Forest Ecology and Management 392 (2017) 21–35

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Carbon dynamics and structural development in recovering secondary forests of the northeastern U.S.

Andrea R. Urbano [a], William S. Keeton [b,*]

[a] Rubenstein School of Environment and Natural Resources, University of Vermont, 81 Carrigan Drive, Burlington, VT 05405, USA
[b] Gund Institute for Ecological Economics, University of Vermont, 81 Carrigan Drive, Burlington, VT 05405, USA

ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 14 February 2017
Accepted 16 February 2017

Keywords:
Secondary forests
Structural development
Aboveground biomass
Forest carbon
Plantation forestry
Natural regeneration

ABSTRACT

There is a high degree of uncertainty regarding biomass accumulation and carbon storage potential in secondary temperate forests. Improving this understanding is vital for managing these forests as carbon sinks, a part of climate change mitigation efforts. A critical question is how secondary stand development in eastern U.S. forests has influenced long-term recovery from 19th century agricultural abandonment, and how this has affected aboveground carbon storage and co-varying stand-scale habitat characteristics. To answer this question we employed a longitudinal study based on twelve years of empirical data (2001–2013) collected from 60 permanent monitoring plots within 16 reference stands at Marsh-Billings-Rockefeller (MBR) National Historical Park in Woodstock, VT. We also used 150 years of documentary data from park management records. MBR Park was the first parcel of land actively reforested in the U.S. The Park's current forest mosaic reflects a history of alternate reforestation pathways and varied successional trajectories indicative of secondary forest recovery occurring across the broader northeastern forest landscape. This research evaluates the effects of reforestation pathways (planting vs. natural regeneration), management regimes (long-term low harvest intensities at varied harvest frequencies), and stand development trajectories on biomass outcomes and late-successional habitat. We generated biometrics indicative of stand structural complexity, including the H' structural diversity index, and aboveground biomass (live trees, snags, and downed coarse woody debris pools) estimates. Multivariate analyses evaluated the predictive strength of reforestation pathway, management history, and site characteristics relative to aboveground carbon pools and stand structural complexity. Classification and Regression Tree (CART) analysis ranked reforestation method as the strongest predictor of long-term mean total aboveground carbon storage, while harvest frequency, and stand age were selected as secondary variables. CART ranked percent conifer as the strongest predictor of H', while harvest intensity and frequency were selected as secondary variables. Our results suggest that a variety of long-term recovery pathways converge on high levels of aboveground carbon storage, including both conifer plantations and naturally regenerated hardwood stands, but silvicultural management can dramatically alter those trajectories. Total aboveground biomass (i.e., carbon) co-varied with H' ($R^2 = 0.25$). Thus, our dataset showed a positive relationship between forest carbon storage and structural complexity, supporting the concept of multifunctional forestry emphasizing late-successional habitats.

Contents

* Corresponding author.
E-mail address: william.keeton@uvm.edu (W.S. Keeton).

http://dx.doi.org/10.1016/j.foreco.2017.02.037
0378-1127/

1. Introduction

1.1. Understanding carbon dynamics in recovering secondary forests

Carbon sequestration in forests offsets about 14% of the United States' annual greenhouse gas emissions (Joyce et al., 2014). A major contributor to this service has been secondary forest regrowth in the eastern U.S. following 18th and 19th century agricultural abandonment (Woodall et al., 2015). Yet the strength of this sink, both in terms of potential carbon storage magnitude and rates/timeframe of continued net positive uptake, is uncertain in relation to long-term secondary forest development. While a variety of methods, including empirical modeling, have been used to determine that secondary eastern U.S. forests are currently a net carbon sink (Ollinger et al., 2002; King et al., 2015), a limitation is the rarity of empirical observations of long-term carbon dynamics in stands with known establishment dates and documented management histories, with some notable exceptions (e.g., Fahey et al., 2005). Consequently, there is debate whether secondary forests, particularly on sites where productivity may be impaired by historic clearing and agricultural uses, have the potential to regain carbon storage levels documented in primary forests (Rhemtulla et al., 2009; Keeton et al., 2011). Understanding the carbon storage potential of secondary forests is critical for accurate projections of national, and global carbon budgets (Pan et al., 2011; Birdsey and Pan, 2015). It is additionally relevant to rapidly developing compliance and voluntary carbon markets, in which emissions offsets generated through improved management projects in secondary forests is a key feature and long-term projections are required (Ray et al., 2009; Kerchner and Keeton, 2015). In this study we report on an empirical dataset addressing important sources of uncertainty in the aboveground carbon dynamics of recovering secondary forests.

Secondary forests in the U.S. Northeast store approximately 53 Mg of C/ha (Birdsey and Lewis, 2003). This is a net reduction from historic levels and indicates potential for continued carbon storage additions, especially in the context of the reported maximum potential aboveground biomass ranges of 216–267 Mg/ha (Hoover et al., 2012) and 250–450 Mg/ha (Keeton et al., 2011; Gunn et al., 2014) as some forests develop towards an old-growth condition. Estimates for the age at which aboveground biomass will peak in secondary northern hardwood and conifer forests in the northeastern U.S., however, vary widely. While early theoretical models predicted peaks after about 170 years of development (Bormann and Likens, 1979), some have suggested that secondary forests subject to anthropogenic stresses, including soil loss and nutrient depletion, may reach peak biomass substantially earlier (e.g., after less than one century) and at lower magnitudes (Fahey et al., 2005; Siccama et al., 2007; Bose et al., 2014). Others, relying on data from old-growth and primary forests found peaks in biomass much later in stand development (230–260 years of stand age, Tyrrell and Crow, 1994) with the potential for sustained increases for up to 400 years, depending on interactions with natural disturbances and other factors (Ziegler, 2000; Keeton et al., 2011; Gunn et al., 2014; McGarvey et al., 2015). These varied findings leave open the question of how biomass accumulation dynamics operate in secondary forests. Furthermore, little research has investigated how more than a century of continuous silvicultural management may have influenced these recovery processes. Consequently, these questions are the focus of our study.

1.2. Carbon in late-successional secondary forests

The U.S. Northeast's secondary forests are now mostly between 40 and 140 years of age (Lorimer and White, 2003), although forest cover is once again declining due to sub-urban/ex-urban development (Foster et al., 2011). Despite regrowth, it is uncertain if secondary northern hardwood, conifer, and mixed hardwood-conifer forests are recovering towards a high carbon storage condition yielding climate change mitigation benefits. Successional dynamics in eastern temperate forests have been profoundly altered by the region's unique land-use history, leading to multiple pathways of compositional development (Foster et al., 1998; Foster and Aber, 2004; McLachlan et al., 2000). Current trends in forest growth suggest a decrease in U.S. forest carbon uptake (Woodall et al., 2011), likely because eastern secondary forests are maturing and approaching equilibrium conditions for net primary productivity (NPP) (Fahey et al., 2010), but due also to a variety of anthropogenic stresses (Ollinger et al., 2002, 2008). Larger trees, however, contribute disproportionately greater amounts of carbon to total aboveground storage than smaller trees (Brown et al., 1997). In fact, continued forest growth is predicted to remain a driving mechanism for carbon accumulation in the U.S. Northeast and Mid-Atlantic states (Thompson et al., 2011), as growth rates and net positive biomass additions can increase with tree size for many temperate species (Stephenson et al., 2014). However, NPP may decline at slower rates than previously predicted in late successional forests, possibly yielding a greater upper limit to carbon storage (Carey et al., 2001; Luyssaert et al., 2008).

Previous research has suggested that late-successional forest structure in northern hardwoods varies widely depending on disturbance history (Lorimer and Halpin, 2014). Thus, it is unclear