Environmental Science & Technology

Article

pubs.acs.org/est

# Interactive Effects of Environmental Change and Management Strategies on Regional Forest Carbon Emissions

Tara W. Hudiburg,[†,∥] Sebastiaan Luyssaert,[‡] Peter E. Thornton,[§] and Beverly E. Law[†,*]

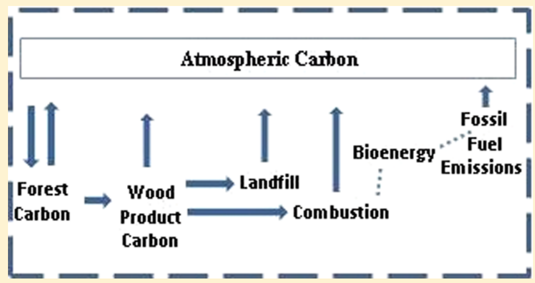
[†]Department of Forest Ecosystems and Society, Oregon State University, 321 Richardson Hall, Corvallis, Oregon 97331, United States.

[‡]Laboratoire des Sciences du Climat en de l'Environnement, CEA CNRS UVSQ, Centre d'Etudes Ormes des Merisiers, 91191 Gif Sur Yvette, France

[§]Oak Ridge National Laboratory, Climate and Ecosystem Processes Environmental Sciences Division, P.O. Box 2008, Oak Ridge, Tennessee 37831-2008, United States

Supporting Information

**ABSTRACT:** Climate mitigation activities in forests need to be quantified in terms of the long-term effects on forest carbon stocks, accumulation, and emissions. The impacts of future environmental change and bioenergy harvests on regional forest carbon storage have not been quantified. We conducted a comprehensive modeling study and life-cycle assessment of the impacts of projected changes in climate, $CO_2$ concentration, and N deposition, and region-wide forest management policies on regional forest carbon fluxes. By 2100, if current management strategies continue, then the warming and $CO_2$ fertilization effect in the given projections result in a 32−68% increase in net carbon uptake, overshadowing increased carbon emissions from projected increases in fire activity and other forest disturbance factors. To test the response to new harvesting strategies, repeated thinnings were applied in areas susceptible to fire to reduce mortality, and two clear-cut rotations were applied in productive forests to provide biomass for wood products and bioenergy. The management strategies examined here lead to long-term increased carbon emissions over current harvesting practices, although semiarid regions contribute little to the increase. The harvest rates were unsustainable. This comprehensive approach could serve as a foundation for regional place-based assessments of management effects on future carbon sequestration by forests in other locations.




## INTRODUCTION

North America is currently a net source from anthropogenic and natural processes of $CO_2$ to the atmosphere due to the dominance of fossil fuel emissions,[1] and U.S. forests compensate by removing up to 25% of the North American emissions.[2] The persistence of the U.S. forest sink will depend on the interaction of future climate, environmental change, and management, especially in the western states where an increase in drought, fire, and insect-related mortality have reduced forest productivity.

Globally, climate change is expected to have positive impacts on forest carbon sequestration through accelerated growth because of $CO_2$ fertilization[3] and increased nitrogen deposition.[4] Predicted and observed climate change impacts on western U.S. forests include dry areas becoming drier, changes in species composition, and increased mortality from drought stress, insect outbreaks, and fire[5−7] that may outweigh the positive effects on growth. Because changes in current management strategies (e.g., an increase in harvest) have the potential to diminish or enhance climate change and natural disturbance impacts, it is essential to quantify the interactive effects of climate change, increased atmospheric $CO_2$, nitrogen deposition, and proposed management strategies.

In efforts to improve forest health, provide energy security, and reduce $CO_2$ emissions (a potent greenhouse gas), intensive management plans have been considered or implemented.[8,9] Thinning to reduce the occurrence of wildfire has been a strategy on both public and private forestland for several decades and many have reported a reduction in emissions[10,11] while others have shown that the carbon saved is small compared to that removed in treatment.[12,13] Recent studies have examined the effects of changes in forest management intensity on forest carbon cycling and emissions associated with use of wood for bioenergy.[14−17] The basic assumptions used to justify increased harvest intensity for bioenergy are that (1) forest bioenergy is thought to be carbon neutral because the forest will regrow new biomass to replace removed carbon,[8] and (2) emissions from disturbance related mortality will be reduced or avoided.[18] This is contrary to comprehensive studies that account for the baseline carbon sink and show an increase

**Received:** July 2, 2013
**Revised:** September 17, 2013
**Accepted:** October 18, 2013
**Published:** October 18, 2013

in emissions compared to business-as-usual management (BAU) for decades to hundreds of years.[19−21]

These studies assume a one-to-one substitution of fossil fuel-based energy by bioenergy. The production of bioenergy increases the supply of energy and therefore reduces the price, leading to substantially lower substitution efficiency.[22] Furthermore, these studies did not examine the expected changes to the baseline carbon sink associated with climate change, which requires the use of a predictive model. The change ultimately depends on the interplay of regional conditions such as current and future sink strength, climate, and intensity of natural and anthropogenic disturbances. To improve assessments, long-term predictions are needed, along with consideration of the interactive effects of climate change and increasing nitrogen deposition.

Here, we go beyond recent studies by simulating the effects of varying management strategies on forest carbon dynamics while accounting for future environmental change (climate, increasing atmospheric $CO_2$, and nitrogen deposition). We focus on the 12 million hectares of forests in Oregon, U.S., where there is a wide range of climate, productivity, management types, and age classes that are representative of temperate forests worldwide (Figure 1; Supporting Information, SI, Table 1). Ecoregion mean annual precipitation ranges from 300−1800 mm yr$^{-1}$, mean stand ages from 30 to 150 years, and net primary production from 130 to 750 g C m$^{-2}$ yr$^{-1}$. We use a framework of model-data integration and complete life-cycle assessment (LCA) intended for place-based regional assessments of potential management effects on the future carbon sequestration by forests. The specific questions we answer are:

1. How will climate change and business-as-usual (BAU) management affect long-term forest carbon dynamics?
2. How will proposed management strategies affect long-term forest carbon dynamics?
3. How do the strategies affect net $CO_2$ emissions to the atmosphere?

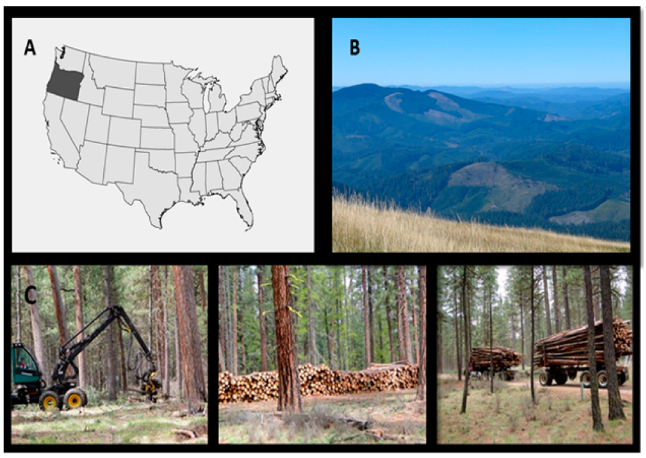



**Figure 1.** (A) Study region (dark gray) is the U.S. Pacific Northwest state of Oregon, (B) Clearcut management in the Oregon Coast Range ecoregion (mesic region, Photo Credit: Beverly Law), and (C) Fuels reduction thinning strategies in the Oregon East Cascades ecoregion (semiarid region, Photo Credit: Brian Hines).

## METHODS

**Carbon Cycle Terminology.** Forests take up carbon dioxide from the atmosphere and store it in biomass and soils and release it back to the atmosphere through plant (autotrophic) and microbial (heterotrophic) respiration. Net primary production (NPP) is net plant growth after accounting for autotrophic respiration. We define net ecosystem production (NEP) as the difference between NPP and heterotrophic respiration ($R_h$). We subtract losses through fire and harvest from NEP to obtain net land-based carbon uptake (net biome production; NBP).[23]

**Model Description.** CLM4 is the land model component of the National Center for Atmospheric Research's (NCAR) Community Earth System Model (CESM).[24] Through the combined use of regional climate data, physiological characteristics, and site physical attributes and history, CLM4 estimates the half-hourly carbon, nitrogen, and water fluxes between the atmosphere and the vegetation and soils. Active model components used in this study include biophysics, hydrology, and biogeochemistry. The land surface is divided into grid cells and the vegetated portion of each grid cell is further divided into plant functional types (PFTs) designated by a percentage cover of the grid cell (MODIS derived). Each PFT has its own leaf and stem area index and canopy height and each PFT competes for water and nutrients on a single soil column.

Recent model improvements include an integrated transient land cover and wood harvest data set for the historical period (1850−2005) and for the IPCC representative concentration pathway (RCP) scenarios or $CO_2$ trajectories (2006−2100).[25] The data set has been formatted for use in CLM4 and was constructed from remote sensing data and inventory observations.[26] The data set is not output from a dynamic vegetation model where PFT changes occur based on climate, stress, and disturbance drivers overtime. This data set is a prescribed human-induced disturbance history of forests which we can use to test the model's ability to simulate historical carbon dynamics following clear-cut or thinning harvests. We use this embedded transient PFT framework to implement our future management scenarios (Figure 1 and Table 1). We use the data set structure to prescribe the annual fraction of land that is transformed from one PFT to another and to prescribe the harvest area rates for each PFT within a grid cell over the simulation period.

**Model Forcing Data Sets (2010−2100).** Because our study region has strong climatic and vegetation gradients, we forced the model with a higher spatial resolution than is typical for CLM4 (1/8th degree or 12 km vs ∼2 degree). We used a regional downscaled data set assembled by the Climate Impacts Group at the University of Washington (http://www.cses.washington.edu/data/ipccar4/). The data set includes daily precipitation, minimum and maximum temperature, and wind speed for the period from 2000 to 2100 for a moderate climate impact scenario and a high impact climate scenario. Because CLM4 also requires shortwave radiation and relative humidity we calculated values incorporating algorithms from DAYMET[27] and methods for subdaily calculations as described by[28] (see SI methods).

According to these forcing data sets, at the end of the 21st century, predicted regional mean annual air temperature increases by 3.7 to 4.9 °C above the mean annual temperature in 2010 (SI Figure 1). Regional annual precipitation increases by 400 mm in the latter half of the century for the high impact

Table 1. Proposed Treatment Scenarios and Descriptions, Treatment Hectares As a Percent of Total Study Region Forested Area, Harvest Removal Rates (%), and Treatment Land Area Restrictions

| scenario | description | proposed treatable area (hectares) | total forest area treated (%) | grid cell harvest area[b] (%) | restrictions |
|---|---|---|---|---|---|
| BAU | continuation of current management practices. | 7 817 656 | 2.2% per year[a] | varies by grid cell and year | the harvest input file was not modified from the historical rates (1990−2010 rates) |
| thin | three 30 year thinning rotations | 4 578 689 | 17% per year | 50% | nonreserved forestland, no roadless areas, current stand densities must be >300 trees per hectare[58,59] |
| clearcut | two 45 year clear-cut rotations in productive ecoregions with historical clearcutting | 2 642 941 | 0.5% per year | 95%[c] | nonreserved, no roadless areas, forestland capable of 10 Mg of merchantable wood per hectare per year |
| combined thin and clearcut | application of thin and clearcut scenarios above | 7 817 656 | 2.2% per year | 50%, 95% | same as above for both |

[a]Harvest rates in Oregon averaged 2% of forested area in 1997 http://www.oregon.gov/odf/pages/state_forests/frp/1997menu.aspx) and range from 1.5−3.0% in the land use history file constructed from forest inventory data and remote sensing data sets.[26] [b]For the thin, clear-cut, and combined thin and clear-cut scenario, the harvest rates and treatment areas *replace* the current BAU management in that grid cell. Because the treatment scenarios include a whole-tree harvest (nonmerchantable residues plus the conventional merchantable wood harvest), the result is an *intensification* of harvest per grid cell rather than an increase in forest area harvested. [c]West Coast clear-cut harvests generate merchantable bole wood at rates of 50−60% of the total wood harvested.[60] The remaining biomass is considering slash or harvest residues. For our bioenergy scenarios, we increase the removals by increasing the area of the grid cell that is harvested. The harvest area rates above result in an average of 85% reduction in the grid cell stem biomass for the clearcuts and an average of a 35% reduction in stem biomass for the thins.[58,59]

scenario, but does not increase for the moderate scenario. However, the predicted precipitation patterns vary seasonally and spatially in both scenarios. Regional relative humidity remains fairly constant overtime for both future climates, increasing by only 1.5−3% over the 90-year period. Results and figures are presented as an average of the future forcing data set simulations (2 climate × 2 RCP pathways) for BAU and the proposed management strategies and we use the range of results as standard error estimates.

NCAR supplies half degree gridded aerosol, land cover change, aerosol and nitrogen deposition forcing data sets for future simulations according to the RCP scenarios defined for the fifth IPCC assessment. We used the NCAR spatial interpolation tools to regrid these data sets to our regional 1/8th degree resolution. To align our downscaled climate forcing data sets with the RCP scenarios, we chose to use the RCP4.5 and 8.5 pathways that lead to a radiative forcing level of 4.5 W $m^{-2}$ (approximately 550 ppm atmospheric $CO_2$ concentration) and 8.5 W $m^{-2}$ (approximately 1000 ppm) by the end of the century as they represent both a moderate and high impact scenario. We constructed global (single value per year) $CO_2$ forcing data sets. For these RCP scenarios, nitrogen deposition steadily declined in the moderate scenario while slightly increasing in the high one (SI Figure 1d).

**Model Evaluation.** Subregional model parametrization with observations (e.g., physiology, carbon allocation patterns, and wood combustion factors) greatly improves predictions at local to regional scales, which are the appropriate scales for place-based evaluation of environmental impacts and management options. Model spin-up, calibration and evaluation, historical simulations, and model development were completed.[29] We improved model estimates by making modifications to CLM4 to allow physiological parameters, mortality rate, biological nitrogen fixation, and wood allocation to vary spatially by PFT within an ecoregion based on field plot data in the region (>100 study sites). Using this regionally specific model version, we compared modeled ecoregion NPP, stem biomass, and $R_h$ with over 3000 forest inventory plots in the region. Model estimates of mean NPP and $R_h$ fell within the observed range of uncertainty in all ecoregions (SI Figure 2a), and statistical tests of model-data fidelity indicated good to adequate model performance at 15 km resolution across several age classes (see ref 29 for further details). These modifications and evaluations indicate that CLM4 is capable of capturing carbon dynamics following wood harvests. Simulations also compared well with seasonal gross photosynthesis (GPP) dynamics when compared with eddy-covariance tower data in both mesic and semiarid ecoregions (SI Figure 2b,c). Finally, the regional total NPP for forests was 57.6 Tg $Cyr^{-1}$, a value close to the observed total of 58.2 × 6.5 TgC $yr^{-1}$ calculated from inventory data.[30] The regional modeled total NEP for 2001−2006 was also close to the reported value from inventory data (12.8 versus 15.2 ± 1.6 TgC $yr^{-1}$;[30]), and Biome-BGC modeled results (17.0 ± 10 TgC $yr^{-1}$).[31]

To evaluate our fire predictions, we compared historical estimates of CLM4 simulated burn area with remote sensing data sets (Monitoring Trends in Burn Severity; MTBS[32] and Global Fire Emissions Database; GFED[33]). Before modification, CLM4 overestimated burn area compared to the remote sensing estimates and woody biomass combustion compared with observations[34,35] resulting in an overestimation of fire emissions by an average of 60%. Although developing the fire submodel to more accurately predict burn area was beyond the

Table 2. Increase or Decrease to Statewide Carbon Fluxes, Fire, and Harvest in Tg C $yr^{-1}$ Due to Climate Change for the BAU Scenario and the Difference between the Proposed Treatment Scenarios and Continuation of BAU

| scenerio | NPP[a] | $R_h$[b] | NEP[c] | fire | harvest | NBP[d] |
|---|---|---|---|---|---|---|
| BAU | 13.3 ± 3.1 (+20%) | 9.1 ± 1.2 (+17%) | 4.2 ± 1.5 (+31%) | 0.8 ± 0.5 (+26%) | no change | 2.6 ± 1.5 (+60%) |
| thin | no change | −0.5 ± 0.3 (−1%) | 0.4 ± 0.2 (+2%) | −0.1 ± 0.1 (−3%) | 1.1 ± 0.7 (+16%) | 0.6 ± 0.3 (−10%) |
| clearcut | no change | −0.7 ± 0.4 (−1%) | 0.8 ± 0.4 (+5%) | −0.3 ± 0.1 (−7%) | 2.5 ± 1.2 (+38%) | −1.5 ± 0.7 (−22%) |
| combined | no change | −1.2 ± 0.6 (−2%) | 1.2 ± 0.7 (+7%) | −0.4 ± 0.2 (−9%) | 3.6 ± 1.8 (+54%) | −2.1 ± 1.0 (−32%) |

[a]Net Primary Production (NPP) = Net plant growth after accounting for respiratory losses. [b]Heterotrophic Respiration ($R_h$) = Respired carbon by microbial decomposition of dead plant material [c]Net Ecosystem Production (NEP) = NPP − $R_h$; Balance between net plant growth and microbial respiration [d]Net Biome Production (NBP) = NEP − fire − harvest; Land-based carbon sink or source strength after accounting for removals

scope of this study, we were able to modify the combustion coefficients of the woody biomass to match our observations in the region. This reduced modeled fire emissions which is an important component of the life-cycle assessment. Uncertainty in emissions was reduced to within 10% of observed values. Further development of the fire model, including a fire suppression algorithm, would help alleviate the high bias in burn area.

**Model Simulations of Scenarios.** We modeled future carbon and nitrogen dynamics from 2010 to 2100 for the state of Oregon located in the Pacific Northwest region of the United States using downscaled regional forcing data sets representing moderate to high-impact climate warming and $CO_2$ concentration pathways (SI Table 2). After accounting for the effects of environmental change (N deposition, increased atmospheric $CO_2$, climate) and predicted burn area, we modeled future forest carbon balance under four potential management scenarios: (1) Continuation of BAU, (2) thinning at-risk forests, (3) clear-cutting nonreserved productive forests, and (4) combined thinning and clear-cutting strategies (Figure 1b,c and Table 1). BAU harvest rates were prescribed based on harvest since the Pacific Northwest Forest Plan was implemented in 1990, when they declined on publically owned forestland, but have remained relatively stable[36] since 2000. The thinning and clear-cut strategies were simulated to represent "whole-tree" harvests, where the nonmerchantable wood was removed and used as a bioenergy feedstock.[37] For the thin, clear-cut, and combined thin and clear-cut scenario, the harvest rates and treatment areas replace the current BAU management in that grid cell. Because the treatment scenarios include a whole-tree harvest (nonmerchantable residues plus the conventional merchantable wood harvest), the result is an intensification of harvest per grid cell rather than an increase in forest area harvested. Treatment years were staggered so that no more than 2.2% of the total forested area was treated each year to be consistent with average regional harvest rates and current mill capacity in the study region (http://www.oregon.gov/odf/pages/state_forests/frp/1997menu.aspx).

*Identification of Treatment Areas.* We define "at-risk" forests as those susceptible to drought, fire, or insect outbreaks. We designed the strategies based on current and pending Oregon forest management plans for using nonmerchantable wood as a bioenergy feedstock[9,38] and the "land sparing and sharing" strategy proposed to thin at-risk forests, clear-cut young forests, and preserve old forests.[30]

Grid cells were identified for treatment harvests based on their current productivity, mean fire return interval (MFRI), projected susceptibility to insect-related mortality, and stand density. Forest inventory data were used to calculate productivity and stand density, MFRI was obtained from the LANDFIRE database,[39] and potential insect mortality areas were identified using published maps of current insect mortality.[40] Areas with low MFRI (<40 years), high stand density due to fire suppression, and areas potentially vulnerable insect damage were chosen for the thinning scenarios in the East Cascades and Blue Mountains and in high density areas of the West Cascades. The grid cells selected for simulated thinning were limited to areas where average FIA derived stand densities are greater than 300 trees per hectare. Portions of the Coast Range, Klamath Mountains, and West Cascades were selected for clear-cut treatments. Only grid cells capable of producing 10 Mg of merchantable wood per hectare per year were treated. Old growth reserves and roadless areas, about 20% of the forested area, were excluded from all treatments. The treatments replaced the current harvest rates for each identified grid cell to ensure there was no spatial overlap of current harvest rates with BAU conditions. For grid cells not selected, the current harvest rates (BAU) remained the same.

To implement the proposed harvest treatments, we modified the harvest area rates in the dynamic land use file used by CLM4 as the prescribed harvest area rate per year (Table 1). For the clear-cut harvests, the PFTs remained constant for each grid cell treated. Thinning opens up forest canopies allowing understory shrubs to grow, effectively transferring overall stand productivity to a different PFT.[41] To more adequately represent vegetation dynamics following thinning, the PFT grid cell weights were modified following a thinning harvest by transferring 20% of the forested PFTs to the shrub PFTs and transferred back to the *forested* PFTs in later years over a 20 year period. Finally, all results are summarized using the grid cell averages for all PFTs present (i.e., competing shrub and grassland area are included). However, we do only include land area where the majority of the grid cell is considered forested, which for this study in Oregon resulted in 12.8 million hectares.

**Life-Cycle Assessment (LCA).** Life-cycle assessments consider forestry-related sources and sinks of carbon from and to the atmosphere and the associated effect on fossil fuel emissions.[42] A complete LCA includes the land-based carbon (NBP), and tracks carbon losses in transport, manufacturing, combustion, and fossil fuel substitution. In ref 17, we developed the LCA approach to quantify net C emissions from wood use and include changes regarding wood end-use, primarily the sole conversion of wood to combined heat and power (CHP) versus use as cellulosic ethanol. All proposed harvests include a merchantable portion used for wood products and a non-merchantable portion used for bioenergy. We included potential mill use of current harvest residues as part of the BAU scenario because up to 25% of harvest and mill residues are already being used internally for bioenergy at some processing facilities.[43] The values associated with the efficiency of wood product and energy conversion, energy inputs for harvest, transport, and manufacturing, and displacement of fossil fuel emissions depend on the site location, facilities available, fossil fuel source, wood products produced, land fill input rates, wood product substitution and many others. We varied the coefficients for several of the life-cycle factors to incorporate the range of observed to potential efficiencies and provide a sensitivity analysis of the results (see LCA details in SI). We combined the range in projected climate impacts with the sensitivity analysis using the propagation of error approach[44] to provide uncertainty estimates of our final net C emissions (see SI methods).

## ■ RESULTS AND DISCUSSION

**Long-Term Forest Carbon Storage Increases with BAU Management.** The mean response of carbon dynamics to regional climate and environmental change results in larger increases in NPP than $R_h$, with the net effect of a 31% increase in net ecosystem production (NEP) for BAU by the end of the 21st century (Table 2, Figure 2a,b). Increases are larger in the semiarid eastern ecoregions compared to the western mesic ecoregions (Figure 3). BAU harvest is current observed harvest levels and assumed to remain constant such that there is no difference in harvest removals, while CLM4-predicted fire emissions increase by an average of 26%. Despite increases in fire emissions and continued harvest removals, regional NBP increases by an average of 60% resulting in increased forest C storage.

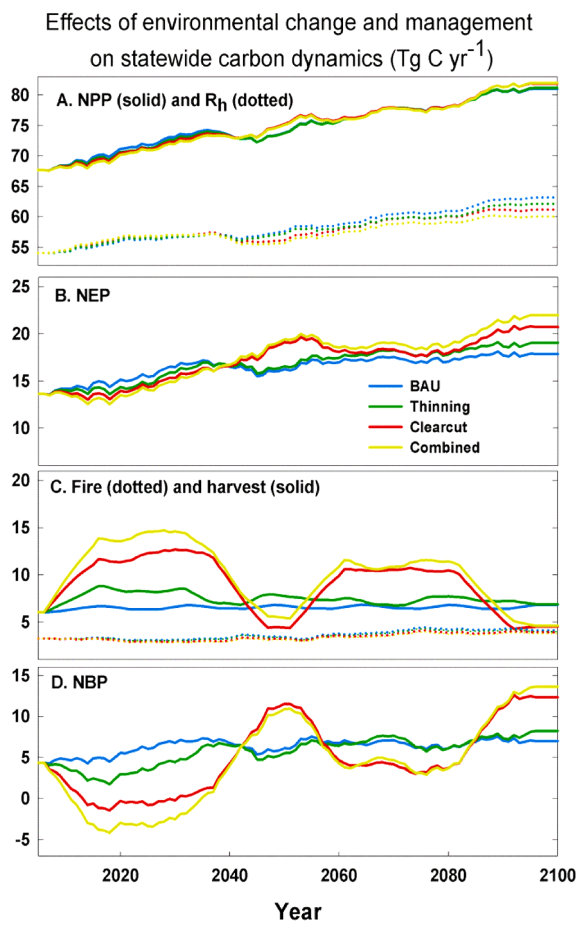



Figure 2. Combined annual effects of environmental change (climate, $CO_2$ fertilization, and N deposition) and management on (A) NPP (solid lines) and $R_h$ (dotted lines, (B) NEP, (C) Fire (dotted lines) and Harvest (solid), and (D) NBP. Each of the proposed management scenarios and BAU are included (BAU = blue, thinning = green, clearcut = red, and combined thinning and clear-cut = gold). For clarity, the values were smoothed using a 10-year running average and uncertainty bands are not shown.

By the end of the 21st century, regional nitrogen deposition, precipitation patterns, and relative humidity do not change significantly (SI Figure 1) and therefore changes in predicted long-term C dynamics are because of climate warming, $CO_2$ fertilization, and/or disturbance. Here, we find that $CO_2$-enhanced productivity is not limited due to sustained increases in regional gross N mineralization and the balance between NPP and $R_h$ is altered so that NBP increases. This is consistent with historical simulations in the southeast U.S., where forests switched from being a C source in the early 1900s to a significant sink in recent decades primarily because of $CO_2$ fertilization and N deposition.[45]

Stand-replacing disturbances through fire and harvest generally have significant effects on NBP and depending on increased disturbance intensity, can reduce long-term forest carbon storage (NBP) because removals exceed gains.[46] In Canadian forests, future model projections found that disturbance intensity and frequency would outweigh the positive effects of environmental change on NBP and reduce net C storage over time.[47] Our results for the Pacific Northwest forests in Oregon, suggest the opposite. Sustained increases in NPP exceed the projected effects of fire and harvest on landscape level carbon uptake, resulting in a mean state-wide increase in NBP. This was particularly evident in the drier ecoregions in the eastside of the state (Blue Mountains and East Cascades), where a substantial increase in NBP was simulated despite an increase in fire emissions (Figure 3c), suggesting the ecosystems are benefitting from increased water use efficiency with $CO_2$ fertilization. Contrary to the regional pattern, NBP decreases in the Klamath Mountain ecoregion because of a proportionally higher increase in fire emissions compared to the other ecoregions. There is uncertainty in model sensitivity to drought stress, and ability to simulate drought-related mortality in the drier ecoregions. Hence, it is possible that simulations result in unrealistically high productivity in response to increased atmospheric $CO_2$ in the dry ecoregions. Significant model development on root and stem hydraulic conductivity will be necessary to improve model results.

CLM4 regional burn area increases by 15% by the end of the century, increasing fire emissions from 3.2 to 4.0 Tg C $yr^{-1}$ (Table 2), consistent with predictions from different model simulations in the region.[48] Different climate scenarios with more prolonged drought, insect-related mortality, and fire beyond what was predicted in this study could reduce the gains in NPP and weaken the baseline NBP sink, however it is unlikely NBP would weaken enough to become a net source of $CO_2$ to the atmosphere.

**Intensified Management Strategies Reduce Long-Term C Gain Compared to BAU.** In contrast to the results of BAU management, we find an overall decrease in NBP for the intensified management scenarios by the end of the 21st century. Cumulative regional NBP is reduced by 10, 22, and 32% compared to BAU for thinning (Table 2 and Figure 2d; green), clearcuts (red), and combined treatments (gold), respectively. Over the 90-year simulation period, summed harvest removals of biomass are greater than BAU by 15, 38, and 54% for thinning, clear-cut, and combined scenarios, respectively (Table 2). The treatments had less impact on fire

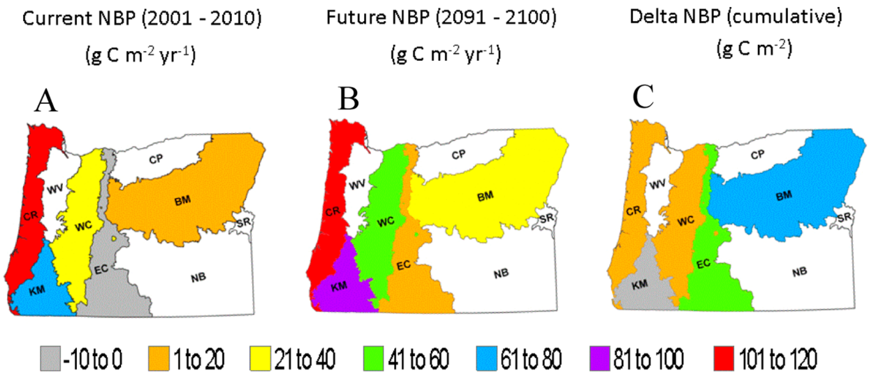



**Figure 3.** Mean ecoregion level current, future, and change in NBP from the climate and RCP scenarios by the end of the 21st century. The delta is the cumulative increase or decrease for each flux from 2010−2099 and is not a comparison between the first decade and the past decade. This represents the total change over the 90 year period and includes the interannual variability. Ecoregions: CR = Coast Range, KM = Klamath Mountains, EC = East Cascades, WC = West Cascades, BM = Blue Mountains, CP = Columbia Plateau, and NB = Northern Basin.

emissions with 3, 7, and 9% reductions compared to BAU. These results emphasize that treatment-associated increases in NEP and reductions in predicted fire emissions do not compensate for the carbon lost due to the wood removals over the 90-year period, leading to the cumulative decrease in NBP.

For each of the management strategies, NEP decreases compared to that of BAU harvest rates in the first 30 years of the simulation period and increases in the last 30 years, resulting in a slight net increase in cumulative forest net C uptake (Figure 2b). There is some evidence that the combination of increased NEP due to climate warming and $CO_2$ fertilization and increased NEP due to reduced $R_h$ in the scenarios is contributing to a period of increased NBP compared to BAU in the past decade of the simulations. The largest reductions in NBP due to the treatments occur in the first part of the century when there is more wood available for harvest, but NBP begins to increase by the end of the 21st century because of a decline in subsequent harvest removals (Figure 2c). Prescribed harvest rates were the same for each harvest cycle (~85% of live biomass for clearcuts and ~35% of live biomass for thinning), however because live biomass carbon had not recovered to initial conditions before the second treatment, harvest removals declined. That is, repeated harvest at these rates, <2.2% of forest area annually, were unsustainable.[49] This is important because the rotation lengths will be determined by both fire prevention measures (20 years is optimal effectiveness[50]) and wood available to meet demands for products and energy. Sustainable harvest strategies for meeting bioenergy and wood product demands will need to account for the initial harvest carbon debt because it is not fully resequestered in forest biomass over the next century.[20] About 25−50% of these losses can be recouped offsite in wood products and substitution of fossil fuels with bioenergy (see LCA methods in the SI).

**Intensified Management Increases Long-Term Net C Emissions to the Atmosphere.** The LCA is needed to track carbon that has left the forests and to compute the final net effect on emissions. The management strategies examined here lead to long-term increased carbon emissions over current harvesting practices, although semiarid regions contributed very little to the increase. None of the intensified management scenarios *reduce* state-wide C emissions to the atmosphere by the end of the 21st century (Figure 4a) after accounting for model uncertainty. Overall, the more intensive clear-cut and

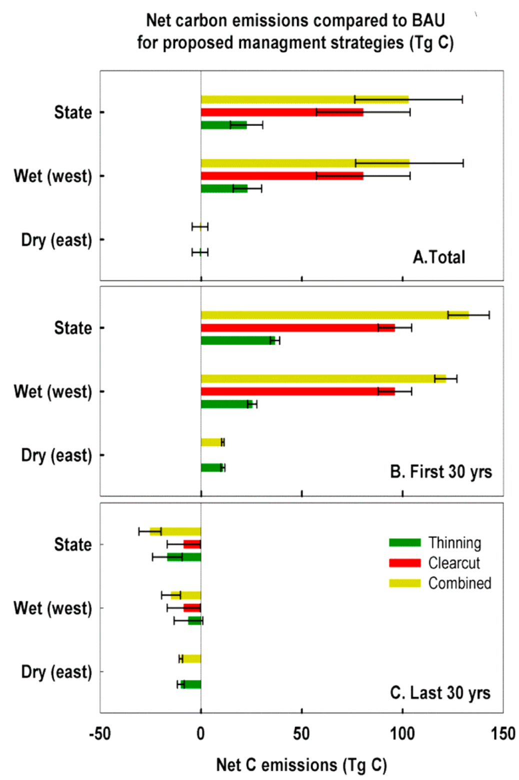



**Figure 4.** Total statewide and subregional change in net C emissions to the atmosphere summed over (A) 2011−2100, (B) from 2011−2040, and (C) 2071−2100 compared to BAU for each management scenario in Tg C. Error bars indicate the estimate uncertainty calculated as the propagated error of the LCA sensitivity analysis, modeled flux uncertainty, and the climate scenarios where parameters were varied according to the reported known range.

combined scenarios increase state-wide emissions to the atmosphere compared to BAU harvest rates over the 90 year period. Over half of the increase in emissions occurs in the first part of the century (Figure 4b), while decreases in the last 30 years (Figure 4c) reduce the overall impact of all three scenarios. Spatially, net carbon emissions are significantly increased in the mesic westside ecoregions (Figure 4a), whereas there is no significant net increase in the semiarid portion of the region for all management scenarios. Similar to the state-wide results, the majority of the increases for the all three scenarios are in the first 30 years of treatments whereas emissions are reduced compared to BAU in the last 30 years (2070−2100) in all ecoregions, partly because harvest rates were not sustainable and were reduced in the subsequent treatment cycles due to lack of available wood that met harvest criteria. Therefore, the increase in state-wide emissions is mainly driven by conditions in the mesic ecoregions.

Implementation of intensified management strategies (thinning, clear-cut, and combined scenarios), do not result in net statewide reductions to carbon emissions over the next 90 years despite inclusion of *all* wood product and bioenergy substitutions. This is consistent with results from similar studies in other regions[19,21,51,52] and contrary to other studies that do not account for the baseline sink or climate change.[37,53,54] It is important to note that off-site emissions may have been underestimated because we did not account for $CO_2$ emissions associated with building roads and infrastructure into the forests for repeat thinnings (http://www.oeconline.org/our-work/economy/sustainablebiofuels/chapter6). Estimates of infrastructure emissions range from 3 to 25% of total life-cycle emissions of fossil fuel and bioenergy production.[55]

We have quantified model uncertainty, used a range of environmental change scenarios, and conducted a sensitivity analysis of the LCA factors to compute an overall uncertainty for our net emission estimates (see SI methods). After accounting for uncertainty, the management-associated increases in net carbon uptake (NEP), reduction in fire emissions, and associated wood product sinks and substitutions are not sufficiently large enough to balance the life cycle emissions of wood bioenergy by the end of the 21st century. For the less intensive thinning treatment in the semiarid ecoregions, the management scenario does not increase net C emissions compared to BAU, and emissions reductions are being realized by the end of the 21st century. This indicates that the long-term effects of intensified management for bioenergy combined with environmental change may decrease $CO_2$ emissions to the atmosphere in the semiarid ecoregions. However it takes nearly 60 years for the net C emissions trend to become mostly positive, primarily because of the subsequent harvest removals. If the bioenergy treatments were only implemented in the semiarid Blue Mountains and East Cascades, then total state-wide emissions *may not increase* by the end of the 21st century compared to an increase of 102 ± 26 Tg C if all ecoregions are treated.

**Management Implications.** The approach of integrating ecoregion-specific model-data analysis and a complete LCA provides a framework for place-based assessments of potential management effects on future carbon sequestration by forests in other regions. Policy and management plans need to consider the land-based sink in addition to off-site wood usage when evaluating options for bioenergy from forest biomass. In this study, all of the scenarios significantly increase long-term state-wide $CO_2$ emissions with the majority of the emissions produced from the intensification of management in the more mesic ecoregions of the western third of Oregon. The thinning scenario in the semiarid ecoregions may not increase emissions compared to BAU, and shows that in some areas with a dry climate and large fuel supply, fuels reduction may be useful, although our emissions estimates associated with management are likely low due to lack of accounting for building of roads and infrastructure for repeat thinning. The clear-cut and combined management scenarios are examples of "slow in and fast out" where consumption (increased emissions from bioenergy) exceeds growth,[56] such that forest carbon that took decades to centuries to accumulate is rapidly lost to the atmosphere through harvest for bioenergy. The greatest concern is the impact of intensive management for bioenergy on soil fertility, biodiversity, and other ecosystem services. If soil fertility is impacted and fertilization used, then it would add nitrous oxide emissions ($N_2O$) to the atmosphere, another potent greenhouse gas that would exacerbate the emissions problem. This has not been adequately addressed in analyses thus far.[49,57]

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

Additional methods explaining model forcing data sets and the life-cycle assessment, supporting figures and tables illustrating model simulations, model evaluation, life-cycle assessment parameters, and climate scenarios. This material is available free of charge via the Internet at http://pubs.acs.org.

## ■ AUTHOR INFORMATION


### Corresponding Author

*Phone: 541-737-6111; fax: 541-737-1393; e-mail: bev.law@oregonstate.edu.

### Present Address

‖Department of Plant Biology, 1206 W. Gregory Drive, Urbana, Illinois


### Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

This research was supported by the Global Change Education Program administered by the Oak Ridge Institute for Science and Education, under contract between the U.S. Department of Energy and Oak Ridge Associated Universities and the Environmental Research Terrestrial Carbon Program (Award No. DE-FG02-04ER64361). This study is part of a regional North American Carbon Program project. SL was funded by the ERC Grants 242564.

## ■ ABBREVIATIONS

| | |
|---|---|
| NPP | Net Primary Productivity |
| NEP | Net Ecosytem Producvity |
| NBP | Net Biome Productivity |
| BAU | Business-as-usual |
| LCA | Life-cycle assessment |
| $R_h$ | Heterotrophic respiration |
| CLM4.0 | Community Land Model version 4.0 |
| C | Carbon |
| N | Nitrogen |
| $CO_2$ | Carbon dioxide |
| PFT | Plant functional type |
| RCP | Representative concentration pathway |
| NCAR | National Center for Atmospheric Research |
| CHP | Combined heat and power |
| MTBS | Monitoring Trends is Burn Severity |
| GFED | Global Fire Emissions Database |

## ■ REFERENCES


(1) King, A. W.; Hayes, D. J.; Huntzinger, D. N.; West, T. O.; Post, W. M. North American carbon dioxide sources and sinks: Magnitude, attribution, and uncertainty. *Front. Ecol. Environ.* **2012**, *10* (10), 512−519.

(2) Pan, Y.; Birdsey, R. A.; Fang, J.; Houghton, R.; Kauppi, P. E.; Kurz, W. A.; Phillips, O. L.; Shvidenko, A.; Lewis, S. L.; Canadell, J. G.; Ciais, P.; Jackson, R. B.; Pacala, S. W.; McGuire, A. D.; Piao, S.; Rautiainen, A.; Sitch, S.; Hayes, D.; Large, A. Persistent carbon sink in the world's forests. *Science* **2011**, *333* (6045), 988−993.

(3) Anderson-Teixeira, K. J.; Miller, A. D.; Mohan, J. E.; Hudiburg, T. W.; Duval, B. D.; DeLucia, E. H. Altered dynamics of forest recovery under a changing climate. *Global Change Biology* **2013**, *19* (7), 2001−2021.

(4) Law, B. Biogeochemistry: Nitrogen deposition and forest carbon. *Nature* **2013**, *496* (7445), 307−308.

(5) Evangelista, P. H.; Kumar, S.; Stohlgren, T. J.; Young, N. E. Assessing forest vulnerability and the potential distribution of pine beetles under current and future climate scenarios in the Interior West of the U.S. *Forest Ecol. Manag.* **2011**, *262* (3), 307−316.

(6) van Mantgem, P. J.; Stephenson, N. L.; Byrne, J. C.; Daniels, L. D.; Franklin, J. F.; Fule, P. Z.; Harmon, M. E.; Larson, A. J.; Smith, J. M.; Taylor, A. H.; Veblen, T. T. Widespread increase of tree mortality rates in the western United States. *Science* **2009**, *323* (5913), 521−524.

(7) Westerling, A. L.; Hidalgo, H. G.; Cayan, D. R.; Swetnam, T. W. Warming and earlier Spring increase western U.S. Forest wildfire activity. *Science* **2006**, *313* (5789), 940−943.

(8) Malmsheimer, R. W.; Bowyer, J. L.; Fried, J. S.; Gee, E.; Izlar, R. L.; Miner, R. A.; Munn, I. A.; Oneil, E.; Stewart, W. C. Managing forests because carbon matters: Integrating energy, products, and land management policy. *J. Forestry* **2011**, *109* (Supplement 1), S7−S51.

(9) *Oregon Senate Bill. 1072*; 73rd Oregon Legislative Assembly—2005 Regular Session: Salem, OR, 2005.

(10) Hurteau, M. D.; North, M. Carbon recovery rates following different wildfire risk mitigation treatments. *Forest Ecol. Manag.* **2010**, *260* (5), 930−937.

(11) Stephens, S. L.; Moghaddas, J. J.; Hartsough, B. R.; Moghaddas, E. E. Y.; Clinton, N. E. Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Can. J. Forest Res.* **2009**, *39*, 1538−1547.

(12) Campbell, J. L.; Ager, A. A. Forest wildfire, fuel reduction treatments, and landscape carbon stocks: A sensitivity analysis. *J. Environ. Manag.* **2013**, *121* (0), 124−132.

(13) Mitchell, S. R.; Harmon, M. E.; O'Connell, K. E. B. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. *Ecol. Appl.* **2009**, *19* (3), 643−655.

(14) Haberl, H.; Beringer, T.; Bhattacharya, S. C.; Erb, K.-H.; Hoogwijk, M. The global technical potential of bio-energy in 2050 considering sustainability constraints. *Curr. Opin. Environ. Sustain.* **2010**, *2* (5−6), 394−403.

(15) Holtsmark, B. Harvesting in boreal forests and the biofuel carbon debt. *Clim. Change* **2012**, *112* (2), 415−428.

(16) HoltsmarkB.The outcome is in the assumptions: Analyzing the effects on atmospheric $CO_2$ levels of increased use of bioenergy from forest biomass*GCB Bioenergy*;2012.

(17) Hudiburg, T. W.; Law, B. E.; Wirth, C.; Luyssaert, S. Regional carbon dioxide implications of forest bioenergy production. *Nat. Clim. Change* **2011**, *1* (8), 419−423.

(18) Hurteau, M. D.; Hungate, B. A.; Koch, G. W.; North, M. P.; Smith, G. R. Aligning ecology and markets in the forest carbon cycle. *Front. Ecol. Environ.* **2012**, *11* (1), 37−42.

(19) McKechnie, J.; Colombo, S.; Chen, J.; Mabee, W.; MacLean, H. L. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environ. Sci. Technol.* **2011**, *45* (2), 789−795.

(20) Mitchell, S. R.; Harmon, M. E.; O'Connell, K. E. B. Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy* **2012**, *4* (6), 818−827.

(21) Walker, T; Cardellichio, P; A, C.; al., E. *Biomass Sustainability and Carbon Policy Study. NCI-2010-03*; Manomet Center for Conservation Sciences,: Massachusetts, 2010.

(22) York, R. Asymmetric effects of economic growth and decline on $CO_2$ emissions. *Nature Clim. Change* **2012**, *2* (11), 762−764.

(23) Chapin, F.; Woodwell, G.; Randerson, J.; Rastetter, E.; Lovett, G.; Baldocchi, D.; Clark, D.; Harmon, M.; Schimel, D.; Valentini, R.; Wirth, C.; Aber, J.; Cole, J.; Goulden, M.; Harden, J.; Heimann, M.; Howarth, R.; Matson, P.; McGuire, A.; Melillo, J.; Mooney, H.; Neff, J.; Houghton, R.; Pace, M.; Ryan, M.; Running, S.; Sala, O.; Schlesinger, W.; Schulze, E. D. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* **2006**, *9*, 1041−1050.

(24) Lawrence, D.; Oleson, K. W.; Flanner, M. G.; Thorton, P. E.; Swenson, S. C.; Lawrence, P. J.; Zeng, X.; Yang, Z.-L.; Levis, S.; Skaguchi, K.; Bonan, G. B.; Slater, A. G. Parameterization improvements and functional and structural advances in version 4 of the community land model. *J. Adv. Model. Earth Syst.* **2011**, *3* (M03001), 27.

(25) Lawrence, P. J.; Feddema, J. J.; Bonan, G. B.; Meehl, G. A.; O'Neill, B. C.; Oleson, K. W.; Levis, S.; Lawrence, D. M.; Kluzek, E.; Lindsay, K.; Thornton, P. E. Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the community climate system model (CCSM4) from 1850 to 2100. *J. Climate* **2012**, *25* (9), 3071−3095.

(26) Hurtt, G. C.; Frolking, S.; Fearon, M. G.; Moore, B.; Shevliakova, E.; Malyshev, S.; Pacala, S. W.; Houghton, R. A. The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biol.* **2006**, *12* (7), 1208−1229.

(27) Thornton, P. E.; Running, S. W.; White, M. A. Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.* **1997**, *190*, 214−251.

(28) Göeckede, M.; Michalak, A. M.; Vickers, D.; Turner, D. P.; Law, B. E. Atmospheric inverse modeling to constrain regional-scale $CO_2$ budgets at high spatial and temporal resolution. *J. Geophys. Res.* **2010**, *115* (D15), D15113.

(29) Hudiburg, T. W.; Law, B. E.; Thornton, P. E. Evaluation and improvement of the Community Land Model (CLM 4.0) in Oregon forests. *Biogeosciences* **2013**, *10* (10), 453−470.

(30) Law, B.; Hudiburg, T.; Luyssaert, S., Thinning effects on forest productivity: Consequences of preserving old forests and mitigating impacts of fire and drought. *Plant Ecolo. Divers.* **2012**, *In press.*

(31) Turner, D. P.; Ritts, D.; Law, B. E.; Cohen, W.; Yang, Z.; Hudiburg, T.; Campbell, J. L.; Duane, M. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. *Biogeosciences* **2007**, *4*, 597−612.

(32) Eidenshink, J.; Schwind, B.; Brewer, K.; Zhu, Z. L.; Quayle, B.; Howard, S. A project for monitoring trends in burn severity. *Fire Ecology* **2007**, *3* (1), 3−20.

(33) van der Werf, G. R.; Randerson, J. T.; Giglio, L.; Collatz, G. J.; Mu, M.; Kasibhatla, P. S.; Morton, D. C.; DeFries, R. S.; Jin, Y.; van Leeuwen, T. T. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997−2009). *Atmos. Chem. Phys.* **2010**, *10* (23), 11707−11735.

(34) Campbell, J.; Donato, D.; Azuma, D.; Law, B. Pyrogenic carbon emission from a large wildfire in Oregon, United States. *J. Geophys. Res.* **2007**, 112.

(35) Meigs, G.; Donato, D.; Campbell, J.; Martin, J.; Law, B. Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon. *Ecosystems* **2009**, *12* (8), 1246−1267.

(36) Turner, D.; Ritts, W. D.; Yang, Z.; Kennedy, R. E.; Cohen, W. B.; Duane, M. V.; Thornton, P. E.; Law, B. E. Decadal trends in net ecosystem production and net ecosystem carbon balance for a regional socioecological system. *Forest Ecol. Manag.* **2012**, *262*, 1318−1325.

(37) Routa, J.; KellomÄKi, S.; KilpelÄInen, A.; Peltola, H.; Strandman, H. Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. *GCB Bioenergy* **2011**, *3* (6), 483−497.

(38) Siemers, E. Northwest Energy plans $300M Oregon biomass investment. *Portland Business Journal* **2011**, pp http://www.sustainablebusinessoregon.com/articles/2011/03/northwest-energy-plans-300m-oregon.html.

(39) USGS. The National Map LANDFIRE: LANDFIRE National Existing Vegetation Type layer. In *U.S. Department of Interior, Geological Survey*; U.S. Department of Interior, Geological Survey: 2009; http://gisdata.usgs.net/website/landfire/.

(40) Raffa, K. F.; Aukema, B. H.; Bentz, B. J.; Carroll, A. L.; Hicke, J. A.; Turner, M. G.; Romme, W. H. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of Bark Beetle eruptions. *Bioscience* **2008**, *58* (6), 501−517.

(41) Campbell, J.; Alberti, G.; Martin, J.; Law, B. E. Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada. *Forest Ecol. Manag.* **2009**, *257* (2), 453−463.

(42) Law, B. E.; Harmon, M. E. Forest sector carbon management, measurement and verification, and discussion of policy related to climate change. *Carbon Manag.* **2011**, *2* (1), 73−84.

(43) Lippke, B.; Oneil, E.; Harrison, R.; Skog, K.; Gustavsson, L.; Sathre, R. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Manag.* **2011**, *2* (3), 303−333.

(44) Williams, C. A.; Collatz, G. J.; Masek, J.; Goward, S. N. Carbon consequences of forest disturbance and recovery across the conterminous United States. *Global Biogeochem. Cycles* **2012**, *26* (1), GB1005.

(45) Tian, H.; Chen, G.; Zhang, C.; Liu, M.; Sun, G.; Chappelka, A.; Ren, W.; Xu, X.; Lu, C.; Pan, S.; Chen, H.; Hui, D.; McNulty, S.; Lockaby, G.; Vance, E. Century-scale responses of ecosystem carbon storage and flux to multiple environmental changes in the southern United States. *Ecosystems* **2012**, *15* (4), 674−694.

(46) Gough, C. M.; Vogel, C. S.; Harrold, K. H.; George, K.; Curtis, P. S. The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. *Global Change Biol.* **2007**, *13* (9), 1935−1949.

(47) Kurz, W. A.; Stinson, G.; Rampley, G. Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Philos. Trans. R. Soc. B: Biol. Sci.* **2008**, *363* (1501), 2259−2268.

(48) Rogers, B.; Neilson, R.; Drapek, R.; Lenihan, J.; Wells, J.; Bachelet, D.; Law, B. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. *J. Geophys. Res.* **2011**, *116*, G03037.

(49) SchulzeE.-D.KörnerC.LawB. E.HaberlH.LuyssaertS.Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral*GCB Bioenergy*, 2012.

(50) Stephens, S. L.; Moghaddas, J. J.; Edminster, C.; Fiedler, C. E.; Haase, S.; Harrington, M.; Keeley, J. E.; Knapp, E. E.; McIver, J. D.; Metlen, K.; Skinner, C. N.; Youngblood, A. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecol. Appl.* **2009**, *19* (2), 305−320.

(51) Mika, A. M.; Keeton, W. S. Factors contributing to carbon fluxes from bioenergy harvests in the U.S. Northeast: An analysis using field data. *GCB Bioenergy* **2013**, *5* (3), 290−305.

(52) Davis, S. C.; Dietze, M.; DeLucia, E.; Field, C.; Hamburg, S. P.; Loarie, S.; Parton, W.; Potts, M.; Ramage, B.; Wang, D.; Youngs, H.; Long, S. P. Harvesting carbon from eastern U.S. Forests: Opportunities and impacts of an expanding bioenergy industry. *Forests* **2012**, *3* (2), 370−397.

(53) Lippke, B.; Gustafson, R.; Venditti, R.; Volk, T.; Oneil, E.; Johnson, L.; Puettmann, M.; Steele, P. Sustainable biofuel contributions to carbon mitigation and energy independence. *Forests* **2011**, *2* (4), 861−874.

(54) Sathre, R.; Gustavsson, L.; Bergh, J. Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization. *Biomass Bioenergy* **2010**, *34* (4), 572−581.

(55) Strogen, B.; Horvath, A. Greenhouse gas emissions from the construction, manufacturing, operation and maintenance of U.S. distribution infrastructure for petroleum and biofuels. *J. Infrastruct. Syst.* **2012**.

(56) Körner, C. Slow in, rapid out—Carbon flux studies and Kyoto targets. *Science* **2003**, *300* (5623), 1242−1243.

(57) Perlack, R.; Stokes, B. *U.S. Billion-Ton Update:Biomass Supply for a Bioenergy and Bioproducts Industry*; Oak Ridge National Laboratory: Oak Ridge, TN, 2011.

(58) Harrod, R. J.; Peterson, D. W.; Povak, N. A.; Dodson, E. K. Thinning and prescribed fire effects on overstory tree and snag structure in dry coniferous forests of the interior Pacific Northwest. *Forest Ecol. Manag.* **2009**, *258* (5), 712−721.

(59) Skog, K. E.; Ince, P. J.; Spelter, H.; Kramp, A.; Barbour, R. J. *Woody Biomass Supply from Thinnings to Reduce Fire Hazard in the U.S. West and Its Potential Impact on Regional Wood Markets*. Forest Products Society: Madison, WI, 2008; p 3−14.

(60) Harmon, M. E.; Harmon, J. M.; Ferrell, W. K.; Brooks, D. Modeling carbon stores in Oregon and Washington forest products: 1900−1992. *Climatic Change* **1996**, *33* (4), 521−550.