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Impacts of disturbance history on forest carbon stocks and fluxes: Merging satellite disturbance mapping with forest inventory data in a carbon cycle model framework

Christopher A. Williams [a,*], G. James Collatz [b], Jeffrey Masek [b], Chengquan Huang [c], Samuel N. Goward [c]

[a] Graduate School of Geography, Clark University, Worcester, MA, USA
[b] NASA Goddard Space Flight Center, Biospheric Sciences Laboratory, Greenbelt, MD, USA
[c] Department of Geography, University of Maryland, College Park, MD, USA

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ABSTRACT

Forest carbon stocks and fluxes are highly dynamic following stand-clearing disturbances from severe fire and harvest and this presents a significant challenge for continental carbon budget assessments. In this work we use forest inventory data to parameterize a carbon cycle model to represent post-disturbance carbon trajectories of carbon pools and fluxes for specific forest types growing in high and low site productivity class settings. We then apply these trajectories to landscapes and regions based on forest age distributions derived from either the FIA data or from Landsat time series stacks (1985–2006) for 54 representative scenes throughout most of the conterminous United States. We estimate the net carbon uptake in forests caused by post-disturbance growth and decomposition ("regrowth sink") for forested regions across the country. At the landscape scale, the prevailing condition of positive net ecosystem productivity (*NEP*) is in stark contrast to local patches with large sources, particularly in the west where fires and clear cuts create contiguous disturbed patches. At the continental scale, regional differences in disturbance rates reflect management patterns of high disturbance rates in the Southeastern and South Central states, and lower disturbance rates in the Northeast and Northern Lakes States. Despite low contemporary disturbance rates in the Northeast and Northern Lakes States (0.61 and 0.74% y^{-1}), the regrowth sink there remains of moderate to large strength (88 and 57 g C m^{-2} y^{-1}) owing to the continued legacy from historical clearing. Large regrowth sinks are also found in the Southeast, South Central, and Pacific Southwest regions (85, 86, and 95 g C m^{-2} y^{-1}) where disturbance rates also tend to be higher (1.59, 1.38, and 0.93% y^{-1}). Overall, the Landsat-derived disturbance rates are elevated relative to FIA-derived rates (1.19 versus 0.93% y^{-1}) particularly for western regions. The differences only modestly adjust regional- and continental-scale carbon budgets, reducing *NEP* from forest regrowth by about 8%.

1. Introduction

Forest disturbance is a widespread phenomenon across North America (Goetz et al., 2012) and can have profound impacts on a host of ecosystem services including carbon storage and uptake. Disturbances arise from a wide range of agents including harvests, insects, pathogens, fires, hurricanes and droughts. Many of these disturbance processes are episodic and highly variable in space and time, and there is growing indication of increased rates under the pressure of a changing climate (e.g. Allen et al., 2010). Thus, large-area monitoring is needed to identify which areas are being disturbed by what mechanisms, how rates of disturbance may be changing, and to assess impacts on a range of important services that forest ecosystems provide.

Satellite imagery is a powerful tool for monitoring disturbance area and post-disturbance recovery. Given its moderate resolution (~30 m) and long temporal coverage (since 1985, earlier for the MSS era), Landsat provides an unparalleled record of forest disturbance and regrowth dynamics (Cohen, Harmon, Wallin, & Fiorella, 1996; Cohen, Spies, & Fiorella, 1995; Cohen et al., 2002; Goward et al., 2008; Kennedy, Cohen, & Schroeder, 2007; Schroeder, Cohen, & Yang, 2007). This record is of great value for regional to continental assessments of forest change. For example, Landsat imagery has been used to construct maps of forest age for single scenes (approximately 180 × 180 km each) (Binford, Gholz, Starr, & Martin, 2006; Masek & Collatz, 2006) or even an entire region such as Oregon–California, (Law et al., 2004; Turner et al., 2007). This prior work identified challenges from low accuracy of mapped stand age and also offered too small a sample to quantify US or North American rates of change. The Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Masek et al., 2008) offers a step in the right direction toward a wall-to-wall record of stand-clearing disturbances across North America though its most recent

* Corresponding author at: 950 Main Street, Worcester, MA 01610, USA. Tel.: +1 508 793 7323; fax: +1 508 793 8881.
E-mail address: cwilliams@clarku.edu (C.A. Williams).

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generation offered a 5- to 10-year mapping interval which is too coarse to identify disturbances and track regrowth where the surface reflectance signal recovers quickly. The recent North American Forest Dynamics (NAFD) project (Goward et al., 2008) uses a sample of 50 Landsat scenes to quantify annual to biennial rates of forest disturbances across the conterminous US over the past two and a half decades (Fig. 1), with data available for five additional scenes used for algorithm development and testing. This paper combines the NAFD disturbance rates with other data to assess carbon impacts of recent disturbances across the conterminous US.

Forest inventory data can help to quantify the temporal dynamics of standing stock recovery following disturbance as they record biomass stocks with stand age. However, inventories have not typically monitored carbon belowground and correspondingly lack information on soil carbon and heterotrophic respiration, thus presenting an incomplete quantification of post-disturbance carbon dynamics. A more complete view can be obtained with ecosystem process models that simulate litter and soil carbon flows, especially when constrained to produce stock regrowth that is consistent with age–biomass relationships reported in forest inventories (Masek & Collatz, 2006; Song & Woodcock, 2003; Williams, Collatz, Masek, & Goward, 2012; Zaehle et al., 2006). Forest inventory data are also valuable for characterizing the area of forests in different age classes, particularly for large-scale, regional applications. However inventories sample only a small fraction of forested area and may have sizeable biases especially for local applications. This warrants the use of more complete, fine-resolution geospatial data, such as from the Landsat record, to expand beyond plots to regional and continental scales.

The analysis reported here combines strengths of the above approaches in a manner similar to the work of Cohen et al. (1996), Law et al. (2004), Masek and Collatz (2006), and Turner et al. (2007) to arrive at a more detailed and comprehensive assessment of the carbon consequences of past and present forest disturbance and regrowth across the conterminous United States. It offers one of the first demonstrations of merging national forest inventory data (and uncertainties) with a large-area satellite disturbance record and carbon cycle model to obtain regional and conterminous US estimates of carbon consequences. The basic method builds on our recent work (Williams et al., 2012) documenting post-disturbance carbon stock and flux trajectories for specific forest types and regions across the US as derived from an inventory-constrained carbon cycle model. This study adds another dimension by applying trajectories to landscapes with forest age maps obtained from a combination of forest inventory data and a Landsat disturbance detection product (Goward et al., 2008; Huang, Goward, Masek, et al., 2009; Huang, Goward, Schleeweis, et al., 2009; Huang et al., 2010a). Utilizing the disturbance maps of Goward et al. (2008) (Fig. 1), we apply this methodology to 54 Landsat scenes spread across the conterminous United States spanning its major forest type and climate settings. For comparison we apply the same approach using age distributions derived from the Forest Inventory and Analysis (FIA) database analysis of Williams et al. (2012) in place of the satellite-derived disturbances. We also apply results to all forestlands across the conterminous US to evaluate consistency of carbon balance estimates at the national level.

2. Methods

2.1. Overview

The core approach involved calculating regional and national disturbance rates, carbon fluxes, and carbon stocks based on the product of characteristic post-disturbance carbon flux and stock (Q_{afp}) specific to forest age, forest type, and site productivity class strata, with the area of land in each strata (A_{afp}), consistent with Williams et al. (2012). Region-total or national mass fluxes and stocks, as well as their uncertainties (δ, described further below), were calculated by summing over forest age, forest type, and productivity class strata, as

$$\begin{aligned} Q_{reg} &= \sum_a \sum_f \sum_p \left(Q_{afp} A_{afp} \right) \\ \delta Q_{reg} &= \sum_a \sum_f \sum_p \left(\delta Q_{afp} \delta A_{afp} \right) \end{aligned} \tag{1}$$

The area in each class was obtained in two ways and results are compared. The first relied solely on FIA data describing the area of forest land across strata. The second approach used a series of Landsat-based disturbance maps to estimate the area of land in younger age classes (<21 years) and then involved adjusting the FIA age histogram to characterize the age distribution of the remaining land classified as undisturbed in the Landsat record. Data sources for each step are described in the following Section 2.2.

In addition to regional and national assessments, we produced maps of carbon fluxes and stocks for each Landsat scene on a nominal 1 km × 1 km grid. Each grid cell (x,y) of area A_{cell} (~0.01 × 0.01°) was assigned a single forest type (e.g. Aspen–Birch) but with proportions

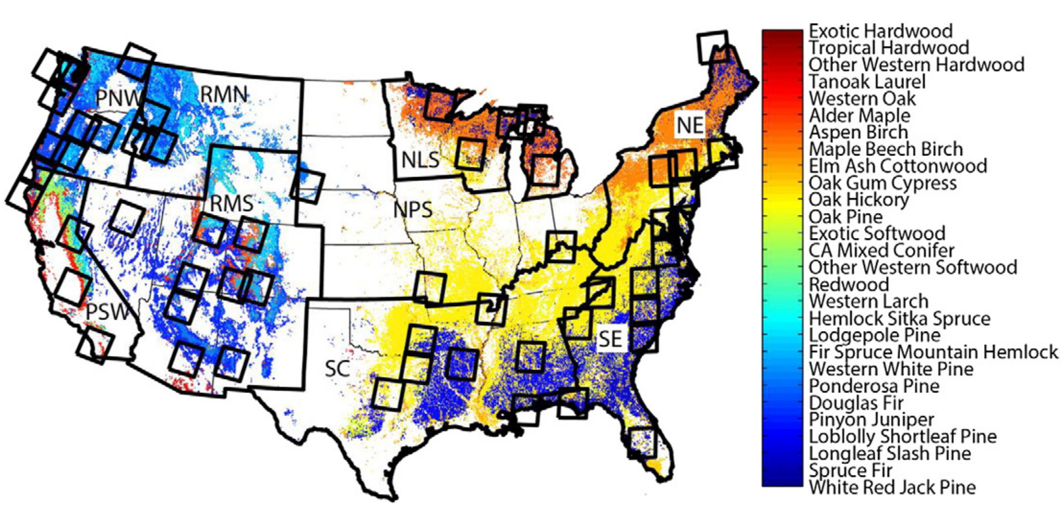

Fig. 1. Conterminous U.S. Forest Type Groups (Ruefenacht et al., 2008) shown with the distribution of Landsat scenes (squares) in NAFD sample. Thick state boundaries trace Forest Service regions. Colors loosely differentiate FIA forest type groups.