Forest Ecology and Management 259 (2010) 1363–1375

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

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

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ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form 18 December 2009
Accepted 26 December 2009

Keywords:
Carbon sequestration
Wood products
Structural retention
Harvesting frequency
Sustainable forest management
Northern hardwood forests

ABSTRACT

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

1. Introduction

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

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0378-1127/$ – see front matter
doi:10.1016/j.foreco.2009.12.029

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

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

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

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

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

2. Methods

2.1. Study area and selection of study sites

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

2.2. Model description

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