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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 socioecological 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.

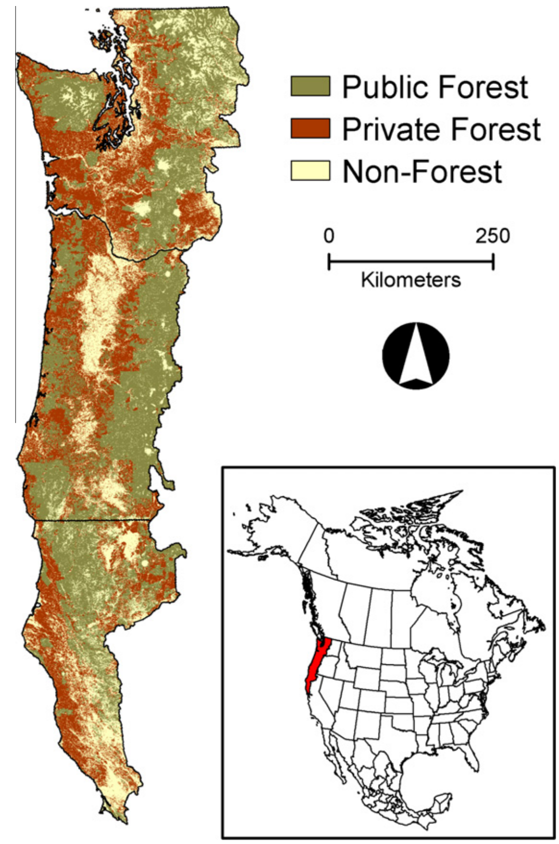

Fig. 1. Forest ownership over the Northwest Forest Plan area.

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

(>250) age bins and assigned the bin interval midpoint for stand age. Effective fire suppression in our region began about the same time as increased logging (e.g. Hessburg and Agee, 2003). Thus, stands less than 80 years old were assumed to have originated with a clear-cut harvest, and stands greater or equal to 80 years old were assumed to have originated with a stand-replacing fire.

2.3. Climate inputs

The meteorological inputs to Biome-BGC are daily minimum and maximum temperature, precipitation, humidity, and solar radiation. We used a 28-year (1980–2007) time series at 1 km resolution developed with the Daymet model (Thornton et al., 1997; Thornton and Running, 1999). These data are based on interpolations of meteorological station observations using a digital elevation model and general meteorological principles.

2.4. Soil inputs

Coverages for soil texture and depth (CONUS, 2007) were obtained from the Soil Information for Environmental Modeling and Ecosystem Management group at Penn State University (Miller and White, 1998). These surfaces of soil characteristics were based on the USDA/NRCS State Soil Geographic Database (STATSGO).

2.5. Biome-BGC parameterization and application

The parameterization of ecophysiological constants in Biome-BGC is cover type and ecoregion specific. Our values were from the literature (White et al., 2000) and our field measurements (Law et al., 2006). Representative values are given in Turner et al., (2007). For the conifer cover class (89% of forests in our final cover map), a final parameter optimization was performed at the ecoregion scale to minimize bias in the age-specific patterns in wood mass relative to USDA Forest Inventory and Analysis (FIA) plot data (Hudiburg et al., 2009; Turner et al., 2011). Two parameters – the fraction of leaf nitrogen as rubisco (FLNR) and the annual mortality (%) – were optimized simultaneously by comparing observed and predicted woodmass at all FIA plot locations using a plausible range of parameter values. FLNR has been used previously in optimization exercises with Biome-BGC because the model net primary production is sensitive to it, and its value is poorly constrained by measurements (Thornton et al., 2002; Turner et al., 2003b). Mortality is likewise poorly constrained and it has a strong influence on simulated woodmass.

Our analysis is specifically aimed at accounting for disturbance effects on carbon budgets, thus we specified the fate of all biomass pools at the time of a simulated disturbance. In the case of clear-cut harvest, the ratio of removals to residues was based on Turner et al., (1995), and for fire, the proportions of each carbon pool that were combusted were from Campbell et al. (2007).

To run the model at a given point, there is an initial "spin-up" for approximately 1000 years to bring the slow turnover soil carbon pools into near equilibrium with the local climate. The 28 years of climate data were recycled as needed for that purpose. The model then simulates one or two prescribed disturbances in specific years as the simulation is brought up to 2007.

Our earlier studies in this region have shown that the scale of the spatial heterogeneity associated with land management is significantly less than 1 km (Turner et al., 2000). However, because of the computational demands of the model spin-ups, it was not possible to do an individual model run for each 25 m resolution grid cell in the study area. Thus, the model was run once in each 1 km cell for each of the 5 most common combinations of cover type and disturbance history. Following that procedure, 92% of 1 km cells in the study had greater than 80% of their area directly accounted for. For mapping the carbon stocks and fluxes, an area-weighted mean value across the cover type by disturbance history classes was calculated for each 1 km cell.

2.6. Harvest removals

Harvest removals in terms of volume are tracked at the county level in Washington by the Department of Revenue (DOR, 2009), in Oregon by the Oregon Department of Forestry (ODF, 2006), in California by the California State Board of Equalization (CSBE, 2008). Data not on line was obtained directly from these agencies. These values in terms of volume were converted to carbon mass using the carbon densities in Turner et al. (1995) and the assumption that biomass is 50% carbon. County-level averages were area weighted in cases where county boundaries crossed NWFP boundaries.

2.7. Fire emissions

Estimates of direct emissions from forest fire were based on (1) our remote sensing analysis for area burned and fire severity, (2) carbon stocks (i.e. fuel loads) in the burned areas from the Biome-BGC simulations, and (3) transfer coefficients that quantified the proportion of each carbon stock that burned based on our post-fire field studies in the region (Campbell et al., 2007).

2.8. Uncertainty assessment

Previous studies have examined uncertainty in our Landsat-based change detection (Cohen et al., 2002,2010) and stand age mapping (Duane et al., 2010), in the DAYMET climate interpolations (Thornton et al., 2000; Daly et al., 2008), in Biome-BGC parameterization (Thornton et al., 2002; White et al., 2000; Wang et al., 2009; Mitchell et al., 2009), and in the effects of including fire intensity in the fire emissions estimate (Meigs et al., in press). Here we focus on comparisons of region wide flux estimates with changes in stocks based on forest inventory data.

3. Results

Forests cover 73% of the study area and the ratio of private to public forestland (Fig. 1) is approximately one to one (52–48%). The age class distribution of the forests in 2000 differs between ownership classes, with a larger proportion of older forests on public lands (Fig. 2).

The most conspicuous feature of the record of harvest removals is the sharp drop between the late 1980s and the mid 1990s (Fig. 3). The peak harvest years over our 27-year record were in

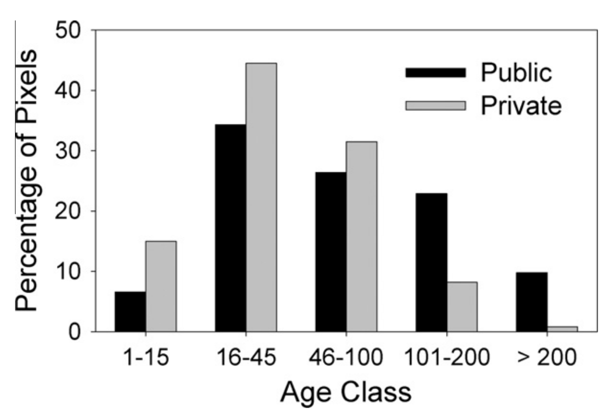

Fig. 2. Forest age class distribution in 2000 by ownership class.

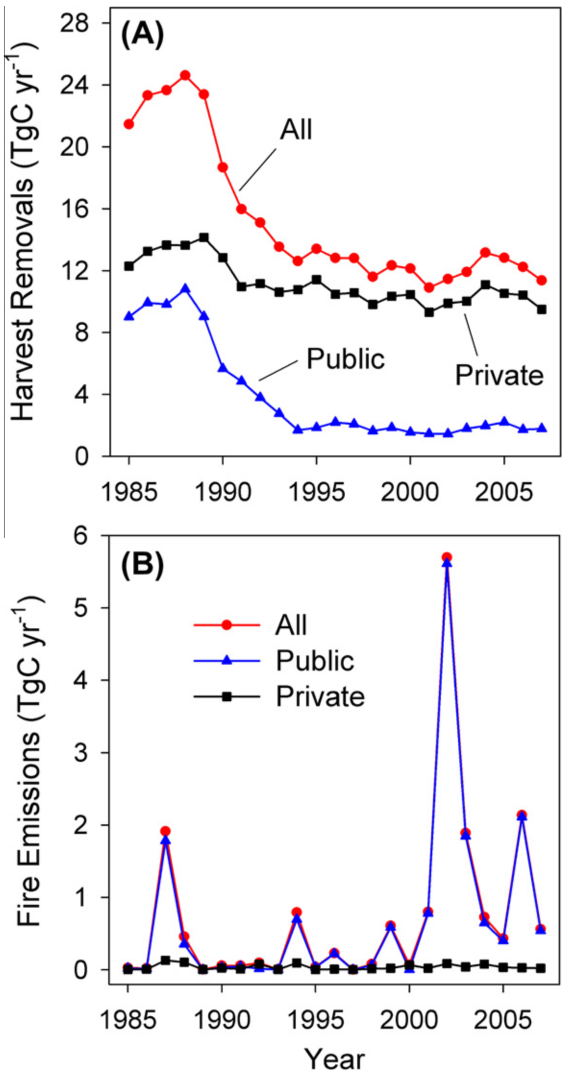

Fig. 3. Annual harvest removals (A) and direct fire emissions (B) for the NWFP area 1985–2007.

the mid to late 1980s when especially large volumes were associated with logging of old-growth forests on public lands. Harvest removals on public lands fell from a high of 10.8 TgC $year^{-1}$ in 1988 to a low of 1.5 TgC $year^{-1}$ in 2000. Removals on private land were nearly stable, averaging 11.3 (SD 1.3) TgC $year^{-1}$ over that period. In the 2003–2007 interval, there was a small increase in the harvest level on private lands because of high wood demand associated with an economic upturn.

Direct emissions from forest fires showed strong interannual variation (Fig. 3), with highest emissions in relatively warm years, as has been reported for the western US as a whole (Westerling et al., 2006). Fire emissions were predominantly on public lands (95%) of all area burned), reflecting in part their remoteness. Current polices on federal land calls for suppressing all fires except in Wilderness areas, but success in fire suppression varies widely. The magnitude of direct fire emissions during the study period was not large relative to logging removals (Fig. 3). We estimated that the extraordinarily large Biscuit Fire in southern Oregon in 2002 released 4.9 TgC directly into the atmosphere, still considerably less than annual logging removals in Oregon.

Mean NEP for the 2003–2007 interval (Fig. 4) showed a general pattern of decrease in moving from the mesic heavily managed coastal ecoregion to the cooler, mostly public ownership forestland in the Cascade Mountains. That spatial pattern reflects both a climatically driven gradient in potential forest productivity (Latta et al., 2009) and the larger proportion of private forestland in the Coast Range, which is managed for high productivity. Mean NEP (2003–2007) tended to be higher on public than private land (163 vs. 138 gC m^{-2} $year^{-1}$) reflecting the significantly smaller proportion of the area with negative NEPs (Fig. 5). These post-disturbance stands are typically a large carbon source because of reduced NPP and increased heterotrophic respiration associated with decomposition of logging or fire residues (Campbell et al., 2004; Amiro et al., 2010).

Both private and public lands were a NECB source in the late 1980s because of the high rate of harvest removals (Fig. 6). The biggest difference in pre- and post-NWFP carbon flux was the increase in public land NECB (Fig. 6), rising from an −48 gC m^{-2} $year^{-1}$ source in the late 1980s to an 141 gC m^{-2} $year^{-1}$ sink in the late 1990s and 136 gC m^{-2} $year^{-1}$ sink in the 2003–2007 interval. A carbon source is expected during periods when harvest removals exceed wood production. The primary factor driving the change in NECB was the large decrease in timber removals (Fig. 3). A small proportion of the increase in mean NEP on public lands for the 1995–1999 interval relative to the 1985–1989 interval was due to a more favorable climate for NEP (Potter et al., 2003; Turner et al., 2007), which is also reflected on private lands, and a change in the age class distribution such that fewer stands were in the 0–10 year age class with large negative NEP. On private land, NECB increased from −76 gC m^{-2} $year^{-1}$ in the late 1980s to 29 gC m^{-2} $year^{-1}$ in the late 1990s and 16 gC m^{-2} $year^{-1}$ in the 2003–2007 interval, driven by both the more favorable NEP and a small reduction in harvest level.

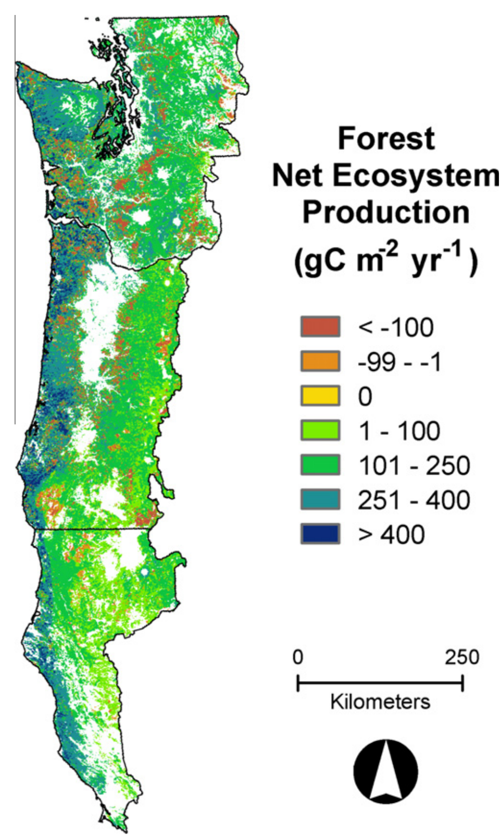

Fig. 4. Net ecosystem production for the NWFP area (2003–2007 mean).

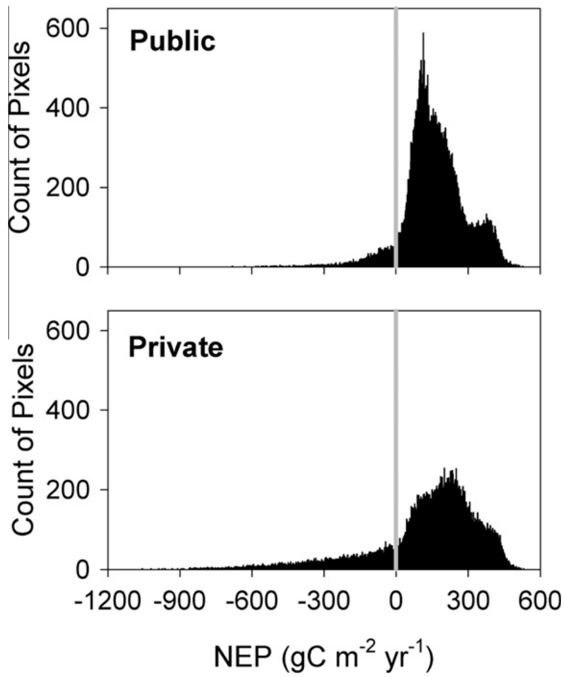

Fig. 5. Frequency distribution for NEP (2003–2007) by ownership class.

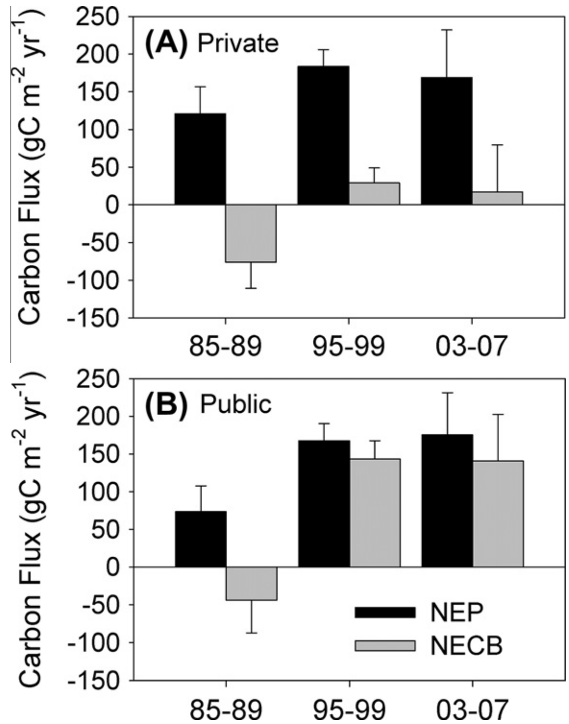

Fig. 6. Net ecosystem production (NEP) and net ecosystem carbon balance (NECB) on public and private lands in the NWFP area. Values are means and 5 year standard deviations. (NECB = NEP–harvest–fire).

4. Discussion

4.1. The response of regional carbon sequestration to management

At the time of the arrival of settlers to the Pacific Northwest in the mid 19th century, it is estimated that about two thirds of the forested area was old conifer forest, i.e. greater than 150 years of age (Strittholt et al., 2006). This large carbon stock had accumulated over a period of centuries against a background of infrequent stand replacing disturbances, notably fire (Garman et al., 1999). Since the late 19th Century, these stocks have been significantly drawn down by intensive harvesting. A small proportion of that harvested carbon remains as products still in use or in landfills (Harmon et al., 1996), while the remainder has been returned to the atmosphere.

Previous to the implementation of the NWFP, harvest rates on both public and private forestland were high enough that NECB was negative. Essentially, the volume of harvest removals was greater that the volume of net growth. However, by the late 1990s, the large harvest reduction on public forest land resulted in a gradually increasing NEP as the proportion of the land base that was very young, hence with highly negative NEP, decreased. Also, the large area that had been harvested in previous decades was coming into a period of strong carbon accumulation. Because most of the stem carbon from forest growth remained in the forest, the NECB became increasingly positive.

On private forest land in the study area, there was a small decrease in harvest level by the late 1990s relative to the pre-NWFP period. That harvest rate approximated the rate of net ecosystem production, thus NECB came close to zero. NECB is expected to tend towards zero in a managed land base with an even age class distribution maintained by a level of clear-cut harvesting that matches net growth of merchantable wood (Smithwick et al., 2007). The mean NEP in that case is a balance of mostly young to mature stands with strongly positive NEP and smaller areas of recently harvest stands with negative NEPs (Fig. 5).

Direct fire emissions in the study area have generally been small relative to NEP and harvest removals. Mean emissions for the 1995–1999 period were 0.2 TgC year^{-1} compared to a mean NEP of 27 TgC year^{-1} and mean harvest removals of 12.6 TgC year^{-1}. The fire emissions on public land did increase in the 2002–2006 period, but that included the anomalously large Biscuit fire in southwest Oregon (the largest contiguous fire in Oregon's history). The slow decomposition of dead wood left after the Biscuit fire will exert a downward influence on regional NEP for another decade or more (Amiro et al., 2010; Meigs et al., in press) but as the stock of woody debris declines and regrowth increase, NEP in the disturbed area will become strongly positive.

4.2. Uncertainty in flux estimates

Our simulation of carbon loss from the land base for 1985–1989 period is supported by retrospective forest inventory analyses. Donnegan et al. (2008, Fig. 31) and Campbell et al. (2010, Fig. 28) reported decreases in the volume of growing stock on timberland in Oregon and Washington in the late 1980s. The comparable report for California (Christensen et al. (2008, Fig. 28) suggests a modest increase during that period. Inventory based estimates of changes in wood volume also suggest an increase in wood volume on public lands for western Oregon and Washington after 1990, whereas the volume on forest industry lands was stable (Smith and Heath, 2004; Alig et al., 2006). A USDA Forest Service analysis that included all carbon stocks found a positive NECB for all three states in recent years, but there is not a break out by public vs. private land (Woodbury et al., 2007).

Uncertainty on the estimated direct fire emissions is improved here over our previous analyses (Turner et al., 2007) because we used the MTBS estimates for fire extent and severity (Meigs et al., in press). Our estimate of direct C emissions for the 2002 Biscuit Fire in Oregon here was 4.9 TgC, which compares to 3.8 TgC in a detailed study by Campbell et al. (2007) and 5.3 TgC in the national level study of Weidinmyer and Neff (2007).

Given the significant area of older forests that remain on public lands, there is strong interest in understanding the degree to which relatively old forests continue to accumulate carbon. Eddy covariance measurements in the study region and elsewhere (Law et al., 2001; Luyssaert et al., 2008) tend to suggest continuing sinks, as do chronosequence studies of forest inventory data (Lichstein et al., 2009; Hudiburg et al., 2009). However, Monte Carlo analysis of modeled NEP based on individual flux measurements did not support a significant carbon sink at the Wind River flux tower in our study region (Harmon et al., 2004) and a multiyear record of eddy covariance measurements at the site found an average sink of only -49 gC m^{-2} $year^{-1}$ (Falk et al., 2008). The Biome-BGC model runs here generally simulated small sinks in old growth forests, with significant interannual variation associated with climate.

The accurate mapping of stand age is a key issue in reducing uncertainty in regional simulations of forest carbon flux in western coniferous forests. Here we used a time series of Landsat images at intervals of 3–5 years in the early Landsat record, and an annual interval in the more recent years, to capture stand replacing disturbance. We did not account for partial disturbance events such as insect outbreaks and thinning. These events are beginning to constitute an increasing proportion of disturbance events in this region, and as our skill in detecting them with Landsat data increases (Kennedy et al., 2010), they can begin to be incorporated in the carbon cycle simulations. Field studies of thinning and insect outbreaks suggested that NPP and NEP decrease for over a decade after these non-stand replacing disturbances (Campbell et al., 2009; Pfeifer et al., 2010; Brown et al., 2010).

Stands over 30 years of age were mapped here using spectral data from Landsat and reference plot data from FIA (Duane et al., 2010). Relationships of stand age to spectral data were relatively weak, and alternative approaches such as gradient nearest neighbor analysis (Ohmann and Gregory, 2002) that incorporate additional information such as slope and aspect may improve the stand age mapping process. Application of lidar and radar (Kellndorfer et al., 2011) could also help in this regard. Coarse resolution (1 km or greater) mapping of stand age (Pan et al., 2011) is problematic for detailed carbon cycle simulation in our study region because the scale of the heterogeneity in stand age is generally finer than 1 km (Turner et al., 2000).

4.3. Management for multiple ecosystem services

The ecosystem services paradigm aims to take into consideration multiple services and stakeholders (de Groot et al., 2010). It is particularly relevant in the case of managing public forestland because there are likely to be significant trade-offs among wood production, carbon sequestration, and conservation of biodiversity associated with different management strategies. Modeling efforts that incorporate one or more ecosystem services are beginning to be developed (e.g. Nelson et al., 2009) but they are difficult to implement, in part because of extensive data requirements. Remote sensing of land cover, land use, and disturbance (Masek et al., 2011) offers the opportunity to study ecosystem services in a spatially-explicit manner over large areas, which can be important when management varies in space and time. The use of simulation models to quantify ecosystem services is also desirable because it clarifies the mechanisms involved. In this study, we established a remote sensing/modeling framework for assessing the ecosystem service of carbon sequestration within a regional socioecological system in which the additional ecosystem service of maintaining biodiversity was of interest. The management regime devised to conserve biodiversity meant a reduction in harvests. We were able to isolate the relative importance of harvest intensity, fire, and climatically-driven gradients in forest productivity on the rate of carbon sequestration. Future deliberations within the NWFP socioecological system can thus take into account this additional ecosystem service.

Efforts to monetize ecosystem services opens the possibility of explicitly evaluating trade-offs among them (Daily et al., 2000). Multiple studies have evaluated the carbon sequestration potential of forests in the Pacific Northwest and how it relates in economic terms to the value of timber harvests (Depro et al., 2008; Im et al., 2010). The economic valuation of biodiversity conservation is more difficult and will rely in part on assessing the vulnerability of a given species to extinction (Edwards and Abivardi, 1998). Spatially-explicit analyses that track habitat availability and population structure could be juxtaposed with spatially-explicit simulation of carbon flux to estimate a net benefit. As the scale required to effectively manage multiple ecosystem services continues to expand (Peters et al., 2009), a spatially-explicitly approach based on remote sensing becomes more essential both in terms of reconstructing historical change and monitoring responses to management. Spatially-explicit simulation of responses to different policy scenarios is also beginning to be employed for management purposes and may provide a means of communication among stakeholders (Carpenter et al., 2006) and for integrated analysis of ecosystem services across spatial scales (Hein et al., 2006).

5. Summary and Conclusions

The implementation of the Northwest Forest Plan in 1993 created a socioecological system framework for natural resource management in the region. Carbon sequestration is one among multiple ecosystem services that are provided by forests, and the combination of remote sensing and carbon cycle modeling offers the opportunity to quantify its magnitude and trends in a spatially-explicit manner. Here we found that previous to the NWFP, the NECB of forest land in the study area was generally negative (i.e. losing carbon). By the late 1990s and into the following decade, a harvest reduction on public lands driven by the implementation of the NWFP had resulted in a large carbon sink. On private forest land, subject to a much smaller harvest reduction, the NECB approached zero. Direct losses of carbon from fire emissions were generally small relative to NECB. The spatially and temporally explicit nature of our carbon balance monitoring framework permits the ecosystem service of carbon sequestration to be juxtaposed with co-occurring ecosystem services such as wood production and conservation of biodiversity. This type of framework can move society in the direction of examining trade-offs among multiple ecosystem services.

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