Global and Planetary Change 143 (2016) 66–80

Contents lists available at ScienceDirect

Global and Planetary Change

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

Invited review article

Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts

Christopher A. Williams [a,*], Huan Gu [a], Richard MacLean [a], Jeffrey G. Masek [b], G. James Collatz [b]

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

A R T I C L E I N F O

Article history:
Received 31 December 2015
Received in revised form 2 June 2016
Accepted 2 June 2016
Available online 4 June 2016

Keywords:
Forest ecology and management
Carbon sequestration
Climate change
Global environmental change
Carbon balance and management

A B S T R A C T

Disturbances are a major determinant of forest carbon stocks and uptake. They generally reduce land carbon stocks but also initiate a regrowth legacy that contributes substantially to the contemporary rate of carbon stock increase in US forestlands. As managers and policy makers increasingly look to forests for climate protection and mitigation, and because of increasing concern about changes in disturbance intensity and frequency, there is a need for synthesis and integration of current understanding about the role of disturbances and other processes in governing forest carbon cycle dynamics, and the likely future of this and other sinks for atmospheric carbon. This paper aims to address that need by providing a quantitative review of the distribution, extent and carbon impacts of the major disturbances active in the US. We also review recent trends in disturbances, climate, and other global environmental changes and consider their individual and collective contributions to the US carbon budget now and in the likely future. Lastly, we identify some key challenges and opportunities for future research needed to improve current understanding, advance predictive capabilities, and inform forest management in the face of these pressures.

Harvest is found to be the most extensive disturbance both in terms of area and carbon impacts, followed by fire, windthrow and bark beetles, and lastly droughts. Collectively these lead to the gross loss of about 200 Tg C y^{-1} in live biomass annually across the conterminous US. At the same time, the net change in forest carbon stocks is positive (190 Tg C y^{-1}), indicating not only forest resilience but also an apparently large response to growth enhancements such as fertilization by CO_2 and nitrogen. Uncertainty about disturbance legacies, disturbance interactions, likely trends, and global change factors make the future of the US forest carbon sink unclear. While there is scope for management to enhance carbon sinks in US forests, tradeoffs with other values and uses are likely to significantly limit practical implementation. Continued and expanded remote sensing and field-based monitoring capabilities and manipulative experimentation are needed to improve understanding of the US forest carbon sink, and assess how disturbance processes are responding to the pressures of global environmental change. In addition, continued development and application of holistic, decision support tools that consider a range of forest values are needed to enable managers and policy makers to use the best available information for guiding forest resources now and into the future.

Contents

* Corresponding author.

http://dx.doi.org/10.1016/j.gloplacha.2016.06.002
0921-8181/

1. Introduction

Ecological disturbances strongly influence local to global land carbon storage (Chapin et al., 2012). They affect ecosystem metabolism (productivity and respiration), alter how fixed carbon is allocated, influence species composition and ecosystem structure, directly release carbon to the atmosphere or relocate it (i.e. wood products), and cause internal carbon transfers among ecosystem storage pools most importantly from live to dead. Disturbance events typically result in a near-term net reduction in ecosystem carbon stocks. Ensuing recovery is often gradual. Thus disturbances tend to have the aggregate effect of reducing land carbon stores even if disturbance processes are integral for the health and maintenance of forest ecosystems.

Disturbance events are globally ubiquitous and rising in both frequency and severity (Allen et al., 2010; van Mantgem et al., 2009). In the US, disturbance rates have generally been stable in the east since the 1980s, but the west has seen trends toward elevated tree mortality and stand scale disturbances in response to warming and drought, more frequent and larger fires as well as outbreaks of bark beetles and other pests (Masek et al., 2013; Raffa et al., 2008; Schleeweis et al., 2013; van Mantgem et al., 2009; Westerling et al., 2006). Nationwide rates of forest disturbance measured at a stand scale with remote sensing (order 1000 m^2) average about 1.1% per year, but regions with intensive forestry such as the southeast experience 1.5% per year, rising even higher in the mountain West (>2%) where drought, fire and bark beetle disturbances have hastened (Masek et al., 2013; Schleeweis et al., 2013; Williams et al., 2014a). These rates place US forest cover change as high as anywhere in the world (Hansen et al., 2013).

Forests of the conterminous US currently hold about 40 Pg C in 270 million hectares of land (EPA, 2015). US forests are estimated to sequester about 0.20 Pg C y^{-1} (excluding wood products) offsetting 13% of annual US carbon dioxide emissions from fossil fuel combustion (1.5 Pg C y^{-1}) (EPA, 2015). Exactly what causes US forests to sequester so much carbon is not fully understood but one undeniable sink mechanism is the recovery of forests from past disturbances (Birdsey et al., 2006). Both historical and contemporary disturbances cause US forests to hold only about half of their theoretical maximum stocks (Williams et al., 2014a) and this imposes an age structure effect, or a so-called regrowth sink, that causes forestlands to naturally accrue carbon over time. Much of this regrowth sink is offset by disturbance emissions that take place offsite (i.e. wood products and processing emissions) or occurred previously (i.e. historical fire emissions). Thus, a sizeable portion of today's sequestration is compensating for the carbon losses from yesterday's disturbances. Indeed, US reporting to the UNFCCC indicates that contemporary harvesting removes 0.13 Pg C y^{-1} and fires release another 0.03 Pg C y^{-1} (EPA, 2011; EPA, 2015), which combine to offset some or all of the forest carbon sink from post-disturbance recovery (Williams et al., 2012b).

Meanwhile, US forests appear to be experiencing enhanced growth, contributing about 0.10 to 0.15 Pg C y^{-1} to the total carbon sequestration in forests (Williams et al., 2012b; Zhang et al., 2012). Proposed enhancement mechanisms include climate trends, atmospheric inputs (CO_2, N), management, and/or afforestation (e.g. Houghton, 2003; Thomas et al., 2009; Williams et al., 2012b), but the precise mix of drivers remains unclear. Evidence of enhanced growth is mounting, consistent with a doubling of the global sink for atmospheric CO_2 since the 1960s from ~2.4 to 5 Pg C y^{-1} in 2010 (Ballantyne et al., 2012) attributed largely to the land rather than ocean (Le Quéré et al., 2009), principally from increased carbon storage in global forests (Pan et al., 2011). Notably, this global-scale land sink trend offset about half the increase in fossil fuel and deforestation emissions since 1960 (Ballantyne et al., 2012), slowing the rate of increase in atmospheric greenhouse gases. Temperate and boreal forests, including those in the US, contribute substantially to this global forest sink for atmospheric carbon.

Enhanced land carbon storage is one of the most efficient and effective mechanisms at work mitigating anthropogenic carbon emissions, but this service could be in jeopardy as the changing climate threatens both forest carbon stocks and uptake (Allen et al., 2010; Anderegg et al., 2013a; Anderson-Teixeira et al., 2013; Bentz et al., 2010; Choat et al., 2012; Dale et al., 2001; Reichstein et al., 2013; Turner, 2010; U.S. Department of Agriculture, 2012; Williams et al., 2014a). Disturbance processes are one of the key vectors by which climate change initiates large-scale forest carbon releases (Peterson et al., 2014). Warming and drying is expected to drive further increases in the frequency and extent of high severity wildfire, drought, hurricane, and insect disturbances (Bender et al., 2010; Bentz et al., 2010; Dillon et al., 2011; Liu et al., 2010; Marlon et al., 2012) and recent trends in the US suggest that we may already be seeing this effect. Associated forest carbon releases have the potential to act as a significant feedback to climate change, and have even been identified as a possible tipping point in earth's climate system with the possible drying and collapse of major forest carbon stores such as in the Amazon (Lenton et al., 2008). Coupled with the expected decline in age-related regrowth from historical forest clearing, net sink strength in US forests appears poised to decline in coming decades, though the national scale impacts have yet to be fully quantified.

While these broad patterns are generally recognized, a comprehensive, quantitative synthesis is lacking. Estimates of each individual disturbance process are known to vary but have yet to be compared. Furthermore, the full suite of processes has yet to be integrated for a comprehensive, country-wide carbon balance assessment.

This paper seeks to fill that gap, presenting a review of the current state of knowledge regarding the impact of disturbances on the US forest carbon budget. It builds on a number of recent contributions that outline the theory, drivers, mechanisms, and extent of disturbance impacts on the carbon cycle of forests across North America (Amiro et al., 2011; Goetz et al., 2012; Hicke et al., 2012; Kasischke et al., 2013, 2011; Masek et al., 2011) by providing, here, a quantitative synthesis of carbon balance impacts from all of the major drivers. We first provide a general overview of how disturbance events alter the forest carbon cycle, and how impacts vary with disturbance attributes such as type and severity. We then present a synthesis of reported impacts of disturbances on the carbon balance of the conterminous US, spanning harvest, fire, insect outbreaks, drought, and windthrow events. We consider their combined role in the US-wide carbon budget now and into the future. Lastly we identify some key challenges and opportunities for future research needed to improve current understanding, advance predictive capabilities, and inform forest management in the face of these pressures.