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

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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

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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