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Potential increases in natural disturbance rates could offset forest management impacts on ecosystem carbon stocks

John B. Bradford [a,*], Nicholas R. Jensen [b], Grant M. Domke [c], Anthony W. D'Amato [b]

[a] USGS, Southwest Biological Science Center, Northern Arizona University, P.O. Box 5614, Flagstaff, AZ 86011, United States
[b] University of Minnesota, Department of Forest Resources, 115 Green Hall, 1530 Cleveland Ave. N, St. Paul, MN 55108, United States
[c] USDA Forest Service, Northern Research Station, 1992 Folwell Ave., St. Paul, MN 55108, United States

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ABSTRACT

Forested ecosystems contain the majority of the world's terrestrial carbon, and forest management has implications for regional and global carbon cycling. Carbon stored in forests changes with stand age and is affected by natural disturbance and timber harvesting. We examined how harvesting and disturbance interact to influence forest carbon stocks over the Superior National Forest, in northern Minnesota. Forest inventory data from the USDA Forest Service, Forest Inventory and Analysis program were used to characterize current forest age structure and quantify the relationship between age and carbon stocks for eight forest types. Using these findings, we simulated the impact of alternative management scenarios and natural disturbance rates on forest-wide terrestrial carbon stocks over a 100-year horizon. Under low natural mortality, forest-wide total ecosystem carbon stocks increased when 0% or 40% of planned harvests were implemented; however, the majority of forest-wide carbon stocks decreased with greater harvest levels and elevated disturbance rates. Our results suggest that natural disturbance has the potential to exert stronger influence on forest carbon stocks than timber harvesting activities and that maintaining carbon stocks over the long-term may prove difficult if disturbance frequency increases in response to climate change.

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1. Introduction

As atmospheric carbon dioxide concentrations continue to increase, scientists and land managers are exploring mitigation options that maximize the amount of carbon stored in terrestrial ecosystems (Malmsheimer et al., 2008). About 60% of the world's terrestrial carbon is contained in forest ecosystems, so the response of forests to changes in climate or disturbance regime can have implications for regional and global carbon cycling (Winjum et al., 1992; Dale et al., 2001; Ryan et al., 2010; McKinley et al., 2011). The amount of carbon stored within a forest does not remain fixed through time; as trees mature and increase in size, corresponding carbon stocks also increase, and these relationships between forest age and ecosystem carbon pools are well recognized. In temperate forests, forest carbon stocks typically increase with age until becoming relatively stable after ~100–150 years, while net ecosystem carbon balance often peaks much earlier and gradually declines to near zero (Pregitzer and Euskirchen, 2004; Bradford and Kastendick, 2010; Williams et al., 2012). Disturbance events (natural or anthropogenic) that alter forest stand age will influence site-level carbon stocks and fluxes (Kashian et al., 2006; Gough et al., 2007; Gough et al., 2008; Nave et al., 2010). Likewise, landscape to regional disturbance regimes or management strategies that alter forest age–class distributions over large areas will ultimately drive changes in landscape to regional carbon stocks (Heath and Birdsey, 1993a; Pregitzer and Euskirchen, 2004; Mouillot and Field, 2005; Birdsey et al., 2006; Depro et al., 2008a; Scheller et al., 2011).

With changes to global climate already occurring (Bernstein et al., 2007), natural disturbance regimes are also expected to become more frequent and of higher intensity (Westerling, 2006; Littell et al., 2009; Schelhaas et al., 2010). Stand-replacing natural disturbance events such as wildfire, insect and pathogen outbreaks, and windstorms typically result in short-term losses in forest carbon stocks, potentially shifting forests from carbon sinks to carbon sources (Kurz et al., 2008b; McKinley et al., 2011; Scheller et al., 2011; Stinson et al., 2011) and potentially influencing climatic conditions via other mechanisms, notably altered albedo and energy balance (Randerson et al., 2006; Anderson et al., 2010). Likewise, the frequency (or rate) of disturbance across large areas can also dramatically alter the potential for carbon storage. At regional scales, increases in disturbance frequency can result in widespread loss of forest carbon stocks (Kurz et al., 2008b; Rogers et al., 2011), while decreases in disturbance frequency are

* Corresponding author. Tel.: +1 928 523 7766.
E-mail address: jbradford@usgs.gov (J.B. Bradford).

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estimated to increase ecosystem carbon stocks by nearly 100% in some regions (Hudiburg et al., 2009).

Similarly, forest management, specifically timber harvesting, can influence forest carbon stocks by both removing carbon from the ecosystem (in harvested material) and by shifting carbon into detrital pools where it is subsequently returned to the atmosphere via decomposition (McKinley et al., 2011). The ecosystem-level consequences of carbon removal and elevated decomposition depend, in large part, on the silvicultural system employed. In Minnesota, the relative intensity of silvicultural systems used has decreased over the last decade, and while other regeneration methods are utilized, clearcutting and other even-aged approaches remain the predominant system employed among all forest management organizations (D'Amato et al., 2009). Forest management practices applied over large areas can alter regional carbon stocks and these effects can be assessed by examining changes in regional forest age distribution. As with natural disturbance, the frequency and intensity of harvesting influence the resulting age distribution and dictate the magnitude of carbon stock change (Birdsey et al., 2006; Depro et al., 2008a; Nunery and Keeton, 2010; Heath et al., 2011a). Although a number of studies have examined the potential landscape- to regional-scale consequences of forest harvesting practices (e.g. Depro et al., 2008b; Nunery and Keeton, 2010; Heath et al., 2011a; McKinley et al., 2011; Stinson et al., 2011; Peckham et al., 2013), and other work has characterized how natural disturbance regimes can alter forest carbon dynamics over large areas (e.g. Kurz et al., 2008a; Kurz et al., 2008b; Hudiburg et al., 2009; Rogers et al., 2011), few studies have contrasted the relative magnitude of these consequences or have attempted to propagate uncertainty through the calculations (although see Williams et al., 2012). In particular, few studies have assessed how changes in disturbance regimes may interact with actual, planned harvest regimes to impact carbon stocks and cycling. Since any attempts to utilize forest harvesting as a tool for enhancing ecosystem carbon stocks must occur in the context of climate change and associated intensifying forest disturbances (Dale et al., 2001; Millar et al., 2007), understanding the simultaneous carbon consequences of both harvesting and natural disturbance regimes is crucial.

To better understand the landscape-scale impact of timber harvesting practices on forest carbon stocks and to place those impacts in the context of potential alterations in the natural disturbance regime, we simulated varying levels of both harvesting and natural disturbance across the Superior National Forest (SNF), in northeastern Minnesota. Our specific objectives were (1) to characterize the current age structure across eight forest types on the SNF and their relationships to carbon stocks, and (2) to use the forest type-age class–carbon stock relationships to simulate the consequences of low and high natural disturbance rates concurrent with 0%, 40%, 100%, and 200% rates of the annual planned harvest levels for forest-wide carbon storage over the next 100 years.

2. Methodology

2.1. Study location

The SNF occupies approximately 812,000 ha of forest land in northeastern Minnesota, of which 292,000 ha is designated as wilderness in the Boundary Waters Canoe Area Wilderness (BWCAW). The climate is composed of short, mild summers and long, cold winters (July avg. 19 °C, January avg. −15 °C), and receives approximately 60–80 cm of precipitation annually (PRISM, 2010). Soils range from shallow, nutrient-poor sands of glacial outwash and areas of exposed granitic bedrock to silty-loams in bedrock cracks and depressions (Prettyman, 1978). Forests across this area consist of eight dominant community types: red/white pine (*Pinus resinosa* Aiton/*P. strobus* L.), jack pine (*Pinus banksiana* Lamb.), spruce/fir (*Picea glauca* (Moench) Voss/*Abies balsamea* (L.) Mill.), lowland conifer (*Picea mariana* (Mill.) Britton, Sterns & Poggenb./*Thuja occidentalis* L.), upland hardwood (*Quercus rubra* L./*Acer rubrum* L.), lowland hardwood (*Fraxinus nigra* Marsh.), northern hardwood (*Acer saccharum* Marsh.), and aspen/birch (*Populus tremuloides* Michx./*Betula papyrifera* Marsh.).

2.2. Forest inventory data

We utilized data collected by the USDA Forest Service, Forest Inventory and Analysis (FIA) program, which maintains and periodically measures plots that are systematically distributed approximately every 2430 ha across the 48 conterminous states of the US, to estimate current forest conditions and develop forest type-age class–carbon stock relationships. Each plot containing a forest land use is comprised of a series of smaller plots (i.e., subplots) where tree- and site-level attributes – such as diameter at breast height (dbh) and tree height – are measured at regular temporal intervals (Bechtold and Patterson, 2005). Estimates of live tree aboveground carbon (bole, top and limbs, stump, coarse roots, and saplings) were calculated from tree attributes (Woudenberg et al., 2010) on 1,683 FIA plots within the three counties in which the SNF resides; St. Louis, Lake, and Cook counties (Fig. 1). Estimates of carbon in standing (Smith et al., 2003) and downed dead wood (Smith et al., 2004), forest floor (Smith and Heath, 2002), and understory vegetation (Birdsey, 1996) were developed from models based on geographic area and forest type, and in some cases, live tree stand density, stand age, and growing stock volume. Estimates of carbon in soil organic matter (but not forest floor), are based on the STATSGO soil database (USDA Soil Conservation Service, 1991) and regional forest types (Amichev and Galbraith, 2004) and assumed to remain constant across stand age in each forest type (Heath et al., 2003). Estimates of carbon in forest ecosystem pools are based on regional averages and reflected the best available data at the time of analysis. The uncertainty associated with the models and/or model coefficients used to develop component estimates is beyond the scope of this study. That said, Heath and Smith (2000) conducted an uncertainty analysis on estimates of forest carbon developed using many of the component models used in this study. This study assumes that soil organic carbon (SOC) is unchanged by harvest or disturbance scenarios (Nave et al., 2010), so this pool has been excluded from results where it could mask any potential management influences. Estimates of stand age for each forest type were based on tree cores from two or three dominant or co-dominant site trees from the overstory of each plot. The variance of stand age estimates increases with increasing stand heterogeneity and therefore may have large errors (U.S. Department of Agriculture, 2010).

2.3. Model approach

Forest harvesting and natural disturbance scenarios were examined using the Forest Age Class Change Simulator (FACCS). FACCS combines estimates of stand age distributions (assuming stands are even-aged as indicated by D'Amato et al., 2009) over large forested areas with relationships between age and carbon stocks to estimate carbon stocks over large study areas. By altering stand age distribution in response to prescribed disturbance or harvest rates, FACCS calculates the potential impact on carbon stocks. FACCS utilizes estimates of stand age, forest land area, and carbon stocks by forest type to estimate forest-wide age distributions and carbon stock changes in response to specified harvest and disturbance regimes over a target planning horizon (Domke et al., 2012). In particular, the model links estimates of forest land area

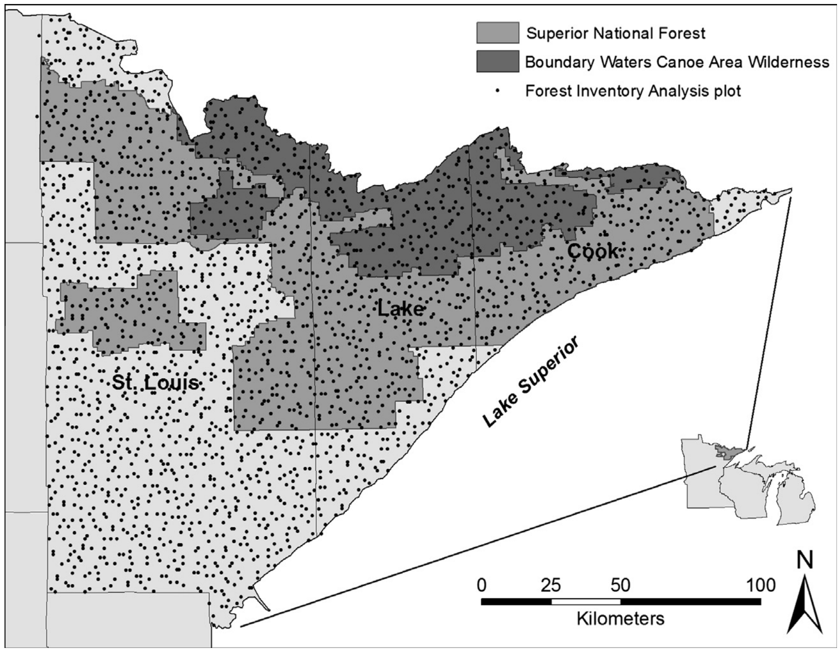

Fig. 1. The Superior National Forest and approximate Forest Inventory and Analysis plot locations within Lake, Cook, and St. Louis counties, Minnesota.

by age class and forest type to continuous forest type specific age class–carbon yield curves to build a matrix of forest carbon estimates over space and time. FACCS estimates are constrained by two basic assumptions: (1) the land area (and the proportion of area in each forest type) remains fixed throughout the planning horizon, and (2) harvest activities and incorporated disturbance rates are applied forest-wide and simulated on an annual basis. Harvest scenarios were based on the SNF Land and Resource Management Plan (henceforth "forest plan"), and included 40%, 100%, and 200% of the planned harvest rates, each simulated with simultaneous natural disturbance rates of 1% or 3%. Forest disturbance rates were applied uniformly across the entire area by individual age classes in the model. Within each age class, the disturbance rate was applied randomly across the area in that age class. The design allows area to be disturbed multiple times throughout the planning horizon. Scenarios were examined over a 100-year planning horizon and carbon stocks are presented at 10, 20, 50, and 100 years in the simulations.

2.4. Curve fitting of pools/types

To incorporate continuous forest type specific age class–carbon yield curves for this study area into FACCS, we quantified the relationships between carbon pools and stand age for the eight forest types using field- and model-based estimates from FIA plots across Cook, Lake, and St. Louis counties. These stand age–carbon pool relationships were analyzed using 19 candidate statistical regression models, including linear, power, exponential increase, and exponential increase to a maximum functions, all with and without intercept terms (Bradford and Kastendick, 2010). Akaike's information criterion (AIC_C) values and weight of evidence for each model (w_i) were used to determine the best-fitting model for each carbon pool following Burnham and Anderson (2001), which was utilized in FACCS to represent how carbon stocks relate to stand age in each forest type. Statistical analysis was performed using *nlin* procedure in SAS version 9.1 (SAS, 2001).

2.5. Management and disturbance scenarios

Actual harvest volumes on the SNF from 2004–2009 were summed and organized into the eight forest type classes. These total harvest volumes were then averaged over this six-year period and the percentage of each forest type contribution to total harvest volumes were calculated (Table 1). The forest plan specifies the annual maximum harvest volumes at 0.241 M m^3 (102 million board feet). Annual harvest goals by forest type for these scenarios were then calculated by applying the actual annual six-year harvest proportion of each forest type to the 0.241 M m^3 maximum harvest

Table 1
Summary of forest type inventory data from Superior National Forest, MN.

Forest type	Area (ha)	FIA plots (#)	Harvest proportion[a] (%)	Max. harvest[b] (Mm^3)	FIA Forest type codes
Red/white pine	51,244	73	13.1	0.032	102, 103
Jack pine	64,598	68	14.2	0.034	101
Spruce/fir	74,224	142	7.7	0.018	121, 122
Lowland conifer	170,288	345	5.5	0.013	125, 126, 127
Upland hwd	40,347	43	0.6	0.001	401, 409, 503, 962
Lowland hwd	26,991	114	0.5	0.001	517, 701, 702, 704, 706, 708
Northern hwd	36,632	95	1.2	0.003	801, 805, 809
Aspen–birch	347,517	769	57.3	0.138	901, 902, 904, 905
Total	811,841	1649	100.0	0.241	

[a] Harvest proportions calculated using a combination of reported pulpwood and sawtimber volumes harvested from 2004–2009.
[b] Maximum annual harvest volume (Mm^3) taken from Table TMB-11 in the SNF Land and Resource Management Plan EIS.

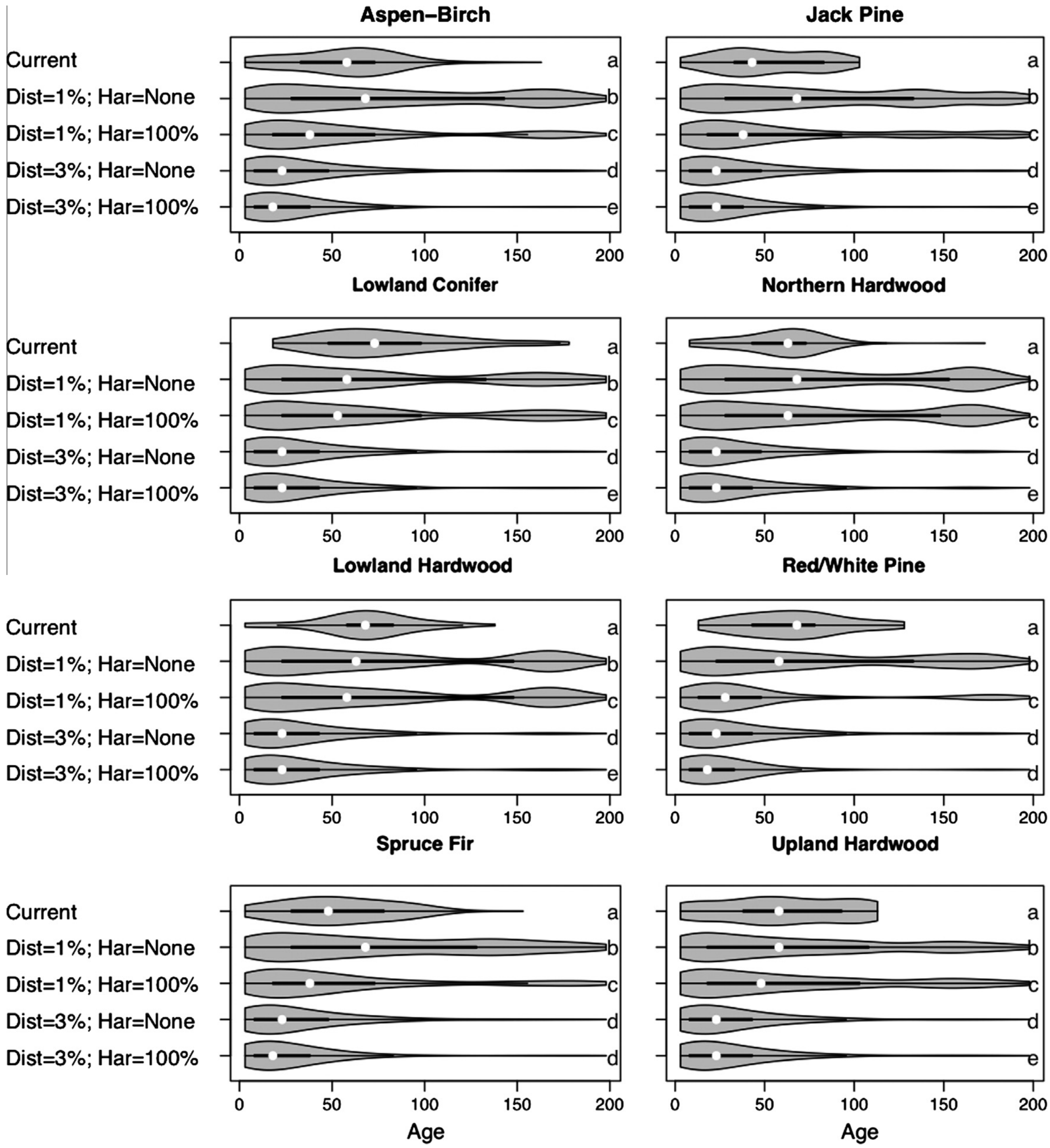

Fig. 2. Simulated age distributions of eight forest types on the Superior National Forest resulting from harvest and disturbance scenarios. Rotated kernel density plots depict the range and distribution of stand ages, and interior boxplots show the 25th and 75th quartiles and medians. Letters indicate statistical difference of Kolmogorov–Smirnov tests.

volume, and declaring the resulting harvest amounts to represent the 100% forest plan harvest amounts. The 40% and 200% harvest rates are simply those percentages of the 100% harvest goals. The effective annual harvest rates for the entire Superior NF ranged from 0.05–0.35% of forest area. Rotation lengths assigned to each forest type in the model were based on minimum harvestable ages specified in the forest plan.

The Boundary Waters Canoe Area Wilderness (BWCAW) is designated as 'reserved' forest land, and receives no active forest management activity; therefore, acreage under reserved status on the SNF was treated as 'no action' acreage in all scenarios with harvesting and was not subject to harvests in the model. All other SNF forest land (not reserved status) was treated as 'general forest' management areas, and received management consistent with that designation in the forest plan.

Two levels of natural mortality were included in our simulations of harvest effects on carbon storage. A lower natural mortality rate of 1% was assumed to mimic the small, patchy disturbances resulting from individual tree death and localized mortality from wind and pests (Ravenscroft et al., xxxx; Shinneman et al., 2010). An elevated mortality rate of 3% was selected to reflect the magnitude of recent disturbance events on the SNF, such as the 1999 Blowdown, and 2006 Cavity Lake and 2007 Ham Lake wildfires (Fites et al., 2007; Woodall and Nagel, 2007; Nelson et al., 2009). With both mortality levels, the simulated rates were applied annually across all age classes and forest types, resetting the affected areas to the initial age class in the same forest type, regardless of management activity.

2.6. Uncertainty estimation

We quantified the magnitude of uncertainty in forest-wide carbon stock estimates introduced by variation in the relationship between stand age and carbon stocks. We calculated 95% confidence

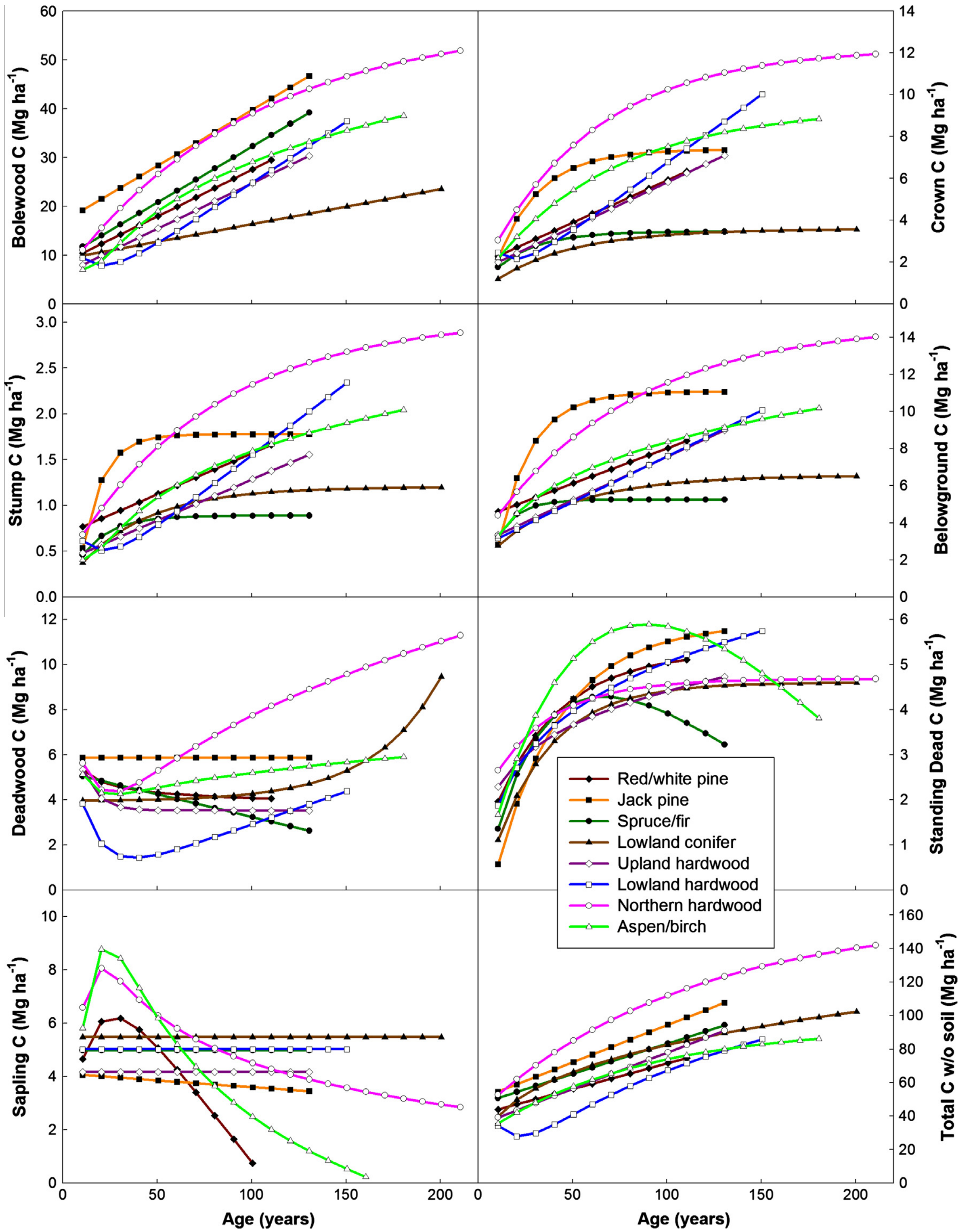

Fig. 3. Overview of forest stand age: carbon pool regression analyses for eight carbon pools and eight forest types on the Superior National Forest. Carbon attributes generated from previously modeled FIA data (understory above/belowground, organic soil, forest floor) are not shown. See Table A2 for model forms and parameter estimates.

limits (CLs) for the regression of carbon stocks as a function of age for the midpoint of each five-year age bin for each forest type. Forest-wide proportional CLs (e.g. % above and below the mean) were then calculated as the weighted mean of all age classes in all forest types (weighted by age class and forest type abundance within the study area) for each scenario (Ott, 1993). This approach to assessing uncertainty incorporates potential error in the regression models between stand age and carbon stocks, but does not account for uncertainty introduced by other sources of variability, including uncertainty in the current or future proportion of forest types within the study area and the impact of low-moderate severity disturbances on carbon stocks (Reinikainen et al., in press). Furthermore, this approach does not characterize the potential for changing climate and atmospheric CO_2 concentrations to alter the relationship between stand age and carbon stocks (Dixon et al., 1994).

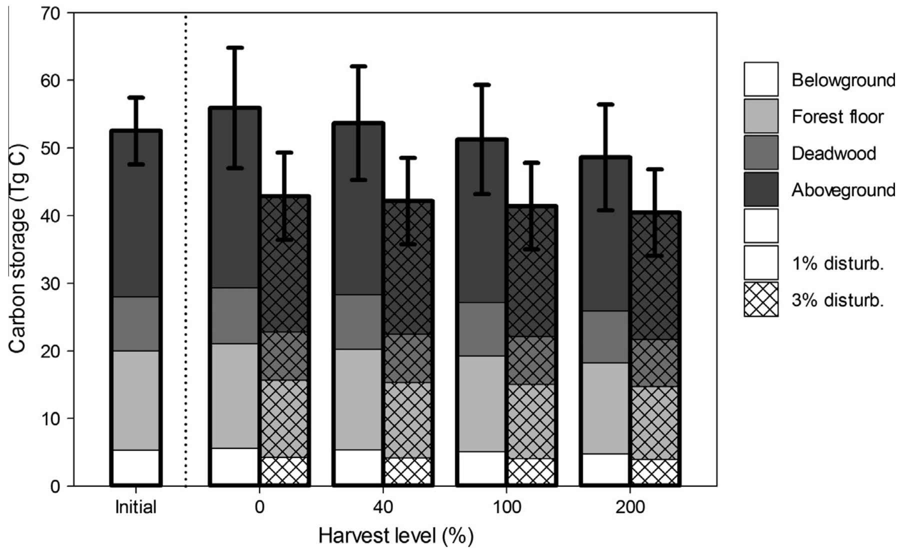

Fig. 4. Comparison of initial forest-wide carbon stocks (excluding soil organic matter) to simulated 100-year carbon stores with multiple harvest levels and disturbance rates. Error bars indicate variability in total carbon (thick lines around entire bars).

3. Results and discussion

3.1. Forest age and carbon stock relationships

Current estimated age structure differs among the eight forest types on the SNF (Fig. 2). Red/white pine, lowland hardwood, northern hardwood, and aspen/birch age structures exhibit unimodal age distributions with the majority of forest type area residing near the mean stand ages (65.3 ± 28.8, 67.5 ± 26.1, 57.1 ± 23.4, and 54.1 ± 27.5, respectively). Jack pine stands were the youngest, with a mean age of 51.7 ± 26.9, while lowland conifer were the oldest, with a large portion of area in older age classes (77.5 ± 36.1). Spruce/fir and upland hardwood forest types both display reasonably uniform age distributions (52.7 ± 29.5 and 59.8 ± 35.2). By the end of the 100-year simulations, these age distributions were all impacted by the harvest and disturbance scenarios. Without harvesting and under low disturbance (1%), the estimated age distributions of all eight forest types widened beyond their initial age range to include substantially older age classes (Fig. 2). Maximum harvesting (100%) with low disturbance similarly altered age distribution in forest types receiving lower harvest proportions, yet shifted the majority of estimated forest land area of more heavily harvested systems into younger age classes (Fig. 2). Increasing the annual disturbance rate to 3% decreased estimated age distributions of all eight forest types, regardless of harvest levels (Fig. 2). 3% annual disturbance generated age distributions with mean stand ages of less than 50 years.

Although the predicted age class–carbon relationships vary across carbon stocks and forest types, significant relationships with stand age were found for all carbon pools except SOC (in all forest types), understory above/belowground in upland hardwoods, and sapling carbon in spruce/fir and lowland conifer (Table A2). Carbon pools comprising live trees (bolewood, crown) increased with age for all eight forest types (Fig. 3). Estimated deadwood carbon displayed mixed results across forest types, showing strong increases with age in northern hardwood and lowland conifer, slight decreases in spruce/fir, upland hardwood, and red/white pine, and remained mostly constant in the other three systems. Estimated carbon in standing dead trees increased with age in all forest types until either reaching the predicted maximum or gradually declining at older ages. Estimated carbon in the sapling pool showed the strongest response to stand age in aspen/birch, northern hardwood, and red/white pine forest types, where a large increase in younger forests eventually declines with age. Overall, the estimated total forest carbon (excluding SOC) was positively associated with stand age in all eight forest types (Fig. 3).

Other studies examining carbon accumulation rates in this region have found similar patterns in forest age–carbon stock relationships. Bradford and Kastendick (2010) measured carbon stocks in chronosequences of red pine and aspen–birch ecosystems in northern Minnesota and described very similar forest age–carbon relationships. These relationships were subsequently found to be consistent with other field measurements of forest carbon in the region (Bradford, 2011). Additionally, work by Domke et al. (2012), which incorporated age–carbon model estimates for tree components in northern Minnesota were similar to estimates of tree carbon in this study.

3.2. Forest-wide carbon pools

Estimated carbon stock density (Mg C ha^{-1}) ranged from a low of 158 Mg C ha^{-1} in upland hardwoods to 336 Mg ha^{-1} in the lowland conifer type. The proportion of estimated total carbon stock density contributed by each carbon pool was similar across all eight forest types (Fig. 4). Soil organic matter was the largest pool in all forest types, storing 60–78% (97–262 Mg C ha^{-1}) of the total carbon on a site. The remaining pools contribute an estimated 7–21% (23–43 Mg C ha^{-1}, aboveground), 4–12% (8–29 Mg C ha^{-1}, forest floor), 3–6% (8–12 Mg C ha^{-1}, deadwood), and 1–5% (5–9 Mg C ha^{-1}, belowground) to total carbon storage per hectare. In lowland conifer and spruce/fir forests, forest floor carbon was greater than the estimated aboveground carbon, 34.6 and 29.3 Mg ha^{-1} compared to 24.6 and 23.4 Mg ha^{-1}, respectively. This large contribution of forest floor carbon is likely due to the presence of peat substrates in these communities.

Our estimates of forest carbon density were consistent with other studies in the northern Lake states (Bradford, 2011) and upper Midwest (Peckham et al., 2013). In a review of carbon stocks across the United States, Heath et al. (2011b) reports the northern national forest system region contains approximately 172 Mg C ha^{-1}, which falls within our estimates for the SNF. In comparing the contribution of individual carbon stocks however, Heath et al. (2011b) report greater amounts of aboveground biomass than the mean 33 Mg C ha^{-1} in this study. This may be due to their utilization of Jenkins et al. (2004) biomass equations, which result in differences due, in part, to estimation procedures.

Table 2
Total forest-wide carbon stock changes on the Superior National Forest under varying disturbance and harvesting scenarios after 100-year simulations.

Carbon pool	Initial (Tg C)	1% Disturbance								3% Disturbance							
		No harvest		40% harvest		100% harvest		200% harvest		No harvest		40% harvest		100% harvest		200% harvest	
		Tg C	%Δ	Tg C	%Δ	Tg C	%Δ	Tg C	%Δ	Tg C	%Δ	Tg C	%Δ	Tg C	%Δ	Tg C	%Δ
Aboveground	24.53	26.62	8.6	25.39	3.5	24.11	−1.7	22.70	−7.4	20.08	−18.1	19.69	−19.7	19.28	−21.4	18.73	−23.6
Belowground	5.31	5.58	5.1	5.33	0.5	5.06	−4.7	4.75	−10.6	4.24	−20.2	4.15	−21.7	4.06	−23.5	3.93	−25.9
Deadwood	8.00	8.22	2.8	8.06	0.7	7.87	−1.6	7.65	−4.3	7.17	−10.3	7.12	−11.0	7.07	−11.7	6.99	−12.6
Forest floor	14.67	15.47	5.5	14.86	1.3	14.18	−3.3	13.49	−8.1	11.36	−22.5	11.18	−23.8	10.99	−25.1	10.77	−26.6
Soil organic	142.46	142.46	0.0	142.46	0.0	142.46	0.0	142.46	0.0	142.46	0.0	142.46	0.0	142.46	0.0	142.46	0.0
Total ecosystem	194.96	198.35	1.7	196.10	0.6	193.68	−0.7	191.04	−2.0	185.31	−5.0	184.60	−5.3	183.85	−5.7	182.88	−6.2

In this study, live tree estimates were developed using the component ratio method (Woodall et al., 2011), which for most species results in lower estimates of biomass and carbon compared to Jenkins et al. (Domke et al., 2012).

3.3. Disturbance and harvest effects on carbon storage

Under the low (1%) natural mortality rate, forest-wide total ecosystem carbon stocks increased with 0% and 40% harvest levels (1.7% and 0.6%, respectively, compared to current values) at the end of the 100-year harvest simulations (Table 2). In scenarios simulating harvesting of 100% and 200% of the forest plan harvest rate, estimated total carbon stocks decreased by 0.7% and 2.0%, respectively, over the 100-year simulation (Fig. 5). Because harvesting practices on the SNF (including the management plan) do not allocate harvesting to forest types exactly proportional to their abundance in the forest, individual forest types and carbon pools did not always follow the same pattern as these forest-wide estimates. In simulations of 0% harvest, estimated jack pine belowground carbon decreased 1.4%, estimated spruce/fir deadwood and belowground stocks decreased 10.2% and 1.1%, and all lowland conifer stocks (SOC) dropped by 1.6–7.4% (Table A1). Additionally, forest types receiving a higher proportion of the overall harvest (aspen/birch, jack pine, and red/white pine, Table 1) reflected greater reductions in carbon stocks than forest types receiving less harvesting. The upland hardwood, lowland hardwood, and northern hardwood forest types only contribute an estimated 2.3% of the total harvest volumes, and as a result are only minimally impacted by harvest level, increasing carbon stocks even at 200% of the planned harvest levels.

Simulating an elevated rate of natural disturbance (3%) resulted in reductions to carbon stocks across all forest types and carbon pools, with the exception of spruce/fir deadwood (Table 2). This negative response of carbon stocks to disturbance was reflected across all harvest levels, although forest types receiving the larger proportion of harvesting (aspen/birch, jack pine, and red/white pine) again showed greater reductions. Estimated forest-wide total ecosystem carbon stocks decreased by 5% under elevated disturbance and no harvesting. Increasing the harvest rate to 200% of the forest plan lowered storage by an estimated 6.2% of current stocks (Table 2).

In the absence of disturbance or harvesting, the potential for forest carbon stocks to increase over the next several decades has been estimated at the regional scale, including the Pacific northwest (Hudiburg et al., 2009; Rogers et al., 2011) and northeast (Nunery and Keeton, 2010) and Lake states (Bradford, 2011; Peckham et al., 2013), as well as the national scale (Depro et al., 2008b; Heath et al., 2011a). However, these studies typically did not assess the combined impact of harvesting and disturbance. Our results suggest that even at an annual natural disturbance rate of 1%, forest carbon stocks can increase when harvesting is limited to 40% or less of the planned rate (Fig. 4).

Including natural disturbance in our estimates of harvesting impacts on carbon stocks also indicates that the potential for enhanced carbon stocks may be lower than other studies have estimated in the absence of disturbance. Under a 1% natural disturbance rate, we estimated an increase of only 1.7% in the no harvest scenario. By contrast, other studies focusing on the potential for altered forest management practices, have estimated potential regional carbon stock increases of 15–50% over the next 50–100 years in the absence of harvesting (Heath and Birdsey, 1993b; Hudiburg et al., 2009; Nunery and Keeton, 2010). Our lower potential highlights the need to recognize limitations imposed by natural disturbances when calculating potential future carbon stocks.

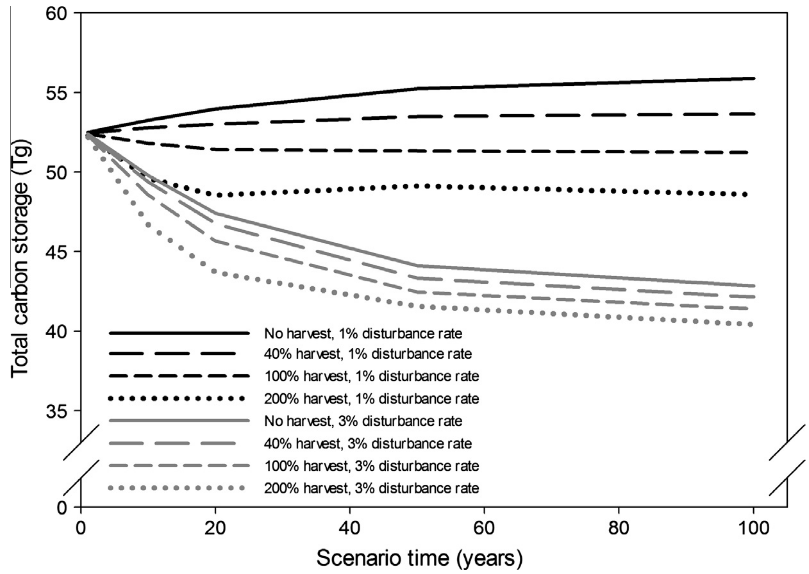

Fig. 5. Timeline of forest-wide total carbon stocks (excluding soil organic matter) on the Superior NF under four harvest-level and disturbance rate scenarios.

Furthermore, our results indicate the relatively modest alterations in the natural disturbance regime may have larger impacts on regional forest carbon dynamics than harvesting, even across a wide range of harvesting intensities. The role of disturbance in defining site-level forest carbon stocks and cycling is well recognized (Pregitzer and Euskirchen, 2004) and the potential impact of disturbance regime on potential future forest carbon stocks over large areas is receiving increased attention (Kurz et al., 2008a). Rogers et al. (2011) estimated that wildfires could decrease ecosystem carbon in the Pacific Northwest by approximately 20% compared to scenarios without fire, and that the magnitude and direction of change relative to current conditions depends on climatic conditions, which dictate total area burned. By contrast, we found that the difference between 1% and 3% natural disturbance equated to approximately 6.5% decrease in total carbon stocks, and that this difference was greatest when harvest intensity was low.

Despite the recognized importance of natural disturbances few studies have attempted to characterize the relative impact of simultaneous changes in harvesting practices and disturbance regimes (although see Kurz et al., 2008b). Our results suggest that variation in harvest intensity could alter total forest-wide carbon stocks by −2% to 2% under a 1% natural disturbance regime, and by −5% to −6.2% under a 3% natural disturbance regime. Thus, the capacity of forest harvesting practices to facilitate carbon uptake by forests within the Superior National Forest may be possible only when natural disturbance rates are relatively modest. If changing climatic conditions elevate the frequency and intensity of natural disturbances as anticipated (Dale et al., 2001; Westerling et al., 2006; Rogers et al., 2011), forests may become carbon sources, and the impact of harvesting practices on the magnitude of that source may be very limited.

While these results suggest that disturbance has a larger influence on carbon stocks than timber harvesting, examining the resulting age distributions from these scenarios offers insight into the driver of these changes. Disturbance scenarios the distribution of stand ages for all forest types to younger age classes, subsequently lowering carbon stocks forest-wide, whereas timber harvesting only affects a fraction of the same area and only in merchantable ages and forest types. The influence of timber harvesting on carbon stocks on the SNF is related to the amount of actual harvest activities occurring. Comparing the current harvest rates on the SNF to other landowners in northeastern Minnesota reveals that SNF harvest rates are fairly low; ownership contributions to the total annual harvest volumes from 2007–2011 in Cook, Lake, and St. Louis counties are as follows: county, 0.632 Mm^3 (39%; 431,872 ha), private, 0.501 Mm^3 (31%; 578,605 ha), state, 0.262 Mm^3 (16%; 285,706 ha), SNF, 0.205 Mm^3 (13%, 849,869 ha), and other, 0.034 Mm^3 (2%, 45,179 ha) (Miles, 2012). Nevertheless, the impacts of doubling the harvest rates on the SNF were secondary to the magnitude of change in carbon stocks with increasing natural disturbance rates (Fig. 5).

Several factors that may impact future carbon stocks on the SNF are not accounted for in this study. While this analysis assesses forest-wide carbon stock response to shifting stand age distributions, changing climatic conditions and atmospheric CO_2 concentrations may fundamentally altered the relationship between age and carbon. In particular, if warming temperatures and higher CO_2 concentrations increase growth rates in the region (Wythers et al., 2013; Peters et al., in press), carbon may accumulate faster in regrowing stands, potentially diminishing the impact of widespread harvests or natural disturbances. However, warmer temperatures may also accelerate decomposition rates, potentially decreasing the substantial amount of carbon stored in soils (Davidson and Janssens, 2006). Thus, this work provides insight into the relative impact of potential harvesting operations and natural disturbances on carbon, and should not be interpreted as a forecast of future forest-wide carbon stocks. In addition, the relationships between stand age and carbon stocks utilized in this work are based on age estimates from FIA methods that include measuring age in only a few trees per plot. While such biases may impact these results, we anticipate the effects are relatively modest, because bias in age determination is likely most prevalent in older stands (age determination in young, actively re-growing stands is probably more easily assessed by a few trees), where carbon stocks are changing relatively slowly in older stands (Fig. 3, Bradford and Kastendick, 2010).

Results presented here about the relative influence of natural disturbances and forest management practices suggest that increasing disturbance frequency has the potential to nullify management impacts on forest carbon. If natural disturbance rates increase substantially above the approximately 1% rates observed over the past several decades (McCarthy, 2001), our results indicate that maintaining or increasing forest-wide carbon stocks will be very challenging. Seeking a balance between disturbance and management may be the key to maintaining carbon stocks and forest-wide planning efforts may need to account for disturbance impacts when setting harvest levels. Although increased rates of disturbance may dictate reduced harvest rates, a complete lack of harvesting would prevent opportunities for creating forest conditions that are more resistant and resilient to disturbance events (Millar et al., 2007).

Acknowledgments

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.07.042.

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