Forest Ecology and Management 328 (2014) 167–178

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth

Andrew N. Gray [a,*], Thomas R. Whittier [b]

[a] USDA Forest Service Pacific Northwest Research Station, 3200 SW Jefferson W, Corvallis, OR 97331, United States
[b] Department of Forest Ecosystems and Society Department, Oregon State University, Corvallis, OR 97331, United States

ARTICLE INFO

Article history:
Received 11 March 2014
Received in revised form 8 May 2014
Accepted 10 May 2014
Available online 16 June 2014

Keywords:
Carbon sequestration
Forest inventory
Harvest
Dead wood

ABSTRACT

The National Forest System (NFS) of the United States plays an important role in the carbon cycle because these lands make up a large proportion of the forested land in the country and commonly store more wood per unit area than other forest ownerships. In addition to sustaining natural resources, these lands are managed for multiple objectives that do not always align with maximizing carbon (C) sequestration. The objectives of this study were to determine C stocks and flux in measured pools on Pacific Northwest Region NFS lands and the major ecological drivers of C flux. We compiled tree, dead wood, and understory vegetation data from 11,435 systematically-placed inventory plots and estimated growth, mortality, decay, removals, and disturbance events based on two full measurements spanning 1993–2007. The area of NFS-administered lands increased by 0.3% during this period and the area in formally-designated protected status increased by 0.7%. There was 1293 Tg C (±11.2 Tg standard error) in non-soil C stocks at the first measurement, which increased by 45 ± 2.2 Tg (3.4%), with 59% of the increase in the live tree pool and the remainder in the dead tree pools. C stocks followed broad regional patterns in productivity while C flux varied at local scales. Fires affected <1% of the forested area per year and were most prevalent in Wilderness areas. Fires reduced C stocks on burned plots by only 9%, and had a negligible effect on the region as a whole. Most tree harvest on NFS lands in the region consisted of partial harvest and had comparable impacts to fire during this period. C sequestration rates were higher (1.2 ± 0.09 Mg/ha/yr) on the west side of the Cascade Mountains, and primarily stayed in the live tree pool, compared to lower rates (0.5 ± 0.04 Mg/ha/yr) east of the Cascades where most of the increase was seen in the down wood pool. We discuss challenges to estimating forest ecosystem carbon stocks, which requires the application of a large number of equations and parameters for measured and unmeasured components, some with scant empirical support. Improved measurements and biomass models applied to networks of permanent plots would enable improved ground-based estimates of the drivers and components of regional changes in C.

Published by Elsevier B.V.

1. Introduction

Forest ecosystems are important components of the terrestrial carbon cycle because of the ability of many of them to store much larger amounts of carbon (C) than other terrestrial ecosystems (McKinley et al., 2011). These C stocks are dynamic as the area in forest land use changes and forests change with natural disturbance, climatic stressors, forest product harvest, and vegetation growth. Understanding the balance of these processes and the resulting C flux between forests and the atmosphere has been a focus of substantial research, given the implication of rising levels of atmospheric carbon dioxide in recent and future changes in climate (IPCC Core Writing Team, 2007). For example, while it is thought that 1–2 Pg C/yr are being stored in terrestrial ecosystems in the northern hemisphere, the magnitude of fluxes in the various vegetation types are not well understood (Pan et al., 2011; Hayes et al., 2012).

In the USA, national forests play an important role in the carbon cycle, as they cover 78.1 million ha and store more wood per unit area than other forest land ownerships (Smith et al., 2009; Heath et al., 2011). National forests are mandated to be sustainably managed for multiple uses, so need to balance many competing objectives, including watershed protection, providing native plant and animal habitat, and furnishing wood products. Not all of the objectives will maximize C sequestration, and in the case of reducing wildfire severity in dry forest types, maximizing C stocks may be undesirable (Stephens et al., 2013). The implications of different

---

* Corresponding author. Tel.: +1 541 750 7252; fax: +1 541 758 7742.
E-mail address: agray01@fs.fed.us (A.N. Gray).

http://dx.doi.org/10.1016/j.foreco.2014.05.015
0378-1127/Published by Elsevier B.V.

land management approaches for mitigating climate change are topics of debate, particularly the impacts of disturbance, long-term storage of harvested wood, decay of dead wood, and vegetation regrowth on C stocks (Mitchell et al., 2009; Malmsheimer et al., 2011; North and Hurteau, 2011; Vose et al., 2012; Hurteau et al., 2013).

The U.S. Forest Service leads efforts to address climate change on all forest lands, including striving to sustain or enhance C sequestration capacity and managing National Forest System (NFS) lands for climate change adaptation (USDA Forest Service, 2011). One strategy being employed consists of an annual Performance Scorecard for each national forest and grassland, which includes requirements for monitoring and for C assessment and stewardship (Coulston et al., 2012). In addition, the 2012 NFS Planning Rule requires national forests to identify and evaluate a baseline assessment of C stocks when revising their land management plans (Code of Federal Regulations, Title 36, sec. 219.6(b)(4)). A wide variety of approaches have been developed to quantify forest ecosystem C stocks and flux that use different accounting frameworks and methods, include different C pools, and apply different metrics of C stocks and flux. Some approaches evaluate a range of scenarios in ecosystem models (e.g., Mitchell et al., 2009). Many approaches use remote sensing models of land cover change tied to climate and ecosystem models to estimate C flux over large regions (Turner et al., 2007; Coops et al., 2009). Forest inventory data are often used to calibrate models of C stocks at a point in time, but the data are also useful to directly estimate regional C flux from repeated field measurements (Smith et al., 2004; Woodbury et al., 2007; Gray et al., 2014). Official estimates of C flux from US forests have relied primarily on the probabilistic sample of the nation's forested lands by the US Forest Service's Forest Inventory and Analysis (FIA) program (U.S. Environmental Protection Agency, 2013).

The national forests of the Pacific Northwest (PNW) Region attain some of the highest C densities in the U.S. (>300 Mg/ha) and have a higher proportion of forests in old age classes (>100 years) than other ownerships (Campbell et al., 2010; Heath et al., 2011). Given the late-successional character of much of the forests, it is not clear how much additional C they are sequestering. While harvest levels on these forests are substantially lower than they were during the 1960–1980s, it appears that the impacts of wildfires and insect outbreaks are increasing in recent decades (Westerling et al., 2006; Meigs et al., 2011). Most of the wood remains on site when trees are killed by these different agents, but it is not clear how rapidly the newly-dead trees decay, how much the older dead wood is consumed by fire, and how rapidly the ecosystem recovers from emitting to sequestering C.

Forest inventory data have been applied to estimate C flux on national forests, often (by necessity) from a combination of different kinds of measurements over time (e.g., Heath et al., 2011). However, remeasurement inventories now exist for some national forests, which enables a more detailed assessment of components of change for trees (i.e., growth, removals, mortality) and drivers of change of tree, vegetation, and down wood pools (e.g., harvest and natural disturbance events). The objectives of this paper were to compile and assess a remeasurement inventory to: (1) determine C stocks and flux in measured pools on Pacific Northwest NFS lands, (2) determine the major ecological and management drivers of C flux, and (3) discuss the strengths and limitations of inventory-based C assessments in relation to alternative approaches.

2. Methods

2.1. Study area

We assessed C stocks and flux on the 10.1 million ha of federal land administered by the Pacific Northwest (PNW) Region of the National Forest System (NFS), found primarily in the states of Oregon and Washington as well as parts of California and Idaho, USA, between 41.8°N and 49.0°N latitude and 116.3°W and 124.7°W longitude (Fig. 1). NFS lands in this region occur in a great variety of conditions, with annual precipitation ranging from 25 to over 350 cm, mean annual temperature from -1 to 12 °C, and elevations from 0 to 3300 m above sea level (Franklin and Dyrness, 1973). We grouped the nineteen national forests into five zones to reflect regional variation in composition and productivity (Fig. 1, Table 1). On average, vegetation west of the Cascade Mountain crest (western Oregon (WOR) and western Washington (WWA) zones) is more dense and productive than that east of the Cascade crest (Blue Mountains (BLUES), northeastern Washington (NEWA), and central Oregon (CEOR) zones). To assess finer-scale patterns within these zones, we grouped plots by 5th order watersheds (USDA Natural Resources Conservation Service et al., 2013).

We also assessed C stocks and flux by the broad land management groups within NFS lands. Twenty-four percent of NFS lands in the region have been nationally designated and are classified as "reserved" from timber production (i.e., where management for production of timber products is precluded; management for other objectives may be appropriate, including incidental tree cutting). Most of the reserved lands are congressionally-designated Wilderness (82%), with the remainder in National Recreation Areas (9%), National Monuments (3%), Wild and Scenic Rivers (3%), and other land management classifications (3%).

2.2. Field data

The primary data used in this study were collected by the Pacific Northwest Region of the U.S. Forest Service for a strategic inventory of vegetation conditions on all NFS lands in the PNW Region (Max et al., 1996), using a probability-based sample design (Olsen et al., 1999). The sample consisted of a systematic square grid at a 5.47 km spacing across all lands, and a denser grid at a 2.74 km spacing outside of designated Wilderness areas, providing a sample density of one plot per 3000 and 750 ha, respectively. Plots were installed using the Current Vegetation Survey (CVS) design (Max et al., 1996) between 1993–1997 and remeasured between 1997–2007 in four spatially- and temporally-balanced panels. The CVS plot remeasurement period ranged from 1 to 14 years with a mean of 7.1 years. Some plots fell on lands that changed ownership and were only measured once. The same grid of plots was also measured with the nationally-standardized Forest Inventory and Analysis (FIA) design starting in 2001 (USDA Forest Service, 2006); we applied the FIA land classification to the data in this study. The FIA measurement overlaps substantially in time with the second CVS measurement and therefore will allow a seamless assessment of change in the future as remeasurement of the plots using the FIA design began in 2011.

The CVS plot design consisted of a cluster of five points within a 1-ha circle, with four points spaced 40.8 m in cardinal directions from the central point (Appendix Fig. A.1). At each point, crews measured live and standing dead trees of different sizes (2.5–7.6, 12.7–33.0, and >33 cm diameter at breast height (DBH; 1.37 m from the ground)) in nested circular subplots of 0.004, 0.020, and 0.076 ha, respectively. Seedlings >15 cm tall and <2.5 cm DBH were counted by species on the smallest subplot size. Trees >76 cm DBH east of the Cascades or >122 cm DBH west of the Cascades were measured on the full 1-ha circle. Crews sampled down wood with the line-intercept method and estimated cover of shrub and forb vegetation on a 15.6 m transect at each point. The vegetation cover protocol changed between measurements: transect distances covered by vegetation were estimated in five segments per transect at time 2 instead of a single percent cover estimate for the whole