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Late-successional and old-growth forest carbon temporal dynamics in the Northern Forest (Northeastern USA)

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ABSTRACT

Comprehensive data on the capacity and rates of change for carbon pools in managed and unmanaged forests is essential for evaluating climate change mitigation options being considered by policy makers at regional and national levels. We currently lack real and long-term data on forest carbon dynamics covering a wide range of forest management practices and conditions. Because of this, selecting the best policies for conserving forest carbon must rely on forest growth and yield models such as US Forest Service (USFS) Forest Vegetation Simulator (FVS) to predict the future forest carbon impacts of management actions. FVS may underestimate the capacity of older stands to accumulate carbon because the model relies on USFS Forest Inventory and Analysis data that lack data from late-successional and old-growth (LSOG) stands. Improving these models will increase the likelihood of selecting policies that successfully use forests to reduce atmospheric carbon. From 1995 to 2002, Manomet Center for Conservation Sciences conducted research on 65 10 m by 50 m permanent plots to evaluate forest structure (standing live and dead trees, and down coarse woody material) in LSOG stands across northern Maine. We re-measured these plots in 2011 to assess long-term carbon sequestration trends in LSOG stands of common forest types in the Northern Forest region for above ground alive, standing dead, and coarse woody material carbon pools. Late-successional (LS) and Old-growth (OG) aboveground live carbon (C) stocks were very high relative to regional mean C stocks (2.0–2.5 times the mean), LS plots were accumulating aboveground live C at a positive rate (0.61 Mg ha^{-1} $year^{-1}$), while C stocks on OG plots are declining (−0.54 Mg ha^{-1} $year^{-1}$). This change is driven by the presence of beech bark fungus (*Nectria* sp.) that is leading to mortality in larger diameter American beech (*Fagus grandifolia*) trees. We also found that the Northeast Variant of the Forest Vegetation Simulator is not a reliable predictor of aboveground live carbon accumulation rates in Northeastern LS and OG stands. This work provides important baselines for understanding the role of older forests and forest management within climate change mitigation strategies in the northeastern US. Late-successional and old-growth forests can play an important role in mitigating climate change, but understanding and quantifying natural disturbance risk to forest carbon stocks is critical for successful implementation of mitigation strategies. Further, regional forest carbon models will need calibration to accurately predict carbon accumulation rates in older forests.

1. Introduction

Global forests have a crucial role for addressing climate change because they store substantial amounts of carbon and are a leading source of emissions due to deforestation (Keith et al., 2009; Yingchun et al., 2012). In the US, the forest products sector also plays a key role by sequestering the equivalent of 10% of domestic greenhouse gas (GHG) emissions (Birdsey et al., 2006; Woodbury et al., 2007). Emerging carbon markets and regional climate change policies now allow emitters of GHGs to offset their emissions through carbon sequestration projects. Forest-based offsets hold great potential in the carbon marketplace, but their role has been limited by quantification uncertainty and concerns over risk of carbon (C) loss caused by natural disturbances (Galik and Jackson, 2009; Hurteau et al., 2009). There has also been the perception that mature forests are destined to achieve a steady state with respect to net exchange with the atmosphere (Jarvis, 1989). Recent studies, however, suggest that old forests may continue to serve as net carbon sinks for longer than previously thought (Luyssaert et al., 2008; Keith et al., 2009; Keeton et al., 2011); hence, the assumption that old forests in the northeastern US (including both late-successional (LS) and old-growth stands (OG)) are net emitters of

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C deserves reexamination. Unmanaged stands, and particularly late-successional and old-growth (LSOG) forests, may sequester an increasing amount of landscape C given the current age distribution of the northeastern U.S. forest.

Less than 1% of the northeastern forest is in an old-growth state (i.e., primary forest) (Davis, 1996) and long-term data on C stock changes over time within LSOG forests is lacking (Keeton et al., 2011). Our review of the stand establishment years (subtracting "stand age" from "measurement year") of the most recent measurement years (2008–2012) of US Forest Service (USFS) Forest Inventory and Analysis (FIA) data for New York and New England (USA) indicates that 0.4% (19 of 4921 plots) date from before 1862; with the oldest plot dating to an establishment around 1795. This small percentage of old forest plots represents a much smaller area than was present in the pre-settlement forest, and thus landscape C stocks are likely much lower now than 300 years ago. In Wisconsin (USA), the current forest C stocks in forests have only recovered to 49% of pre-settlement levels (Rhemtulla et al., 2009). The same conclusion would likely be made for the northeastern US forest, given an older, pre-settlement age-class distribution than current day (Lorimer, 1977; Keeton et al., 2011).

Forests younger than OG but beyond the typical rotation length of commercially managed forests of 50–100 years are often referred to as LS or "mature" forest (Frelich, 2002). LS forest stands represent a larger land area than OG in the northeastern US, but are still limited. In Maine, stand ages from 50–100 years are generally considered "economically mature" and stands over 100 years old are considered LS (Whitman and Hagan, 2007). However, Whitman and Hagan (2007) identified some stands over 80 years of age with LS structural characteristics. The fraction of FIA plots established between 80 and 150 years ago (i.e., representative of our study data) is 31% (1,534 of 4,921 plots). Of these plots, only 8% are greater than 100 years old, indicating that in the absence of harvest or stand-replacing disturbance a large number of plots will be entering a LS condition.

Comprehensive data on the storage capacity and rates of change of C in LSOG forests is essential for evaluating the full range of forest C mitigation and management options and as part of life cycle C accounting. Given the large forest area that may enter the LS class in the northeastern US, understanding the forest carbon dynamics within this age class becomes critical for forest management decision making. The work presented here builds on prior research in the region and provides a long-term (>15 years) evaluation of forest C stocks and rates of change using permanent sample plots in LS and OG stands in Maine (USA). These data are invaluable for assessing forest growth and yield models such as the USFS Forest Vegetation Simulator (FVS) to determine how well they predict the future forest C impacts of management actions. Most models like FVS may underestimate the capacity of older stands to accumulate carbon because data from old forest was lacking (Liu et al., 2011). Emerging forest carbon offset protocols also require field-based benchmarks to evaluate management trajectories. Our goals were to: (1) assess long-term carbon sequestration trends in LSOG stands of common forest types in the Northern Forest region of the northeastern USA; and (2) evaluate the ability of the USFS FVS model to predict carbon biomass accumulation in LSOG stands.

2. Material and methods

From 1995 to 2011, we measured and re-measured permanent plots to evaluate the impacts of harvest regimes on forest structure (standing live and dead trees, and down coarse woody material (DCWM)) on stands across Maine, including partially harvested, LS, and OG stands (Hagan and Grove, 1999; Gunn and Hagan, 2000). Re-measurement of these plots provided a unique opportunity to evaluate changes in carbon stocks to compare trends in carbon accumulation between LS and OG (LSOG) stands. LSOG plots were established in northern hardwood (hardwood) types and spruce-fir (softwood) types (Eyre, 1980). Northern hardwood plots were characterized by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*). Spruce-fir plots were characterized by spruce (*Picea* spp., most *P. rubens*, with occasionally stems of *P. glauca*) and balsam fir (*Abies balsamea*).

OG plots were located in The Nature Conservancy's 2,000-ha Big Reed Forest Reserve, northern Piscataquis County, Maine (centered at 46°20′N and 69°5′W). Prior research by Fraver et al. (2009) on the Reserve determined there was no evidence of stand replacing disturbance on the plots they studied during the last 120–280 years (Fraver et al., 2009). LS plots were located in Kibby and Skinner Townships, northern Franklin County, Maine (centered at 45°25′N and 70°31′W) on private forestland with over 100 years of harvest history. Although these plots had evidence of prior logging, they were classified as LS stands because they lacked evidence of natural or human stand-replacing disturbances based on field observations (e.g., numerous tip-up mounds, fire scars, and even-aged distribution). Stand establishment for LS plots ranged from 80 to 150 years prior to the first measurement. Establishment dates are based on reviews of historical stand maps, logging records, and tree increment cores from the plots. Whitman and Hagan (2007) describe in greater detail the methods we used for distinguishing between LS and OG stands.

2.1. Aboveground forest carbon sampling

In 2011 we re-measured LS plots ($n = 23$) and OG plots ($n = 35$) at the two sites. The plots were permanently monumented and mapped by using GPS (±10 m) and recording nearby landmarks. OG plots were first measured in 1995. LS plots were first measured from 1998 to 2002. In 2011 we re-measured LS plots ($n = 23$) and OG plots ($n = 35$) at the two sites. The plots were permanently monumented and mapped by using GPS (±10 m) and recording nearby landmarks. OG plots were first measured in 1995. LS plots were first measured from 1998 to 2002. We established 10 m × 50 m plots in stands with large trees and a lack of obvious harvest disturbance evidence. The LS pots were established by choosing a starting point and a random cardinal direction for the orientation of the plot from the start point. We chose starting points that allowed the entirety of the plot to be >75 m from road and harvest block (existing and proposed) edges. Plots were large enough to encompass areas of closed canopy and natural tree fall gaps typical of LS and OG stands. Stand sizes in Kibby and Skinner Townships (for LS plots) were generally too small to allow for more than one plot per stand. OG plots were clustered in groups of six plots separated by at least 250 m. Six plot clusters were distributed throughout the 2000 ha forest reserve.

Except for diameters of down coarse woody material (DCWM), the original measurement methods were used in re-measurement (e.g., Gunn and Hagan, 2000): diameter of each live and dead trees (⩾8 cm DBH) was measured at breast height (DBH) and decay stage was assigned for the entire tree (Table 1); for each piece of DCWM (>10 cm mid-point diameter, >30 cm in length) length and mid-point diameter was measured and a decay stage and piece type (i.e., log, top, and whole tree) was assigned (Table 1). Initial DCWM diameters were measured using a linear tape measure held horizontally over the log. The re-measurements used calipers. The initial measurement method may overestimate mid-point diameter compared to the re-measurement method (see Section 3.2). Moreover, in 1995, the dimensions of the entire DCWM piece were recorded if any portion of it fell on the plot. Using the ordinary