67.8	−5.5	−7	83.8	10.5	14	99.5	26.2	36
		2104	67.8	−5.5	−7	83.8	10.5	14	99.5	26.2	36
Total ecosystem	366.7	2054	437	70.6	19	361	−6.2	−2	301	−65.3	−18
		2104	476	109	30	358	−9.2	−3	301	−65.3	−18
Wood products		2054				20.2			37.9		
		2104				27.9			50.2		
Landfills		2054				12.6			24.3		
		2104				29.1			53.7		
Ecosystem + products + landfill	366.7	2054	437	70.6	19	393	26.6	7	364	−3.2	−1
		2104	476	109	30	414	47.7	13	405	38.6	11
Aspen-birch (4,125,002 ha)											
Live tree	317.6	2054	505	188	59	338	20.9	7	235.6	−82.0	−26
		2104	643	325	102	343	25.2	8	235.6	−82.0	−26
Understory	7.2	2054	3.7	−3.5	−48	7.3	0.1	1	10.8	3.6	50
		2104	3.7	−3.5	−48	7.3	0.1	1	10.8	3.6	50
Dead woody material	68.2	2054	68.2	0.0	0	68.2	0.0	0	68.2	0.0	0
		2104	68.2	0.0	0	68.2	0.0	0	68.2	0.0	0
Forest floor	27.9	2054	27.9	0.0	0	27.9	0.0	0	27.9	0.0	0
		2104	27.9	0.0	0	27.9	0.0	0	27.9	0.0	0
Mineral soil	169.6	2054	170	0.0	0	170	0.0	0	169.6	0.0	0
		2104	170	0.0	0	170	0.0	0	169.6	0.0	0
Total ecosystem	590.4	2054	775	184	31	611	21.0	4	512.0	−78.4	−13
		2104	912	322	54	616	25.3	4	512.0	−78.4	−13
Wood products		2054	0.0			29.8			50.5		
		2104	0.0			44.7			67.5		
Landfills		2054	0.0			17.1			30.9		
		2104	0.0			41.7			67.1		
Ecosystem + products + landfill	590.4	2054	775	184	31	658	67.9	11	593.4	3.0	1
		2104	912	322	54	702	112	19	646.6	56.2	10

Estimates include ecosystem carbon pools as well as carbon accumulated in wood products and landfills. Scenarios consist of a no-harvesting scenario and two harvesting scenarios in which 1 or 2% of timberland within the region is harvested annually. Units are in Tg C (10^{12} g C; 1 million metric tons) and can be divided by timberland area to estimate carbon density. Δ and %Δ indicate absolute and relative change in carbon storage between 2004 and 2054 or 2104.

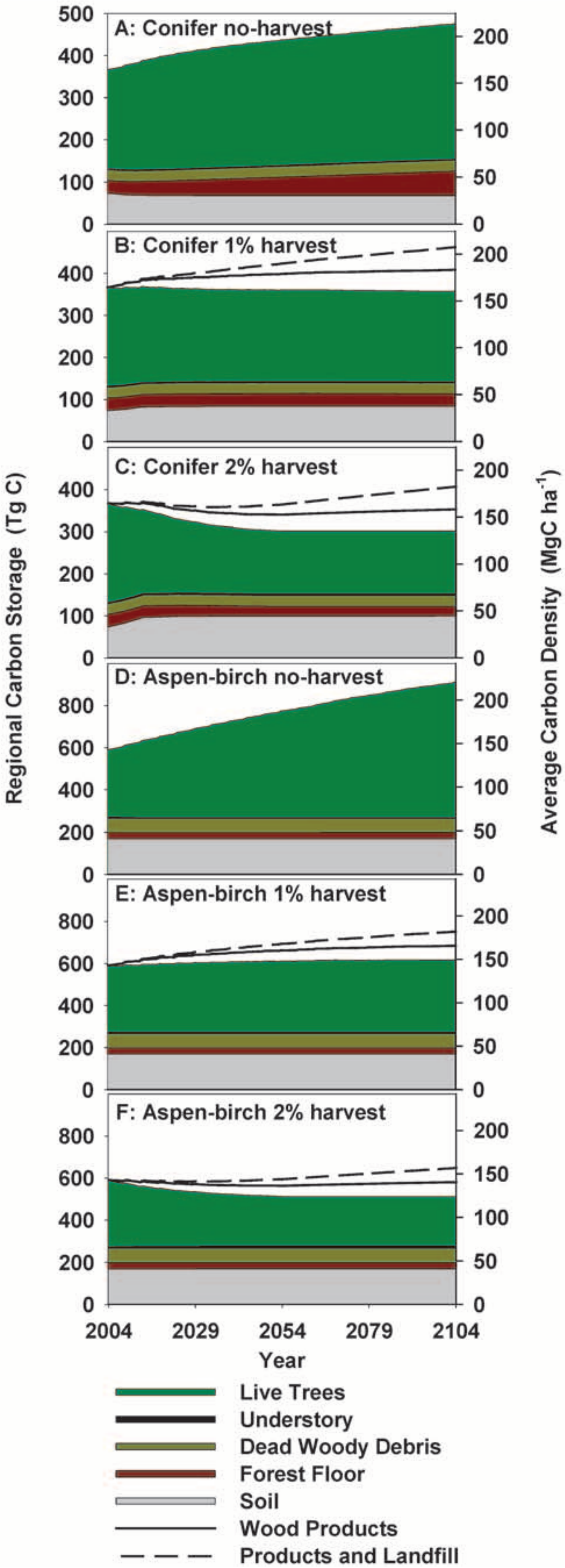

Figure 4.

Figure 4. (continued) Carbon storage estimates in upland conifer (A and B) and aspen–birch (C and D) forests of the northern Lake States from 2004 to 2104 under either a no-harvesting scenario (A and D), 1% annual harvesting (B and E), or 2% annual harvesting (C and F). Carbon stored in ecosystem carbon pools are shown in shaded areas whereas carbon stored in wood products and landfills are shown by dashed lines. Results are expressed in total regional carbon storage (Tg C, left axis) and average carbon density (Mg C ha^{-1}, right axis) (Perala and Alban 1982, Ruark and Bockheim 1988, Alban and Perala 1992, Curtis et al. 2002, Rothstein et al. 2004, Smith et al. 2006, Gough et al. 2007, King et al. 2007).

comparison to ecosystem carbon stocks in 2004, total carbon stocks (ecosystem, wood products, and landfill) increased for both forest types in both harvesting scenarios. In upland conifer forests, 1 and 2% annual harvesting increased total carbon in 2104 by 48 Tg (13%) and 39 Tg (11%), respectively. In aspen–birch forests, harvesting 1 and 2% annually increased total carbon in 2104 by 112 Tg (19%) and 56 Tg (10%), respectively (Table 2).

Discussion

The result that altering timber harvesting can substantially influence forest carbon cycling over large areas is consistent with previous studies. Hudiburg et al. (2009) used a similar combination of age-related carbon stock assessments from chronosequences with FIA-derived regional age structure and estimated that in the absence of stand-replacing disturbance or timber harvesting, ecosystem carbon in forests of Oregon and Northern California could increase by 15% over the next 50 years, compared with the estimated 19–31% increase in this study. These results from the no-harvesting scenario are also comparable with results from Heath and Birdsey (1993), who used FIA data to estimate that, if harvesting ceased, carbon stocks in forests of the northcentral and northeastern United States would increase by 17% between 2010 and 2050. Depro et al. (2008) used age-related patterns in FIA data to estimate that between 2010 and 2050, no harvesting would enhance sequestration of 17–29 Tg C year^{-1} in US public timberlands compared with current activities, whereas aggressive harvesting would decrease sequestration by 27–35 Tg C year^{-1}. At a regional scale, Leighty et al. (2006) examined inventory data for the Tongass National Forest in Alaska and estimated that from 1995–2095, ceasing harvesting would result in an average annual sequestration rate of approximately 0.13 Tg C, compared with an average annual release of approximately 0.8–0.9 Tg C with timber harvesting on 100-year rotations.

The 2% annual harvesting scenario examined in this study is more extreme than the scenarios examined in most previous studies and predicted a 13–18% decline in ecosystem carbon stocks within 50 years. In comparison, both Heath et al. (1993) and Depro et al. (2008) estimated increases in ecosystem carbon under business-as-usual scenarios. Because this study included two extreme scenarios (no harvesting or 2% annual harvesting that results in complete harvesting over 50 years), these results span the maximum potential alteration of harvesting regimes and thus provide "bookends" for estimating impacts on regional carbon stocks. Actual forest management practices will fall somewhere within this range of harvest intensity and thus are likely to be most similar to the 1% annual harvesting scenario, which estimated only modest changes in ecosystem carbon over 50 or 100 years (2–3% decrease in upland conifer and 4% increase in aspen–birch). In comparison, simulations in Finland suggest that altering thinning practices to favor higher stocking levels over a 100-year period could increase ecosystem carbon stocks by up to 11% (Garcia-Gonzalo et al. 2007).

These results suggest that aspen–birch forests have greater potential for enhanced future carbon stocks than upland conifer forests in the northern Lake States. In part, this is simply a consequence of greater prevalence of aspen–birch within the region. Aspen–birch forests cover nearly twice as much area as upland conifer forests in the northern Lake States, meaning that despite the fact that changes in carbon density (i.e., Mg C ha^{-1}) are relatively similar between forest types (Figure 4), changes in regional carbon stocks are substantially higher for aspen–birch. In addition, the larger estimated carbon stocks potential on aspen–birch forests is also a result of current age structure; aspen–birch forests are generally younger than upland conifer forests. Because younger stands accumulate ecosystem carbon faster than older stands (Figure 1), younger aspen–birch stands have the potential for larger increases in carbon density under the no-harvesting scenario (31% in aspen–birch versus 19% in upland conifer). In addition, because younger stands store less carbon than older stands, the estimated decrease in ecosystem carbon stocks resulting from intensive (2% annual) harvesting is smaller in aspen–birch stands (13%) than in upland conifer stands (18%) (Table 2). Although extremely old aspen–birch forests can gradually convert to other forest types (Delcourt and Delcourt 2000), primarily upland conifer or northern hardwoods, those successional transitions were not included in this analysis because the carbon consequences of such conversion are likely to be characterized by gradual replacement of aspen biomass with other species and thus are very modest in comparison with harvesting.

These results provide insight into the potential contribution of these forests to national objectives for carbon sequestration. Current sequestration rates in US forests range between 100 and 200 Tg C $year^{-1}$ (Woodbury et al. 2007, US Environmental Protection Agency 2009), and Birdsey et al. (2000) suggested that in the next century it may be possible to increase carbon sequestration in the US forest sector by 100–200 Tg C $year^{-1}$ using a range of approaches including reduced harvesting and increased carbon retention in durable wood products. Because US forestland covers approximately 300 million ha (Smith et al. 2009), each hectare would need to contribute approximately 0.3–0.6 Mg of carbon sequestration annually to meet the 100–200 Tg C $year^{-1}$ goal. When carbon stored in harvested material is included, all scenarios examined here suggest increases in total carbon over 100 years, indicating net carbon sequestration. In the no-harvesting scenario, upland conifer and aspen increased regional ecosystem carbon stocks over 100 years by 109 and 322 Tg C, respectively, translating into an annual sequestration of 0.49 and 0.78 Mg C ha^{-1} $year^{-1}$, respectively. In contrast, the 1% harvesting scenario estimated 48 and 112 Tg C increases in total regional carbon in upland conifer and aspen–birch forests, respectively, translating into 0.21 and 0.27 Mg C ha^{-1} $year^{-1}$. The more extreme 2% harvesting scenario estimated regional increases of 39 and 56 Tg C, suggesting net sequestration of only 0.17 and 0.14 Mg C ha^{-1} $year^{-1}$ in upland conifer and aspen–birch forests, respectively.

It is worth noting that this study did not take into consideration all of the processes that would influence total carbon cycling in these systems over the next 100 years. Notably, carbon will be emitted from fossil fuels as a result of harvesting, transportation, and processing of forest products (White et al. 2005). On the other hand, ceasing timber harvesting in these forest types would probably lead to carbon emissions as a result of additional timber harvesting in other locations and/or substitution of other products (i.e., plastic or concrete) in lieu of wood (Ruddell et al. 2007). In addition, this study did not incorporate any natural disturbances into the analysis of future carbon stocks. Because natural disturbances are likely to decrease forest carbon stocks (Kashian et al. 2006) and that decrease will be most dramatic in stands with especially high carbon stocks, the no-harvesting scenario would probably be most affected by natural disturbances, suggesting that the differences in ecosystem carbon stocks between the no harvesting and the 1% harvesting scenarios are probably less than these result indicate. Last, this analysis was forced to treat all stands as even-aged, which is undoubtedly a simplification of existing stand-level age structures, although the ramifications of differences in carbon cycling between even-aged and multicohort stands are difficult to assess.

Although this analysis suggests that the no-harvesting scenario appears to come closest to fully satisfying national carbon sequestration goals, but the potential carbon sequestration benefits of ceasing timber harvesting must be balanced against the other diverse objectives of forest management. The 1% harvesting scenario, which is most similar to actual forest management activities, generated sequestration rates that were net positive over the 100-year simulations. In addition, the economic and societal benefits of maintaining a robust forest products industry that could be supported by a 1% annual harvest are substantial. Results from these future forest management scenarios characterize the potential carbon stocks consequences for two abundant, actively managed forest types in the northern Lake States. These insights provide information for forest managers attempting to balance the potentially conflicting objectives of sustained timber production and enhanced carbon stocks.

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