Forest Ecology and Management 336 (2015) 21–34

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Representative regional models of post-disturbance forest carbon accumulation: Integrating inventory data and a growth and yield model

Crystal L. Raymond *, Sean Healey, Alicia Peduzzi, Paul Patterson

USDA Forest Service, Rocky Mountain Research Station, 507 25th St, Ogden, UT 84401, United States

ARTICLE INFO

Article history:
Received 19 April 2014
Received in revised form 8 September 2014
Accepted 19 September 2014
Available online 31 October 2014

Keywords:
Carbon
Disturbance
Forest Vegetation Simulator
Fire
Harvest
Bark beetle

ABSTRACT

Disturbance is a key driver of carbon (C) dynamics in forests. Insect epidemics, wildfires, and timber harvest have greatly affected North American C budgets in the last century. Research is needed to understand how forest C dynamics (source duration and recovery time) following disturbance vary as a function of disturbance type, severity, forest type, and initial C stocks. We used the Forest Vegetation Simulator (FVS) to simulate total C stocks (excluding soil) for 100 years following three types of disturbance (fire, harvest, and insects) with four levels of severity. We initiated the model using empirical data from a large representative sample of forest conditions on the national forest ownership in the Rocky Mountain region (Forest Inventory and Analysis data). Unlike analyses based on stand age, an ambiguous quantity with respect to disturbance history, our approach enables explicit consideration of disturbance type and severity, as well as pre-disturbance forest C. On average, stands became a C sink after fire in 5, 6, 14, and 23 years for low to high-severity fire. Pre-fire C stocks were reached 25–55 years later. Following bark beetle epidemics, on average stands continued to be a C source for 10 years longer than fire and up to 40 years longer in some cases, but pre-disturbance C stocks were reached in a similar amount of time. C stocks following harvest showed the largest initial decline, but on average stands became a sink sooner at 1, 5, 15, and 12 years post-harvest for low to high-severity harvests. Differences in C dynamics based on disturbance type and severity, initial conditions, and forest type demonstrate the importance of considering this variability when modeling forest C dynamics. The regionally averaged models of C response quantified in this study can be combined with remotely sensed data on disturbance type and severity and used with C accounting approaches that rely on growth and yield or state and transition models.

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1. Introduction

Disturbance is well recognized as an important driver of carbon (C) dynamics in forests. In the last century, national and continental C budgets have been greatly affected by insect epidemics (Kurz et al., 2008; Kurz and Apps, 1999), wildfires (Amiro et al., 2001; Houghton et al., 2000), and timber harvest (Houghton and Hackler, 2000; Masek et al., 2011). Forest regrowth following disturbance is a major contributor to the current C sink in forests of North America (Birdsey et al., 2006; Goodale et al., 2002; Houghton et al., 1999). More research is needed to understand how forest C dynamics after disturbance vary by forest type and disturbance type and severity. This information can improve estimates of C stocks and fluxes for reporting under national and international policies. It can also inform the development of management practices to maintain or enhance forest C sinks, thereby reducing greenhouse gas (GHG) emissions that contribute to climate change.

The effects of disturbance on forest C dynamics are often quantified at individual sites or national and continental scales, but similar information is needed at regional and sub-regional scales to inform management decisions that are implemented at these intermediate scales. For example, the United States Forest Service (USFS) Climate Change Response Strategy (USFS, 2008) and Performance Scorecard (USFS, 2010), require national forest administrative units to report baseline C stocks, as well as changes in these stocks caused by disturbance and forest management. A 2012 revision to the USFS planning rule, which guides development of all unit-level land and resource management plans, requires national forests to assess ecological conditions and trends relevant to forming baseline assessments of C stocks and fluxes (USFS, 2012). These assessments are useful to managers considering actions to

* Corresponding author at: City of Seattle, 700 5th Avenue, Suite 3200, Seattle, WA 98124-4023, United States.

E-mail address: Crystal.Raymond@Seattle.gov (C.L. Raymond).

http://dx.doi.org/10.1016/j.foreco.2014.09.038
0378-1127/Published by Elsevier B.V.

maintain or enhance ecosystem services, such as C sequestration. The USFS owns one fifth of all forestland in the US (Smith et al., 2009), so management of these lands can affect national C budgets.

Baseline C stocks at any time can be quantified with forest inventory data collected as part of the USFS Forest Inventory and Analysis (FIA) program (Smith et al., 2006; Van Deusen and Heath, 2010). As of 2005, estimates from FIA indicate that forestland owned by the USFS contains a mean of 192 Mg C ha^{-1} on 60 million ha for a total of 11604 TgC (Heath et al., 2011). Estimates based on changes in C stocks between two times indicate that these lands are currently sequestering 150 $TgCO_2$ $year^{-1}$ on average (Heath et al., 2011). These estimates of stocks and stock changes are useful baselines under current conditions, but they cannot be attributed to particular management actions or disturbance trends. Ground-based inventory approaches, such as FIA, are limited in their ability to describe the effects of infrequent disturbances, characterize effects for specific forest conditions, or attribute C fluxes to specific disturbance types and severities (Masek and Healey, 2012). Further obscuring the relationship in the FIA data between disturbance and C dynamics is that only 10% of plots are measured per year, making it difficult to capture short-term C response following disturbance.

A more dynamic method is needed to assess the effects of disturbance on past and potential future changes in C stocks. The critical information needed for a dynamic method is the amount of C remaining after disturbances of different types and severities and subsequent changes in total C stocks with time since the disturbance. The rate at which C accumulates on a site can show the long-term effect of the disturbance on forest C stocks by showing the amount of time that the site functions as a source of C to the atmosphere and the time required to sequester the C emitted to the atmosphere from the disturbance and subsequent decomposition. This information can be summarized by models of total forest C as a function of time since disturbance. These models of C accumulation with time since disturbance can be combined with several approaches commonly used to estimate the effects of disturbance on C storage, such as growth and yield tables or state and transition models. Models based on growth and yield tables use pre-defined functions to track forest characteristics (e.g. C stocks) over time as forests change through succession and transition to new conditions via disturbance or management. Two such models commonly used for decision support are the Vegetation Dynamics Development Tool (VDDT; Kurz et al., 1999) and the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al., 2009). The latter is the primary tool used for national reporting of GHG emissions in Canada. A third model of this type, the Forest Carbon Management Framework (ForCaMF; Healey et al., 2014), is being applied across the US National Forest System to respond to C reporting requirements for the USFS. ForCaMF uses a Monte Carlo-based uncertainty framework to assign average C accumulation functions across the landscape based upon remotely sensed data of vegetation and disturbance patterns. The pre-defined functions of C accumulation with time since disturbance vary based on initial forest conditions and disturbance type and severity.

Biogeochemical process models can also provide a dynamic method for accessing past and future trends in C stocks (e.g. Zhang et al., 2012), but disturbance is represented in only a limited way (Liu et al., 2011). In the last decade, significant progress has been made to represent timber harvests (e.g. Masek et al., 2011), bark beetle epidemics (e.g. Edburg et al., 2011), and fire (e.g. Lenihan et al., 2008). However, most process models simulate only stand-replacing disturbances (e.g. Zhang et al., 2012) because C dynamics following disturbances are calibrated with empirical models based on forest age (He et al., 2012; Williams et al., 2012) making it difficult to represent partial disturbances (i.e. disturbances that emit and transfer C but do not reset stand age). If partial disturbances are represented, it is often with simplifications that can affect the rate at which C accumulates after a disturbance. Process models do not simulate individual trees, thus they are unable to capture variation in the species and size of dead trees, residual trees, and woody debris caused by disturbances of different types and severities. This variation can greatly affect C release and accumulation after disturbance (Amiro et al., 2010; Pfeifer et al., 2011) because these factors influence rates of decomposition, regeneration, and tree growth.

The objective of our study was to quantify average C accumulation rates following disturbance using a method that takes advantage of US national inventory data and is sensitive to the effects of disturbance type and severity on C without relying on stand age. We quantified average rates of total forest C (excluding soil) accumulation over 100 years following three types of disturbance (fire, harvest, and insects) with four levels of severity and for six forest types. We investigated multiple levels of severity because partial disturbances are common. Approximately 60% of forest harvests in the US are only partial harvests (Smith et al., 2009), and 68% of the area burned in the U.S. between 1984 and 2010 was categorized as moderate or low severity (Finco et al., 2012).

Our method for quantifying average rates of C accumulation following disturbance, which we demonstrate on the national forest ownership in the USFS Northern Region, combines publically available, nationally consistent FIA data and a commonly used growth and yield model, the Forest Vegetation Simulator (FVS) (Dixon, 2002). Unlike most biogeochemical process models, FVS simulates mixed-species and uneven-aged stands, enabling detailed simulation of disturbance effects specific to tree species and size. We modeled average functions for C accumulation following disturbance by grouping forest stands based on pre-disturbance levels of aboveground live tree C, forest type, and disturbance type and severity – all factors that that can be included in the growth and yield-based accounting systems mentioned above. We initiated FVS with a large dataset drawn from FIA's spatially balanced simple random sample (Bechtold and Patterson, 2005). Thus, the average functions for C accumulation are representative of a wide range of pre-disturbance conditions. By simulating the effects of three disturbance types with four levels of severity, we capture a wide range of responses in total forest C in terms of disturbance type, severity, and pre-disturbance forest conditions. This approach differs from studies that have observed or modeled C response following disturbance for one or a few sites which represent only a small sample of possible initial conditions and disturbance types and severities that could exist in a region.

2. Methods

2.1. Study area

We quantified the average rate and amount of C accumulation with time since disturbance for the forested area of the national forest ownership in the Northern Region (northeastern Washington, northern Idaho, Montana, and northwestern South Dakota, Fig. 1). The Northern Region includes 12 national forests covering 9 million hectares spanning from west to east of the Rocky Mountain Range and into the northern Great Plains. Forests are primarily coniferous, but the large elevation and associated climatic gradient gives rise to diverse forest types. Lower elevation forests west of the Rocky Mountains are a mix of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), *Abies* spp., western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don) and are some of the most productive forests in the region. Higher elevation forests are dominated by subalpine fir (*Abies lasiocarpa*