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Decadal trends in net ecosystem production and net ecosystem carbon balance for a regional socioecological system

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ABSTRACT

Carbon sequestration is increasingly recognized as an ecosystem service, and forest management has a large potential to alter regional carbon fluxes – notably by way of harvest removals and related impacts on net ecosystem production (NEP). In the Pacific Northwest region of the US, the implementation of the Northwest Forest Plan (NWFP) in 1993 established a regional socioecological system focused on forest management. The NWFP resulted in a large (82%) decrease in the rate of harvest removals on public forest land, thus significantly impacting the regional carbon balance. Here we use a combination of remote sensing and ecosystem modeling to examine the trends in NEP and net ecosystem carbon balance (NECB) in this region over the 1985–2007 period, with particular attention to land ownership since management now differs widely between public and private forestland. In the late 1980s, forestland in both ownership classes was subject to high rates of harvesting, and consequently the land was a carbon source (i.e. had a negative NECB). After the policy driven reduction in the harvest level, public forestland became a large carbon sink – driven in part by increasing NEP – whereas private forestland was close to carbon neutral. In the 2003–2007 period, the trend towards carbon accumulation on public lands continued despite a moderate increase in the extent of wildfire. The NWFP was originally implemented in the context of biodiversity conservation, but its consequences in terms of carbon sequestration are also of societal interest. Ultimately, management within the NWFP socioecological system will have to consider trade-offs among these and other ecosystem services.

1. Introduction

Forest carbon flux is an important component of the global carbon cycle, and is believed to account for a sustained land based sink for carbon dioxide (CO_2) in recent decades (Bousquet et al., 2000; Canadell et al., 2007; Le Quere et al., 2009). Because of widespread interest in quantifying greenhouse gas emissions and potentially managing forests to increase the rate of CO_2 sequestration (Pacala and Socolow, 2004), there is strong incentive to quantify current patterns of forest carbon sources and sinks, especially as they relate to forest management. Forest carbon sequestration is increasingly recognized as an ecosystem service and it has begun to be included among indices of sustainability and in modeling exercises that seek to examine interactions among multiple ecosystem services (McDonald and Lane, 2004; Nelson et al., 2009).

The concept of a socioecological system captures the realization that there are nearly always significant interactions between a society and its environment (Berkes and Folke, 1998; Liu et al., 2007; Carpenter et al., 2009). In the Pacific Northwest region of the US, the social subsystem requires that forest lands be managed in a manner consistent with the Endangered Species Act. That requirement has meant the emergence of a socioecological system, i.e. the enactment of the Northwest Forest Plan (NWFP) in 1993 created a region-wide forest management regime. The intent of the NWFP was to conserve species such as the northern spotted owl (*Strix occidentalis*) that had been put at risk from extensive harvesting of older forests on both private and public land (USDA, 1994). An unintended consequence of the NWFP has been a change in the regional forest carbon balance associated with a reduction in harvests. Because carbon flux has become so important in the context of climate change, this change in carbon flux adds a new dimension to the regional socio-ecological system, and region-wide information on carbon flux – and how it relates to other ecosystem services – is needed to inform management deliberations. Here, we evaluate the forest sector carbon budget of the NWFP region over the 1985–2007 period with

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special attention to patterns associated with land ownership since management now varies strongly with ownership.

The Pacific Northwest supports large areas of highly productive coniferous forests and much of the forested area has historically been managed for timber production. However, rates of harvest have varied widely in response to economic and socio-political factors (Garman et al., 1999; Cohen et al., 2002). Previous estimates of forest carbon balance in the region have suggested a significant loss of carbon stocks for the 1953–1987 period (before the NWFP) in association with high rates of harvesting (Cohen et al., 1996; Smith et al., 2004; Alig et al., 2006). Implementation of the NWFP in 1993 resulted in a sharp decrease in harvesting on public lands (Thomas et al., 2006), thus a reduction in the ecosystem service of providing wood, but a gain in terms of conservation of biodiversity and in carbon sequestration. These tradeoffs must optimally be evaluated in a common framework and the modeling effort here is a step in that direction.

Our approach to quantifying net ecosystem carbon balance (NECB) relied on spatially- and temporally-explicit simulations of net ecosystem production (NEP, the balance of net primary production and heterotrophic respiration), harvest removals, and direct fire emissions. The simulation approach incorporates spatial information on soil properties, climate data, and forest distribution and disturbance history. Integration is achieved by application of a carbon cycle process model (Biome-BGC). Opportunities for assessment of uncertainty on our regional flux estimates come from evaluation of carbon stock changes based on forest inventory data.

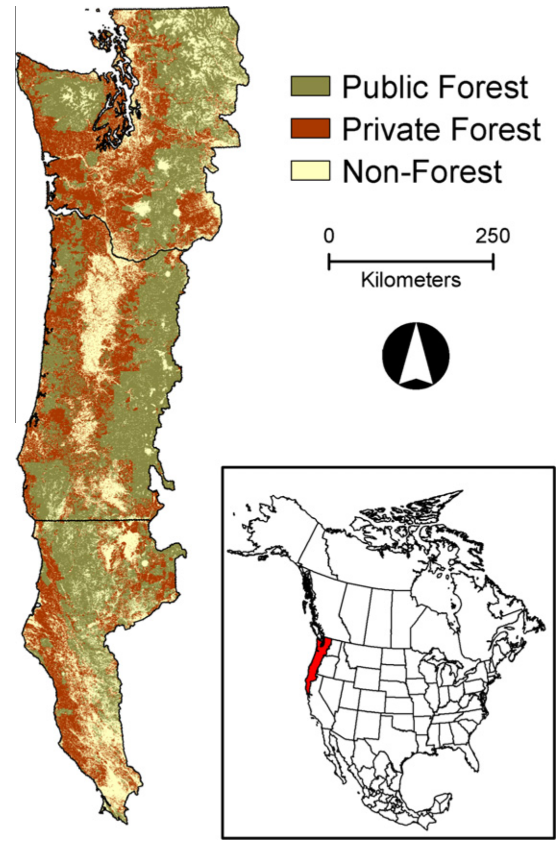

Fig. 1. Forest ownership over the Northwest Forest Plan area.

2. Methods

2.1. Overview

Our carbon flux analysis focused on three terms: (1) net ecosystem production (NEP = net primary production−heterotrophic respiration), (2) the harvest removals (HR), and (3) direct emissions from forest fires (FE). Summary results are expressed as net ecosystem carbon balance (NECB = NEP–HR–FE) which amounts to the net change of carbon stocks on the land base. The carbon balance of private lands was distinguished from that on public lands based on mapped land ownership (Fig. 1). Estimates for each of these three terms were made for each year of the 1970–2007 period, with results aggregated to 5 year means for three intervals: 1985–1989 (the period of maximum harvesting in the region), 1995–1999 (the period after major harvest reductions associated with the Northwest Forest Plan), and 2003–2007 (the most recent period for which all relevant input data was available).

2.2. Mapping net ecosystem production (NEP)

The primary NEP scaling tool in this analysis was the Biome-BGC process-based carbon cycle model (Thornton et al., 2002). Details of our previous applications and uncertainty assessments are documented in several publications (Turner et al., 2003a, 2007, 2011; Law et al., 2004, 2006). Generally, we used spatially-explicit model simulations to produce estimates of carbon stocks, annual net primary production, heterotrophic respiration, and direct fire emissions for each year from 1980 to 2007 over the forested areas in the NWFP domain (Fig. 1). Model inputs include daily climate data, soil texture and depth, land cover type, and stand disturbance history. This data was augmented with reports of harvest removals developed from state level agencies.

Our forest/non-forest coverage was from the National Land Cover Database (NLCD, Vogelmann et al., 2001) which used Landsat (∼30 m spatial resolution) imagery. Cases in which disturbed areas (which had formerly been forests based on Landsat data) were classified as Open or Shrubland by NLCD were reclassified to forest. Within the forest class, forest type was originally designated as evergreen conifer, deciduous broadleaf, and mixed. We reclassified the mixed class as conifer because a mixed class is not supported in the Biome-BGC process model and conifer is the dominant forest type in our region. The final cover type data layer was resampled to the 25 m resolution for ease of overlay with the 1 km resolution climate data (see below). The ownership coverage for Washington and Oregon was from the Bureau of Land Management (BLM, 2011), and for California from the University of California at Santa Barbara (UCSB, 1998). The public ownership class included federal, state, and county lands.

We established a stand age and near term disturbance history for each 25 m grid cell. These disturbance histories consisted of one or two disturbance events that were specified by year and type (fire or clear-cut harvest). Recent (1970–2007) disturbance history on forested pixels was from Landsat-based change detection analysis (Cohen et al., 2002; Kennedy et al., 2010). The only exception was wildfire in the period from 1985–2007 which was from the Monitoring Trends in Burn Severity (MTBS, 2009) database (Eidenshink et al., 2007), also Landsat-based. In that data set (Schwind, 2008), the year of the fire is specified and fire intensity is classified as high, medium, or low.

Disturbances previous to 1972 were prescribed on the basis of estimated stand age, again based on Landsat imagery. Stand age for all pixels not disturbed since 1970 was initially mapped as a continuous variable that was derived from ecoregion-specific relationships between stand age and Landsat spectral data at a set of US Department of Agriculture (USDA) Forest Service Inventory and Analysis plots (Cohen et al., 1995; Duane et al., 2010). To reduce the number of forest type by disturbance history combinations in each 1 km cell, the continuous ages were binned into young (30–75), mature (76–150), old (151–250), and old-growth