AN ABSTRACT OF THE DISSERTATION OF

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Title: Analysis of the Regional Carbon Balance of Pacific Northwest Forests Under Changing Climate, Disturbance, and Management for Bioenergy

Abstract approved:

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Atmospheric carbon dioxide levels have been steadily increasing from anthropogenic energy production, development and use. Carbon cycling in the terrestrial biosphere, particularly forest ecosystems, has an important role in regulating atmospheric concentrations of carbon dioxide. US West coast forest management policies are being developed to implement forest bioenergy production while reducing risk of catastrophic wildfire. Modeling and understanding the response of terrestrial ecosystems to changing environmental conditions associated with energy production and use are primary goals of global change science. Coupled carbon-nitrogen ecosystem process models identify and predict important factors that govern long term changes in terrestrial carbon stores or net ecosystem production (NEP). By quantifying and reducing uncertainty in model estimates using existing datasets, this research provides a solid scientific foundation for evaluating carbon dynamics under conditions of future climate change and land management practices at local and regional scales. Through the combined use of field observations, remote sensing data products, and the NCAR CESM/CLM4-CN coupled carbon-climate model, the objectives of this project were to 1) determine the interactive effects of changing environmental factors (i.e. increased CO2, nitrogen deposition, warming) on net carbon uptake in temperate forest ecosystems and 2) predict the net carbon emissions of West Coast forests under future climate scenarios and implementation of bioenergy programs. West Coast forests were found to be a current strong carbon sink after accounting for removals from harvest and fire. Net biome production (NBP) was 26 ± 3 Tg C yr^{-1}, an amount equal to 18% of Washington, Oregon, and California fossil fuel emissions combined. Modeling of future conditions showed increased net primary production (NPP) because of climate and CO_2 fertilization, but was eventually limited by nitrogen availability, while heterotrophic respiration (R_h) continued to increase, leading to little change in net ecosystem production (NEP). After accounting for harvest removals, management strategies which increased harvest compared to business-as-usual (BAU) resulted in decreased NBP. Increased harvest activity for bioenergy did not reduce short- or long-term emissions to the atmosphere regardless of the treatment intensity or product use. By the end of the 21st century, the carbon accumulated in forest regrowth and wood product sinks combined with avoided emissions from fossil fuels and fire were insufficient to offset the carbon lost from harvest removals, decomposition of wood products, associated harvest/transport/manufacturing emissions, and bioenergy combustion emissions. The only scenario that reduced carbon emissions compared to BAU over the 90 year period was a 'No Harvest' scenario where NBP was significantly higher than BAU for most of the simulation period. Current and future changes to baseline conditions that weaken the forest carbon sink may result in no change to emissions in some forest types.

Analysis of the Regional Carbon Balance of Pacific Northwest Forests Under Changing Climate, Disturbance, and Management for Bioenergy

by
Tara W. Hudiburg

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APPROVED:

Major Professor, representing Forest Science

Head of the Department of Forest Ecosystems and Society

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Tara W. Hudiburg, Author

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CONTRIBUTION OF AUTHORS

For Chapter 2, Tara Hudiburg designed and implemented the study with guidance from Beverly Law and Sebastiaan Luyssaert. Tara Hudiburg, Sebastiaan Luyssaert, and Beverly Law co-wrote the paper and Sebastiaan contributed to parts of the analysis. Christian Wirth provided essential data and methods for the analysis and valuable comments on the manuscript. For Chapter 3, Tara Hudiburg and Beverly Law designed, implemented and co-wrote the paper. Tara Hudiburg did the analysis and Peter Thornton provided guidance and valuable comments on the manuscript. For Chapter 4, Tara Hudiburg designed and implemented the study with guidance from Beverly Law and Peter Thornton. Tara Hudiburg, Sebastiaan Luyssaert, Beverly Law, and Peter Thornton co-wrote the paper.

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Analysis of the Regional Carbon Balance of Pacific Northwest Forests Under Changing Climate, Disturbance, and Management for Bioenergy

by
Tara W. Hudiburg

Chapter 1: Introduction

It is general knowledge that carbon dioxide (CO_2), a greenhouses gas (GHG), has increased from ~260 to near 400 ppm in the Earth's atmosphere since the Industrial Revolution began in the early 1800's as a result of the combustion of fossil fuels for energy and conversion of native vegetation to other uses, primarily agriculture (http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html). Incoming solar radiation that is not absorbed at the Earth's surface is reflected back to the atmosphere as long wave radiation where it can be absorbed by GHGs such as CO_2 and water vapor. This reduces the amount of energy emitted to space and warms the planet. Because CO_2 absorbs energy at some wavelengths that water vapor misses, the extra absorption caused by increased concentrations of CO_2 warms the air more. The residence time of CO_2 in the atmosphere is centuries long so its effect on climate will continue for a millennium, even if emissions are immediately reduced back to pre-industrial levels (Solomon et al. 2009).

Plants absorb CO_2 in the process of photosynthesis, store it temporarily in their biomass, and release it slowly back to the atmosphere as organic matter decays. Forests store the most carbon (50% of dry mass) of any life form, largely because of the annual accumulation of tree wood. Currently, temperate forests in the United States capture ~20% of our fossil fuel emissions (Birdsey 2007). Whether the capacity of forests to sequester carbon can be maintained is a question faced by policy makers and land managers alike, particularly in the face of a changing climate. Disturbances by fire, insects, and diseases that can reduce forest carbon storage have significantly increased in recent years, and this trend is projected to continue (Rogers et al. 2011; van Mantgem et al. 2009; Kurz et al. 2008).

In efforts to improve forest health, create jobs, restore habitat, provide an alternative to fossil fuels, and mitigate climate change, management plans have been implemented to increase utilization of forest biomass for wood products and bioenergy by thinning, rotation-based harvests, and salvage logging. Thinning can be an effective strategy for preventing wildfire where risk is high, especially around homes, farms and industrial sites (Raymond and Peterson 2005, Stephens et al. 2009). Rotation-based harvests provide a steady supply of wood for products and bioenergy and salvage logging makes use of wood that is no longer taking up carbon. The extent that these practices reduce the rate that forests sequester carbon is not well established but could be significant, particularly in regions such as the Pacific Northwest where the potential for biomass accumulation west of the crest of the Cascade Mountains is the highest recorded (Waring and Franklin 1979). The Pacific Northwest, however, contains a wide range of environments representing almost the full range of productivity in North America. Any analysis of carbon dynamics must account for this spatial variation.

Net primary production (NPP) ranges from 100 to 900 g C m^{-2} across the region and (Turner et al. 2007) net ecosystem production (NEP; the balance between photosynthesis and respiration) varies from 0 to 300 g C m^{-2} yr^{-1} (Williams et al. 2012). After accounting for wood removals through fire and harvest (NBP; net biome production), Hayes et al., (2012) estimated that US west coast forests in recent years are a net carbon sink of between 10-20 Tg C yr^{-1} , an amount near the current fossil fuel emissions of Oregon (Gurney et al. 2009).

Forest carbon sinks will change as climate and societal demands change. Harvest rates vary with wood product demand and conservation goals. Fire severity and burn area are increasing with warming climate (Westerling et al. 2006). There are more widespread mortality events in the western US states due to insect outbreaks (Raffa et al. 2008) and drought (Breshears et al. 2008, van Mantgem et al. 2009, McDowell et al. 2010). In order for policy makers to provide effective carbon sequestration strategies involving forests, current and potential forest carbon sinks should be quantified using a variety of climate and management scenarios.

There are a number of approaches available to evaluate the relative merits of various policies on carbon sequestration in forests and in their manufactured products. Approaches range from small case studies of thinning combined with bioenergy to reduce fire and fossil fuel emissions (Winford and Gaither Jr. In Press), to national evaluation of wood product sinks (Lippke et al. 2010), and to continental assessments of combined forest and wood product carbon sinks (Hayes et al. 2012). Although the methods for quantifying net forest carbon uptake varies (i.e. observations, mathematical models, simulation models, remote sensing, or combinations), the method for quantifying the amount of carbon eventually emitted to the atmosphere from wood product use is accomplished using life cycle assessment (LCA).

LCA is used to track forest carbon stocks and emissions in relation to bioenergy production and wood products, however the number of variables used and accounted for differs widely. Some studies include emissions associated with product use and decomposition, but neglect the emissions generated for harvest, transportation, and manufacturing (Routa et al. 2011).Others use a complete LCA for the wood once it leaves the forest, but ignore the baseline carbon uptake and loss from the forest itself (in other words net uptake is assumed to be zero; Lippke et al. 2011). Clearly, removal of any wood reduces *in-situ* carbon storage. However, because of the inconsistencies concerning baseline conditions and LCA variables, there is continued debate about whether forest management strategies that include bioenergy will be carbon neutral (Lippke et al. 2011, Malmsheimer et al. 2011), or will result in an increase in emissions compared to current management practices over the next several decades(Mitchell et al. 2012). In spite of this contention, bioenergy plans and facilities are continuing in the Western US because of asserted local economic considerations (Siemers 2011).

Management policies need to be designed to: (1) not further degrade the forest carbon sink, (2) target areas where it may be increased, (3) avoid detrimental increases in atmospheric CO_2 emissions, and (4) provide energy. The consequences of each management strategy must be compared to baseline conditions that include business-as-usual (BAU) management practices. The overall goal of this study was to evaluate the short and long term effects of climate, disturbance, and potential bioenergy management strategies on regional carbon storage and emissions using existing datasets and an internationally recognized terrestrial ecosystem process model (CLM4; Lawrence et al. 2011).

Chapter 2 addresses the short-term effects of bioenergy management on net CO_2 emissions using a synthesis of spatially representative forest inventory and supplemental plot data and life cycle assessment (LCA) of the wood removals. The specific objectives of this study were to:

1. Determine the current net ecosystem production (NEP) and net biome production (NBP) of US West Coast Forests using observational datasets.
2. Determine the net carbon emissions of forests for current (BAU) and for potential bioenergy management, accounting for *in-situ* and offsite carbon sources and sinks.

Chapter 3 evaluates the use of CLM4 in forests of the Pacific Northwest utilizing independent datasets with different temporal resolutions. The spatially explicit maps of annual carbon stocks and net primary production (NPP) from the dataset compiled in Chapter 1 were used to evaluate the landscape patterns of carbon stocks and fluxes. For seasonal evaluation, observed monthly gross photosynthesis (GPP) from AmeriFlux sites in the region (Krishnan et al. 2009, Thomas et al. 2009) were downloaded from the FLUXNET website (http://fluxnet.ornl.gov/) and compared to modeled monthly GPP. The specific objective of this study was to evaluate the ability of CLM4 model to simulate historical and current carbon and nitrogen dynamics in both standard and modified format.

Chapter 4 uses the fully calibrated CLM4 model to examine the long term effects of varying bioenergy management strategies bioenergy on carbon and nitrogen dynamics under changing environmental conditions. We examined the following research questions:

1. What are the interactive effects of changing climate, increasing atmospheric CO_2, N deposition and land use change on net ecosystem production (NEP)?
2. How do the varying management scenarios affect carbon stocks and fluxes at different spatial scales?
3. Does bioenergy management increase or decrease net CO_2 emissions to the atmosphere compared to BAU by the end of the 21st century?
4. For which ecoregions, does net CO_2 emissions decrease compared to BAU for bioenergy management?

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REGIONAL CO_2 IMPLICATIONS OF FOREST BIOENERGY PRODUCTION

Authors: Tara W. Hudiburg, Beverly E. Law, Christian Wirth and Sebastiaan Luyssaert

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Chapter 2: Regional CO_2 implications of forest bioenergy production

Summary

Mitigation strategies for reducing CO_2 emissions include substitution of fossil fuel with bioenergy from forests (Buyx and Tait 2011), where carbon emitted is expected to be re-captured in the growth of new biomass to achieve zero net emissions (Gustavsson et al. 1995), and forest thinning to reduce wildfire emissions (Hurteau and North 2010). Here we use forest inventory data to show that fire prevention measures and large-scale bioenergy harvest in US West Coast forests lead to 2-14% (46-405 Tg C) higher emissions compared to current management practices over the next 20 years. We studied 80 forest types in 19 ecoregions, and found that the current carbon sink in 16 of these ecoregions is sufficiently strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy. If the sink in these ecoregions weakens below its current level by 30-60 g C m^{-2} yr^{-1} due to insect infestations, increased fire emissions, or reduced primary production, management schemes including bioenergy production may succeed in jointly reducing fire risk and carbon emissions. In the remaining three ecoregions, immediate implementation of fire prevention and biofuel policies may yield net emission savings. Hence, forest policy should consider current forest carbon balance, local forest conditions and ecosystem sustainability in establishing how to decrease emissions.

Main text

Policies are being developed worldwide to increase bioenergy production as a substitution for fossil fuel to mitigate fossil fuel-derived carbon dioxide emissions, the main cause of anthropogenic global climate change (Fargione et al. 2008, Richter Jr et al. 2009). However, the capacity for forest sector bioenergy production to offset carbon dioxide emissions is limited by fossil fuel emissions from this activity (harvest, transport, and manufacturing of wood products), and the lower energy output per unit carbon emitted compared with fossil fuels (Law and Harmon 2011). In addition, forest carbon sequestration can take decades to centuries to return to pre-harvest levels, depending on initial conditions and amount of wood removed (Harmon and Marks 2002). The effects of changes in management on CO_2 emissions need to be evaluated against this baseline. Consequently, energy policy implemented without full carbon accounting and understanding of the underlying processes risks increasing rather than decreasing emissions (Fargione et al. 2008, Searchinger et al. 2009).

In North America, there is increasing interest in partially meeting energy demands through large-scale forest thinning (Richter Jr et al. 2009) with the added benefit of preventing catastrophic wildfire and concurrent carbon loss (Hurteau and North 2010). Although forest thinning can be economically feasible, sustainable, and an effective strategy for preventing wildfire where risk is high (Huggett Jr et al. 2008, Evans and Finkral 2009), it remains unresolved whether this type of forest treatment can satisfy both the aims of preventing wildfire *and* reducing regional greenhouse gas emissions.

For both aims to be satisfied, it needs to be shown that: (1) reduction in carbon stocks due to thinning and the associated emissions are offset by avoiding fire emissions and substituting fossil fuel emissions with forest bioenergy, (2) the change in management results in less CO_2 emissions than the current or 'baseline' emissions, and (3) short-term emission changes are sustained in the long-term. Determination of baseline forest sector carbon emissions can be accomplished by combining forest inventory data and life cycle assessment (LCA) that includes full carbon accounting of net biome production (NBP) on the land in addition to carbon emissions from bioenergy production and storage in wood products (LCA; (Law and Harmon 2011)). NBP is the annual net change of land-based forest carbon (NEP; photosynthesis minus respiration) after accounting for harvest removals and fire emissions.

Our study focused on the US West Coast (Washington, Oregon, and California), a diverse region due to the strong climatic gradient from the coast inland (300 – 2500 mm precipitation per year) and a total of 80 associated forest types ranging from temperate rainforests to semi-arid woodlands (Appendix A Table A1). The region is divided into 19 distinct ecoregions (Omernik 1987) based on climate, soil, and species characteristics, and includes a broad range of productivity, age structures, fire regimes and topography. Mean net primary production (NPP) of the forest types range from 100 to 900 g C m^{-2}

yr^{-1} (this study), falling within the global range of 100 to 1600 g C m^{-2} yr^{-1} reported for temperate and boreal forests (Luyssaert et al. 2008). Forest land ownership is divided fairly evenly between public and private sectors having different management histories and objectives that affect forest carbon dynamics (Hudiburg et al. 2009).

Carbon sequestration rates vary greatly across the region, with mean NEP ranging from -85 g C m^{-2} yr^{-1} in the dry Northern Basin to over 400 g C m^{-2} yr^{-1} in the mesic Coast Range. After accounting for fire emissions and substantial harvest removals, regional NBP remains a significant sink of 26±3 Tg C yr^{-1} or 76±9 g C m^{2} yr^{-1}, similar to the US average (Birdsey 2007) and estimates for the member states of the European Union (Luyssaert et al. 2009). Sixteen of the 19 ecoregions representing 98% of the forest area in the region are estimated to be carbon sinks (Fig 2.1a; exceptions are drier ecoregions where annual productivity is low and fire emissions are relatively high). Thus, the observed regional sink is not solely due to the region's highly productive rainforests that occupy 15% of the area. Within the region, California’s NBP is higher than that of Oregon and Washington (107 versus 53-61 g C m^{-2} yr^{-1}), primarily due to differences in NEP (Appendix A Table A2) and harvest between similar forest types within the same ecoregions that cross state boundaries (Appendix A Discussion and Table A3).

In addition to current management or Business-As-Usual (BAU, characterized by current preventive thinning and harvest levels), we designed three treatments (Appendix A Fig A1a) to reflect the varying objectives of potential forest management systems: forest fire prevention by emphasizing removal of fuel ladders ('Fire Prevention') in fire-prone areas, making fuel ladder removal economically feasible by emphasizing removal of additional marketable wood in fire–prone areas ('Economically Feasible'), or thinning all forestland regardless of fire risk to support energy production while contributing to fire prevention ('Bioenergy Production'). Removals are in addition to current harvest levels and are performed over a twenty year period such that 5% of the landscape is treated each year. Our reliance on a data-driven approach versus model simulations strengthens our analysis in the short-term, but limits our ability to make longer term predictions. Extending our study beyond a 20-year timeframe would over-stretch data use because current forest growth is unlikely to represent future growth due to changes in climate, climate-related disturbance, and land use (Battles et al. 2008, Ryan 2010).

In our study region, we found that thinning reduced NBP under all three treatment scenarios for 13 of the 19 ecoregions representing 90% of the region's forest area. The exceptions where NBP was not reduced were primarily due to high initial fire emissions compared to NEP (i.e. Northern Basin and North Cascades; Appendix A Fig A2). The dominant trend at the ecoregion level was mirrored at the regional level, with the Bioenergy Production scenario (highest thinning level) resulting in the region becoming a net carbon source (Appendix A Table A2 and discussion of state-level estimates). Regionally, forest biomass removals exceeded the potential losses from forest fires, reducing the *in-situ* forest carbon sink even after accounting for regrowth, as found in previous studies with different approaches or areas of inference (Mitchell et al. 2009, Searchinger et al. 2009). Because we have assumed high reductions in fire emissions for the areas treated in each scenario, it is unlikely we are underestimating the benefit of preventive thinning on NBP.

It is important to recognize that even if the land-based flux is positive (a source) or zero (carbon neutral), decreases in NBP from BAU can increase CO_2 emissions to the atmosphere. LCA was used to estimate the net emissions of carbon to the atmosphere in each treatment scenario (Appendix A Fig A1b and Appendix A Tables A4 and A5). LCA at the ecoregion level revealed that emissions are increased for 10 out of 19 of the ecoregions (Fig 2.2), representing 80% of the forest area in the region. The combination of *in-situ* and wood-use carbon sinks and sources emit an additional 46, 181 and 405 Tg C to the atmosphere over a 20 year period (2-14% increase), above that of the BAU forest management scenario for the Fire Prevention, Economically Feasible, and Bioenergy Production treatments, respectively (Fig 2.3).

Sensitivity analysis of our results to a range of fire emission reductions, energy conversion efficiencies, wood product decomposition rates, and inclusion of wood substitution showed that carbon emissions varied -10 to 28% of the optimum values across the scenarios, depending on the combination of assumptions (Appendix A Discussion and Table A6). The analysis revealed that an increase in estimated current fire emissions (which effectively reduces the baseline sink) may decrease total atmospheric C emissions in the Fire Prevention scenario, but only given optimum conditions for all of the other parameters (e.g. 100% energy efficiency). Nevertheless, if fire frequency and intensity increase in the future (Rogers et al. 2011), emissions savings via forest bioenergy production may become possible, especially in ecoregions where the sink is already weak.

Previous case studies showed that harvesting an old-growth forest in the Pacific Northwest (Harmon et al. 1990) or increasing the thinning removals of temperate forests is likely to deteriorate the forest and wood product carbon stock (Nunery and Keeton 2010). However, these studies were limited to a handful of sites, relied primarily on modeled results (Mitchell et al. 2009, Hurteau and North 2010) and did not account for the energy requirements of forest management and wood processing nor for the potential to substitute fossil fuels with bioenergy. We build on these results by including all ecoregions, all age classes (not just old-growth), three treatments including bioenergy production, and sector-based LCA. We found that even though forest sector emissions are compensated for by emission savings from bioenergy use, fewer forest fires, and wood product substitution, the end result is an increase in regional CO_2 emissions compared to BAU as long as the regional sink persists.

To determine a threshold NBP for which bioenergy management reduces atmospheric CO_2 emissions compared to BAU, we applied the same assumptions used in the LCA. We found that if the NBP drops by 50-60 g C m^{-2} yr^{-1} in currently productive ecoregions or 15-30 g C m^{-2} yr^{-1} in currently less productive ecoregions, bioenergy management would come with CO_2 emissions savings compared to BAU (Fig 2.1c). Aggregating the ecoregion thresholds translate into a regional mean NBP of 45 g C m^{-2} yr^{-1} or a 41% reduction on average. Reductions in NBP may occur due to increased mortality and/or decreased growth due to climate, fire, or insect outbreaks. However reductions in NBP from increased harvest does not qualify because harvest increases emissions; wood carbon enters the products/bioenergy chain where subsequent losses occur. We cannot predict from the data when the threshold NBP would occur because a high resolution process-based model with the ability to incorporate future climate, nitrogen deposition, age dynamics, disturbance, and management would need to be utilized, which is beyond the scope of this study.

Ecoregion threshold NBP is dependent on the scenario treatment removals and area because the Fire Prevention treatment targets only those areas most likely to burn. For example, to reduce emissions in the Sierra Nevada, baseline NBP would have to decrease by as much as 84 for the Bioenergy Production scenario versus only 13 g C m^{-2} yr^{-1} for the Fire Prevention scenario. In ecoregions where current sinks are marginal or weakened by climate, fire, or insect outbreaks there may be a combination of harvest intensity and bioenergy production that reduces forest sector emissions. In 9 of the ecoregions where forests are carbon neutral or a source of CO_2 to the atmosphere and/or fire emissions are high for BAU, total CO_2 emissions under the Fire Prevention scenario could be reduced compared to BAU. They provide examples where management strategies for carbon emission reduction or sequestration should differ from the majority of the region; a one-size-fits-all approach will not work (Marland and Schlamadinger 1997). Finally, large areas in the Northern Rockies (i.e. Colorado and Wyoming) are currently experiencing increases in forest mortality due to beetle-kill, a trend which could continue in a warmer climate (Evangelista et al. 2011). These areas may already be at or below the threshold NBP; if so, they could benefit from targeted bioenergy implementation. However, simply lowering current regional harvest intensities in areas where NBP is not weakened also reduces emissions (Appendix A Discussion and Fig A3). Also, as we have assumed large-scale implementation of these strategies in addition to BAU harvest, we may be overestimating future harvest even though harvest has declined significantly since 1990 due to restrictions placed on harvest on federal lands as part of the Northwest Forest Plan. If the strategies were used to substitute for BAU harvest, the outcome on NBP would be much different (i.e. increased for the Fire Prevention scenario).

Our study is one of the first to provide a full carbon accounting, including all of the sinks and sources of carbon emissions from the forestry sector and the current *in-situ* sink for such a large area. Given the diversity of woody ecosystems in the study region ranging from highly productive temperate rainforests to less productive semi-arid woodlands, the trends in response likely apply to other temperate regions globally (Appendix A Table A1) where forests are currently a strong net carbon-sink (i.e. Eastern US, China and Europe), although the extent of the effect remains to be established.

Greenhouse gas reduction plans call for up to 10% reductions in emissions by 2020 and forest-derived fuels are being proposed as a carbon-neutral solution to reducing energy emissions. In all of our proposed scenarios, increases in harvest volume on the US West Coast will on average result in regional emission increases above current levels, although there are a few ecoregions where the tested scenarios could result in emission savings. As long as the current *in-situ* NBP persists, increasing harvest volumes in support of bioenergy production is counterproductive for reducing CO_2 emissions. In this study region, the current *in-situ* NBP in tree biomass, woody detritus, and soil carbon is more beneficial in contributing to reduction of anthropogenic carbon dioxide emissions than increasing harvest to substitute fossil fuels with bioenergy from forests.

Although large uncertainty remains for regional forecasts to year 2050 or 2100, it is expected that forest carbon sinks will diminish over time because of aging of the forests, saturation of the CO_2-fertilization and N-deposition effects, and increased mortality due to climate or insects (van Mantgem et al. 2009, Stinson et al. 2011). This would require new assessments to identify management options appropriate for each situation. Carbon-management is not the sole criteria that should be considered when planning forest management. Our findings should thus also be evaluated against other ecosystem services such as habitat, genetic and species diversity, watershed protection, and natural adaptation to climate change.

Methods Summary

We quantified forest sequestration rates and test forest thinning scenarios across the region using a data-intensive approach which, for the first time, takes into account the diversity of forest characteristics and management. We combined Landsat remote sensing data with inventories and ancillary data to map current forest NEP, NBP, and changes in NBP with three thinning scenarios. The approach can be applied at multiple scales of analysis in other regions.

We combined spatially representative observational data from over 6000 FIA plots (see Appendix A Methods; Appendix A Table A7) with remote sensing products on forest type, age, and fire risk (USGS 2009), a global data compilation of wood decomposition data and 200 supplemental plots (Hudiburg et al. 2009) to provide new estimates of US West Coast (~34 million hectares) forest biomass carbon stocks (Appendix A Table A8), net ecosystem production (NEP, the balance of photosynthesis and respiration), and net biome production (NBP, the *in-situ* net forest carbon-sink accounting for removals). We included all forestland in our analysis across all age classes (20-800 years old) and management regimes. Plot values were aggregated by climatic region (ecoregion), age class, and forest type and this look-up table was used to assign a value to each associated 30 meter pixel.

We use regional combustion coefficients to determine fire emissions. Only 3-8% of live tree biomass is actually combusted and emitted in high severity fire in the Pacific Northwest (Campbell et al., 2007), contrary to other studies that report much higher emissions because they assume 30% of *all* aboveground woody biomass is consumed (Wiedinmyer and Hurteau 2010). Although the latter contradicts extensive field observations (Campbell et al. 2007, Meigs et al. 2009) and modeling studies (Ottmar et al. 2006) in the region, we included 30% as the upper-end combustion factor in our sensitivity analysis (Appendix Table A9).

In addition to the spatially explicit estimates of stocks and fluxes under current management or Business-As-Usual (BAU, current forest harvest), three treatments were designed (Fire Prevention, Economically Feasible, and Bioenergy Production; Appendix A Fig A1a) to reflect the varying objectives of potential future forest management over the next 20 years, within the proposed time period for CO_2 reductions in the U.S. Areas were prioritized for treatment by fire risk and frequency. The proposed treatments result in additional harvest removals because we assume the current harvest rate for wood products will continue in the future. We limit our specific analysis to the short term because this is the timeframe suitable for policymakers, effectiveness of fire protection treatments, and an appropriate use of the data-driven approach. However, to investigate conditions (i.e. sink saturation) that could invalidate our short term results in the long-term, we also calculated the *in situ* NBP at which the atmosphere may benefit from bioenergy removals.

Lastly, we studied the net effects of the thinning treatments on atmospheric CO_2 by a life cycle assessment (LCA) of carbon sources and sinks that includes the post-thinning NBP, and wood use (harvest, transport, manufacturing, decomposition, wood product substitution, conversion and use of bioenergy, and displacement of fossil fuel extraction emissions; Appendix A Fig A1b and Appendix A Table A4 and A5).

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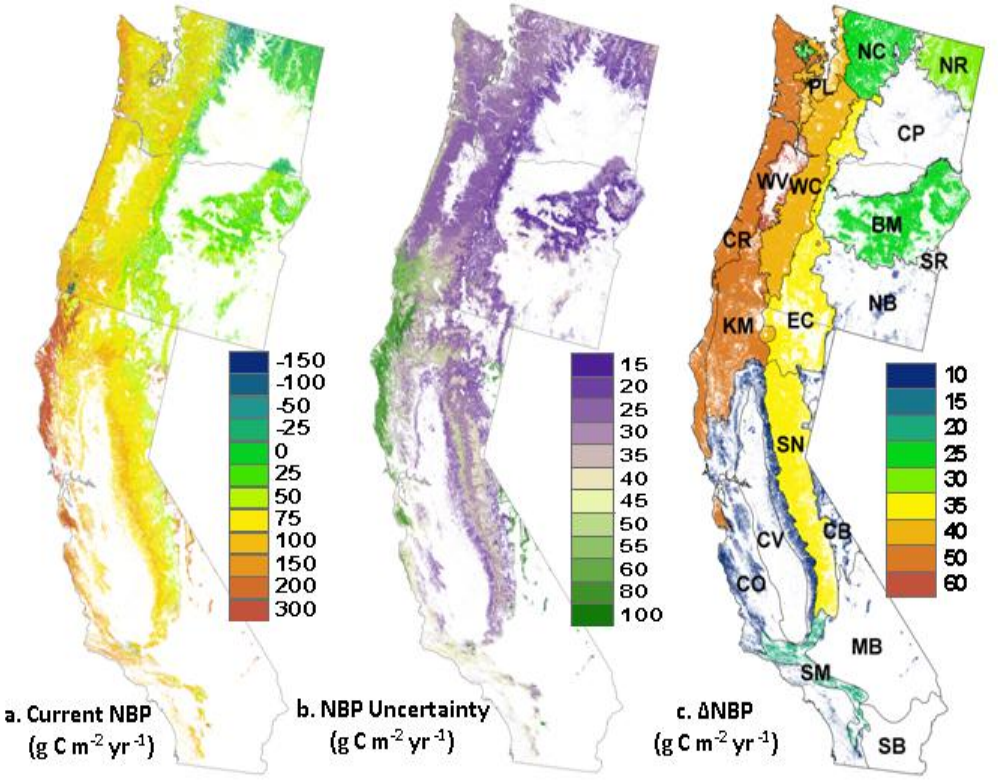

Figure 2.1. Current net biome productivity (NBP), NBP uncertainty, and change in NBP required for zero net emissions compared to business-as-usual (BAU). Positive values indicate forest sinks while negative values are carbon sources to the atmosphere. Uncertainty estimates (b) were calculated using Monte Carlo simulations of mean forest type values for the components of NBP (net ecosystem productivity, fire, and harvest) combined with the uncertainty associated with remote sensing land cover estimates. Change in NBP (c) represents the amount NBP would need to decrease to reach a threshold NPB where bioenergy management may result in emission decreases to the atmosphere.

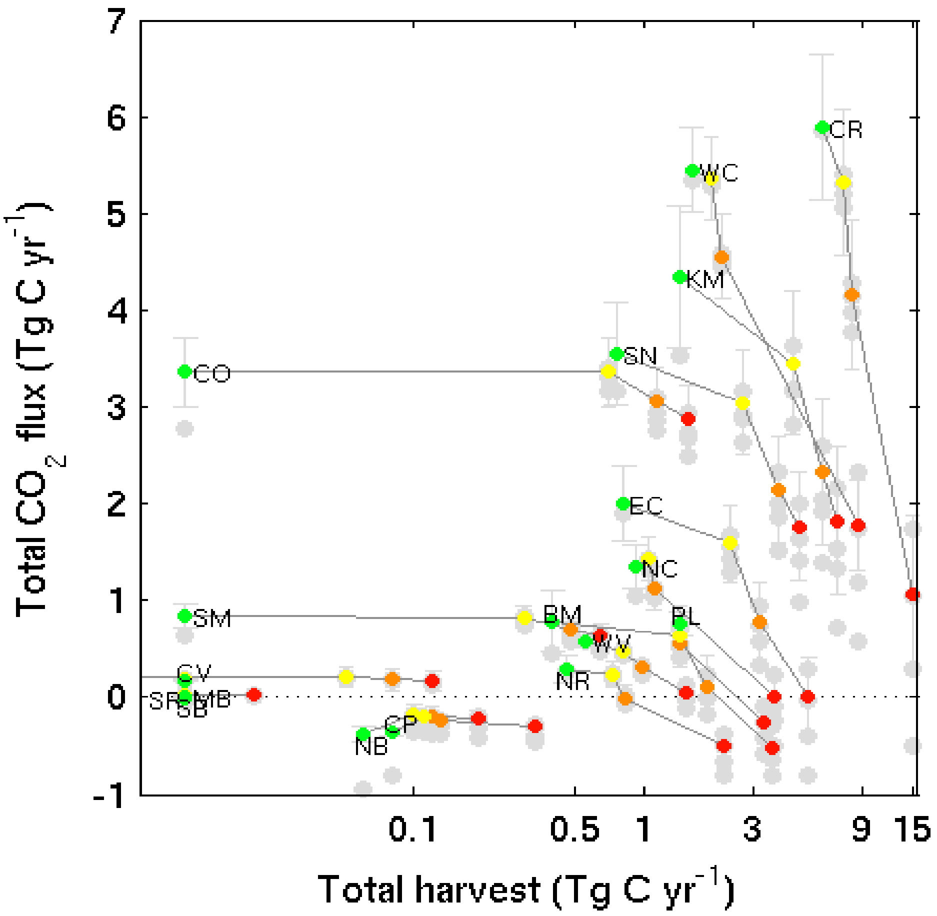

Figure 2.2. Life Cycle Assessment carbon emission trends by ecoregion for each scenario. The x-axis is the total harvest (BAU + treatment) and the y-axis is the total CO_2 flux in Tg C yr^{-1} for each ecoregion. Colored circles represent each scenario (Green = BAU, Yellow = Fire Prevention, Orange = Economically Feasible, and Red = Bioenergy Production). Grey circles are the values for each sensitivity analysis set of parameters and the error bars represent the estimate uncertainty. For most ecoregions, the treatments increase emissions to the atmosphere.

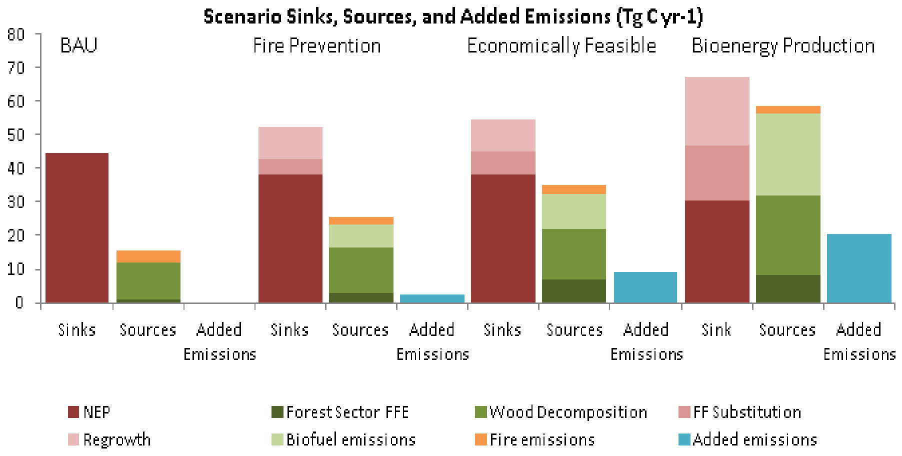

Figure 2.3. Total regional carbon sinks, sources, and added emissions for each scenario. Units are in Tg C yr^{-1}. Life cycle assessment estimates account for changes in carbon on land in addition to emissions associated with production, transport and usage of wood and substitution and displacement of fossil fuel emissions associated with use and extraction. BAU results in the lowest anthropogenic emissions from the forest sector.

Chapter 3: Evaluation and improvement of the Community Land Model (CLM 4.0) in Pacific Northwest Forests

Abstract

Ecosystem process models are important tools for determining the interactive effects of global change and disturbance on forest carbon dynamics. Here we evaluated and improved terrestrial carbon and water cycling simulated by the *Community Land Model* (CLM4), the land model portion of the Community Earth System Model (CESM1.0.4). Our analysis was conducted in Pacific Northwest forests using AmeriFlux and inventory data for the period 2001-2006. We compared simulated variables with a spatially representative dataset of forest carbon stocks, and net primary production (NPP; federal forest inventory data; FIA), and compared simulated gross primary production (GPP) with AmeriFlux eddy-covariance tower data at wet and dry sites in the region. In addition to evaluation of model uncertainty, we tested the use of a downscaled regional forcing dataset at $1/8^{th}$ degree (15 km) resolution versus the standard 1-2 degree (100-200km) forcing dataset supplied for the purpose of global model simulations. We improved model estimates by making modifications to CLM4 to allow physiological parameters (e.g. foliage carbon to nitrogen ratios and specific leaf area), mortality, and wood allocation to vary spatially within a plant functional type (PFT). Prior to modifications, default parameters resulted in underestimation of stem biomass in all forested ecoregions except the Blue Mountains and annual NPP was both over and underestimated. After modifications, model estimates of mean NPP fell within the observed range of uncertainty in all ecoregions (two-sided p value = 0.8) and the underestimation of stem biomass was reduced. At the tower sites, modeled annual GPP fell within the observed range of uncertainty (reduced chi-square statistic < 1) at both sites, however summer GPP was consistently underestimated and did not fall within the observed range of uncertainty. Modeled annual NPP was underestimated by an average of 24% when compared to biometric estimates of NPP at the Metolius site while modeled GPP was underestimated by an average of 30% compared to the eddy-covariance data. However, the ratio of NPP/GPP was nearly identical for both equaling 37% (observed) and 36% (modeled).

The low bias in summer GPP could be due to several possible reasons including variation in seasonal V_{cmax} response to temperature, precipitation, and nitrogen dynamics. We found improved parameterization of foliar nitrogen content and nitrogen availability increased monthly GPP in all months resulting in correct annual sums of GPP, but did not improve seasonal dynamics. This indicates that the model algorithm controlling V_{cmax} response to a variety of other factors including temperature, daylength, and / or soil water content may need revising.

Introduction

Modeling and understanding the response of terrestrial ecosystems to changing environmental conditions and land use change are primary goals of climate mitigation policy (IPCC 2007, Moss et al. 2010, NRC 2010a, Pacala 2010). The Intergovernmental Panel for Climate Change (IPCC) synthesizes estimates of future climate change impacts on terrestrial carbon cycling through the use of a specific set of global circulation models (IPCC 2007). Among them is the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR). The land model component (Community Land Model; CLM) has been extensively used to evaluate and predict the net carbon uptake and loss from terrestrial biomes, particularly forests (Thornton and Zimmermann 2007, Bonan et al. 2011).

Recent assessments of seasonal performance of multiple terrestrial biosphere models indicated better performance in forest ecosystems, particularly in evergreen forests, during the summer growing season than in other biomes and seasons (Schwalm et al. 2010, Schaefer et al. in press). The highest skill across biomes was in models that prescribed canopy phenology and did not use a daily time step (Schwalm et al. 2010). In an assessment with FLUXNET tower data, Schaefer et al. (in press) found that none of the models estimated gross photosynthesis (GPP) at all sites within observed uncertainty. The most important factor influencing model performance was light-use efficiency computed from the slope of the GPP – light response curve. This is influenced by photosynthetic parameters, indicating better parameter values are needed for variables influencing LUE. The model evaluations also suggested more detailed assessments need to be performed with individual models. The photosynthesis model of (Farquhar et al. 1980) is widely used in vegetation models, and an evaluation at more than 200 FLUXNET sites showed that simple PFT classification of photosynthesis parameters introduces uncertainty in photosynthesis and transpiration fluxes (Groenendijk et al. 2012b), and including V_{cmax} seasonality can improve predictions (Groenendijk et al. 2012a). The study suggested focusing on the effects of seasonal foliar N on Vcmax. In an assessment of CLM4 with FLUXNET data, Bonan et al. (2011) also found that the bias in annual GPP could be reduced by including improved estimates of photosynthetic parameters. Finally, CLM4 was also found to overestimate shade-leaf photosynthesis leading to overestimation of canopy GPP when the nitrogen limitation functionality was inactive (Bonan et al., 2012) suggesting a multi-layer canopy could improve initial GPP calculations before downregulation due to nitrogen limitation is imposed.

In this paper, we evaluate the Community Land Model (version 4.0) portion of the Community Earth System Model (CESM1.0.4). CLM4 is the latest in a series of land models developed for the CESM and runs at a half-hourly timestep. CLM4 includes coupled carbon and nitrogen processes and examines the physical, chemical, and biological processes through which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. Recent model releases include improvements to hydrology and an integrated transient land cover and land use change dataset (Lawrence et al. 2011). The transient land cover dataset includes historical wood harvest which is known to have a large influence on Pacific Northwest forest carbon storage and uptake (Harmon et al. 1990, Law et al. 2004). When the carbon-nitrogen biogeochemistry is active, CLM4 uses prognostic canopy phenology to determine leaf and stem area index (LAI and SAI) and vegetation heights. Potential GPP is calculated from leaf photosynthetic rate without nitrogen constraint. Actual GPP is computed from nitrogen limitations to potential GPP.

Our objective was to evaluate carbon stocks and fluxes simulated by CLM4 in forests and woodlands of the Pacific Northwest using independent datasets with different temporal resolutions. Annual carbon stocks and net primary production (NPP) were computed from inventory data that had been scaled to the region with remote sensing data to produce a spatial dataset (Hudiburg et al. 2011), and the seasonal data were gross photosynthesis (GPP) from two AmeriFlux sites in the region (Krishnan et al. 2009, Thomas et al. 2009). Model evaluation with an observation-based spatially representative dataset such as federal forest inventory data (FIA) is critical in order to constrain model estimates, facilitate model development and ultimately reduce model uncertainty. Combined with seasonal data and analysis over a strong climatic gradient, diagnostics can point to areas for model improvements. The specific objectives of this study are to 1) evaluate regional model performance against spatially representative FIA estimates of stem wood biomass and annual NPP; 2) evaluate seasonal model performance against monthly tower GPP utilizing observed physiological parameters; and 3) examine the roles of modeled LUE, temperature, and nitrogen limitation in determining seasonal patterns of GPP. Temperature is a dominant control on the seasonal variation in GPP (Schaefer et al. In Press)whereas nitrogen limitation is a major determinant of seasonal maximum GPP (Bonan et al. 2011).

The accuracy and uncertainty associated with regional estimates of carbon fluxes by CLM4 is unknown because model output is not usually validated against spatially representative observations. The federal forest inventory (FIA) collects data on an annual basis on *all* forestland regardless of ownership or location resulting in an intensively sampled landscape through which modeled estimates of forest carbon stocks and fluxes could be evaluated. FIA data provide measurements that can be used to calculate the carbon density of live and dead trees, woody detritus, and understory shrubs. Wood increment data are also provided, allowing estimation of 5-10 year average bole wood production, depending on the repeat measurement cycle. Combined with remote sensing land cover products, reliable maps of wood carbon stocks , net primary production (NPP) , heterotrophic respiration (R_h), and net ecosystem production (NEP) can be produced (Hudiburg et al. 2011, Law et al. 2012) to validate model output and identify model biases. The associated uncertainty in the FIA estimates can also be calculated providing a range of values or baseline conditions modeling activities should be constrained by before making predictions about future conditions.

Here, we evaluate CLM4 with FIA data maps of wood carbon stocks and NPP averaged for the years 2001-2006 in Oregon forests. We improve on model estimates by calibrating with supplemental plot data collected at over 100 sites across the study area. The region is characterized by tremendous climate variation and it has been recommended that a minimum of 15 km resolution be utilized in such heterogeneous terrain (Salathé et al. 2010). We utilize a new downscaled 200 year 1/8th degree (15 km) resolution dataset specifically designed for use in the Pacific Northwest (Salathe et al. 2007). Furthermore, we also test the model's ability to determine the seasonal timing and magnitude of GPP by comparing modeled estimates with eddy-covariance data in the region, and evaluate tower annual NPP and GPP for consistency (Luyssaert et al. 2009). Finally, we make modifications to model algorithms and plant functional type (PFT) physiological parameterization to improve model performance. By using existing datasets and uncertainty quantification, this research provides a solid scientific foundation for evaluating carbon dynamics under conditions of future climate change and land management practices at local and regional scales.

Methods: Model Description

The model used to simulate these processes is the Community Land Model (CLM4) portion of the Community Earth System Model (CESM 1.0.4) of the National Center for Atmospheric Research (Oleson et al. 2010). CLM4 uses hourly climate data, ecophysiological characteristics, site physical characteristics, and site history to estimate the daily fluxes of carbon, nitrogen, and water between the atmosphere, plant state variables, and litter and soil state variables. State variables are the live and dead carbon pools. CLM4 examines the physical, chemical, and biological processes through which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The basic assumption is that terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of climate. Model components consist of biogeophysics, hydrologic cycle, biogeochemistry and dynamic vegetation. The land surface is divided into five sub-grid land cover types (glacier, lake, wetland, urban, vegetated) in each grid cell. The vegetated portion of a grid cell is further divided into patches of plant functional types (PFTs), each with its own leaf and stem area index and canopy height. The multiple PFTs within the grid cell compete for water and nutrients on a single soil column.

Recent model improvements include updates to hydrology and an integrated transient land cover and land use change dataset that accounts for wood harvest. Updates to the hydrology include improved ground evaporation parameterization and snowpack heating and aging resulting in higher snow cover, cooler soil temperatures in organic-rich soils, greater river discharge, and lower albedos over forests and grasslands (Lawrence et al. 2011). The transient land use dataset has been formatted for use by CLM4 from a global historical transient land use and land cover change dataset (Hurtt et al. 2006) covering the period from 1850–2005. The dataset describes land cover and its change via four classes of vegetation (crop, pasture, primary vegetation, and secondary vegetation.) The dataset also describes the annual fraction of land that is transformed from one PFT to another including the conversion of primary forest to secondary forest which is essential for studies attempting to track forest carbon storage and uptake over time. This dataset essentially provides a human-induced disturbance history of forests which can be used to test the model's ability to simulate carbon dynamics following harvest.

Methods: Model calibration and forcing datasets

CLM4 has over 40 physiological parameters for each of the 17 plant functional types and a default constant mortality rate of 2% for all PFTs. The PFTs include 8 different forested and 3 different shrub land PFTs (Appendix B; Table B1 and B2). We use data collected on 100 supplemental plots located throughout the study region (Figure 3.1) to calibrate the physiology file and mortality rate. Default physiology values were used for parameters where data was unavailable and for parameters which are known to have little influence on biomass and NPP. Assessment and sensitivity analysis of CLM4 to the parameter values has been tested and described (White et al. 2000, Bonan et al. 2011, Lawrence et al. 2011) and we incorporate this knowledge to facilitate our regional calibration. The supplemental plot dataset includes measurements of specific leaf area (SLA; projected), foliar carbon nitrogen ratios, litter carbon nitrogen ratios, and leaf longevity for the major tree species across the study region. We use the PFT mean for each of these parameters in the calibrated physiology file for default model configuration evaluation, heretofore indicated as ‘CLM4’ in figures and text. Prior modeling studies in this region indicate that a dynamic mortality rate that varies with age and/or disturbance type is necessary to predict the correct seasonal and annual carbon fluxes (Turner et al. 2007, Edburg et al. 2011), especially in the drier forest types where mortality decreases as a percentage of live biomass as stands age. Mortality rates in Oregon forests range from 0.5 to 2% (Turner et al. 2007, Hudiburg et al. 2009) in the absence of stand replacing disturbance. Since dynamic mortality algorithms have not been incorporated into CLM4, we chose to use 1.0% as a static mean value for the default configuration simulations. To improve on this, we parameterized CLM4_mod with PFT mortality rates within each ecoregion based on inventory data (Hudiburg et al. 2009). Ecoregions are areas within which ecosystems (and the type, quality, and quantity of environmental resources) are generally similar (Omernik 1987).

Offline simulations of CLM4 are typically forced with the NCEP reanalysis dataset (Qian et al. 2006) provided by NCAR. While this dataset includes the required climate and forcing variables at a sub-daily timestep, the resolution (~2 degree) is not adequate for regional simulations in Oregon. For this reason, we forced the model with a 1/8th degree regional dataset assembled by the Climate Impacts Group at the University of Washington (http://www.cses.washington.edu/data/ipccar4/). Daily gridded historical (1900-2000) and future (2000-2100) data are provided from three different models participating in the IPCC assessment reports. The regional downscaled dataset includes daily precipitation, minimum and maximum temperature, and wind speed. Because CLM4 also requires shortwave radiation and relative humidity we calculated values incorporating algorithms from DAYMET (Thornton et al. 1997) and methods for sub-daily calculations as described by (Appendix B;Göeckede et al. 2010).

Methods: Model simulations and evaluation

All model simulations are summarized in Table 3.1. Model spinups required 650 years to reach equilibrium conditions and were performed using regional physiology parameters and the downscaled climate forcing dataset (PNW). The fire module was turned ‘off’ for spinup because in some ecoregions, biomass would ‘burn up’ before reaching equilibrium conditions. Based on previous experience with CLM4 in the region, fire combustion estimates were reduced by 50%. After spinup, control simulations were run using the different model versions (see model development below). The control simulations were run from 1850-2006 using preindustrial CO_2 and N deposition levels and constant 1850 land cover. Transient simulations of each model version were run by changing CO_2, nitrogen deposition, land use and land cover, and/or climate for the period from 1850-2006. Separate simulations allow for attributing the responses due to climate, land use change, and model versions. Transient CO_2, nitrogen deposition (Ndep), and land cover files are annual files covering the period from 1850-2006. Ndep and land cover are spatially explicit datasets interpolated from a half-degree global dataset, while the CO_2 file is a single value for the entire region which changes annually.

Methods: Observations

We combined spatially representative observational data from over 3125 FIA plots measured during 2001 to 2006 with remote sensing products on forest cover, ecoregion, and age and a global data compilation of wood decomposition data (Wirth et al. 2010) to provide current maps of Oregon (~12 million hectares) forest biomass carbon stocks, heterotrophic respiration (R_h), net primary production (NPP), and net ecosystem production (NEP). We included all forestland in our analysis across all age classes (20-800 years old) and management regimes. Plot values were aggregated by ecoregion, age class, and forest type and this look-up table was used to assign a value to each associated 30 meter pixel. Methods and uncertainty of the inventory biomass and carbon flux calculations are fully described in (Hudiburg et al. 2009, Hudiburg et al. 2011). Tree biomass is calculated using ecoregion- and species-specific allometric equations from diameter at breast height (DBH) and height. Woody detritus length and diameter are recorded along transects for each plot in the FIA dataset. Woody detritus biomass is then calculated from piece volume and decay class density. Wood NPP is calculated using increment data from wood cores collected on the FIA plots, foliage NPP is foliage biomass divided by the average leaf retention time measured at the intensive plots, and fine root NPP is calculated from fine root biomass multiplied by the average root turnover rates from intensive plot data (Appendix A, Table A8).

Monthly mean values of GPP from eddy-covariance tower data and the associated uncertainty for the period from 2001-2006 were downloaded from the AmeriFlux database for two tower sites in the region, one in a mesic forest of the Coast Range ecoregion (Campbell River, BC) and one in a dry forest of the East Cascades (Metolius, OR). The provided uncertainty estimates for the flux tower observations were calculated for the model-data synthesis project by Schwalm et al. (2010). These sites represent mature secondary forest under private ownership (50- 80 years) with contrasting rates of biomass accumulation and NPP primarily due to climatic conditions (Law et al. 2003, Law et al. 2004). Seasonal patterns of modeled GPP are compared with the flux tower observations.

Methods: Uncertainty analysis

We calculated the total uncertainty in the current FIA estimates using the propagation of error approach (Williams et al. 2012). The propagation of error approach is a method for combing error terms to calculate total uncertainty in an estimate. Monte Carlo simulations were used to estimate the uncertainty due to variation in region- and/or species-specific allometry by using the mean and standard deviations for stem biomass and NPP calculated using three alternative sets of allometric equations. The full suite of species-specific equations that use tree diameter (DBH) and height (preferred) were compared to a DBH-only national set (Jenkins et al. 2003) and to a grouped forest type set. Total uncertainty in FIA estimates was calculated as the combined uncertainty of the allometric equations and land cover estimates (10%) using the propagation of error approach (NRC 2010b). Ecoregion level uncertainty estimates are represented in the figures by the grey error bars and in tables with '±' symbols (NRC 2010a). For finer scale evaluation (i.e. grid cell size), the uncertainty in the observations was used to evaluate model performance using the reduced chi-square (x^2) statistic (Schwalm et al. 2010) and model bias defined as the mean of the model-data residuals for different groups of interest. Inventory plot data were grouped by ecoregion and then aggregated by precipitation regime, biome type, and age group within each ecoregion. Plots with annual precipitation greater than 800 mm were considered ‘Wet’ and less than 800 mm as ‘Dry’. FIA forest types are either evergreen needleleaf (ENF), deciduous broadleaf (DBF), or mixed ENV/DBF (MXD). Complete analysis and statistics were performed for all biomes, however since 92% of the forested area in the study region is ENF, we include only the ENF biome in the figures and tables of this document. Age groups are defined as young (< 60 years) and mature (> 60 years).

The reduced x^2 is the squared sum of the residuals normalized by the observation uncertainty and divided by the total number of samples (i.e. the mean x^2 for an arbitrary group of interest):

$$\text{Reduced } x^2 = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{Modeled_i - Observed_i}{2 * \delta_i}\right)^2$$

where, δ is the uncertainty in the i^{th} observation, ‘2’ normalizes the uncertainty to correspond to a 95% confidence interval, and the summation is across the aggregated data groups within each ecoregion (Schwalm et al. 2010). Reduced x^2 values close to 1 indicate model-data unity or agreement. Model bias can be estimated as the mean of the residuals:

$$\text{Bias} = \frac{1}{n}\sum_{i=0}^{n} (Modeled_i - Observed_i)$$

where *i* is the group of interest and positive values indicate average overestimation by the model and negative values indicate average underestimation.

Methods: Model development

The model sensitivity to specific parameter value ranges has been tested and described (White et al. 2000, Thornton et al. 2002).We aimed to reduce overall uncertainly by calibrating with known regional mean values and evaluating with inventory data. This was in part due to an interest in evaluating the default model configuration with the fewest adjustments possible and to utilize the rich regional plot dataset. Testing the performance in a diverse region aids diagnosis of parameter or structural deficiencies. As stated above, the default configuration includes PFT specific physiological variables (no seasonal variation), a constant mortality rate for all forest PFTs, and a single stem wood allocation equation for all woody PFTs. After evaluation with the default configuration, we tested the use of modified model versions where the physiological parameters and mortality rates were allowed to vary within a PFT by ecoregion (CLM4_eco) and where the stem wood allocation equation in addition to the physiological and mortality rates also varied by ecoregion (CLM4_stem).

For CLM4_eco, parameter values for foliar CN ratios, foliar N content in Rubisco, leaf longevity, fine root CN ratios, and specific leaf area (SLA) were adjusted according to field plot data from sites in each of the tested ecoregions in the study area. The PFT physiological variable input file was restructured so that two PFTs were assigned to each ecoregion and surface datasets were modified to reflect the new PFT assignments (Appendix B, Table B1 and B2). The CLM4 mortality module was then modified to assign a different mortality rate based on the PFT. For CLM_stem, the inventory data was used to construct ecoregion-specific allocation to stem wood equations and the equations were added to the CLM4 allocation module (Appendix B, Table 3 and Figure B1.

Results: Modeled results and regional totals

In general, CLM_stem modeled estimates of stem biomass carbon (Figure 2a) followed a west to east gradient with higher values in the productive mesic western ecoregions (i.e. Coast Range, West Cascades) and lower values in the less productive dry eastern ecoregions (East Cascades, Northern Basin). Stem wood biomass peaks in the West Cascades at 360 Mg C ha^{-1} and is lowest in the Northern Basin at 10 Mg C ha^{-1}. NPP is highest in the Coast Range with values up to 1100 g C m^{-2} yr^{-1} and lowest in Northern Basin at less than 100 g C m^{-2} yr^{-1} (Figure 3.2b). Forest NEP ranges from -200 g C m^{-2} yr^{-1} in the Blue Mountains to 350 g C m^{-2} yr^{-1} in the Coast Range (Figure 2c) and R_h ranges from 20 g C m^{-2} yr^{-1} in the Northern Basin to 750 g C m^{-2} yr^{-1} in the Coast Range (Figure 3.2d).

Total simulated regional tree carbon stocks are estimated to be 1.2 Pg C with 61% in the Coast Range and West Cascades alone. For the period from 2001-2006, total forest NPP and NEP averaged 57.6 and 13.2 Tg C yr^{-1} respectively indicating a strong sink in the region. Total modeled harvested carbon equaled 4.9 Tg C yr^{-1} and total fire emissions equaled 2.4 Tg C yr^{-1}. After accounting for these removals, the forest carbon sink is still positive at 6.2 Tg C yr^{-1}.

Results: Spatial evaluation with inventory data

We show ecoregion means of the evergreen needleleaf (ENF) biome because it represents 92% of the forested area in the region and we do not have sufficient regional plot data for the deciduous broadleaf (DBF) biome for evaluation. CLM4 regional modeled mean stem biomass for the period from 2001 – 2006 fell within the observed range of uncertainty in the Coast Range and the West Cascades, was close to observed range of uncertainty in the East Cascades and was underestimated in the Klamath Mountains (Figure 3a; grey error bars indicate observation uncertainty). However, mean simulated biomass was twice the observed mean in the Blue Mountains. Regional mean NPP was within the observed range of uncertainty in the Coast Range, East Cascades and Klamath Mountains, was slightly overestimated in the West Cascades and was again almost twice the observed mean in the Blue Mountains. After modifying the model for ecoregion differences, ecoregion mean stem biomass was within the observed uncertainty in the Blue Mountains, but dropped below the average in the West Cascades. Ecoregion mean NPP was within observation uncertainty in all ecoregions after modification. After modifications, modeled means NPP were not significantly different from observed means (two-sided p value 0.8 respectively) and modeled means of stem biomass fell within the observed range of uncertainty in the majority of the ecoregions.

Ecoregion means are a good first order approximation of model performance and regional total evaluation, but cannot be used to determine the dynamics that may be causing any bias and reveal nothing about model fidelity at a smaller scale. Statistical tests of model performance for stem carbon biomass revealed overall better agreement with inventory data using the CLM_stem version of the model. At 12 km spatial resolution, reduced x^2 statistics indicated adequate model performance *for the region as a whole* for both stem biomass and NPP (overall reduced x^2 was 3 and 2, respectively). This was an improvement from the default configuration by 50% for stem biomass and 30% for NPP. Agreement was best in the West Cascades, Blue Mountains, and Coast Range ($x^2 <= 2$; Table 3.3) followed by the Klamath Mountains and East Cascades ($x^2 <$ 7). The largest improvements were in the Blue Mountains where x^2 was reduced from 15 to 2. Initial CLM4 stem carbon biomass was underestimated by 11 to 41 Mg C ha^{-1} in all ecoregions except the Blue Mountains. After modification, stem carbon biomass was consistently underestimated in all ecoregions. Within ecoregions, performance was generally better in older age classes (Table 3.3).

NPP also improved when using CLM4_stem, primarily because overestimation was reduced in the Blue Mountains and West Cascades (Table 3.3). Overestimation in the Blue Mountains exceeded 100 g C m^{-2} yr^{-1} with CLM4 before modifications were made. However, reduced x^2 statistics for the Coast, Range, East Cascades and Klamath Mountains did not significantly improve. NPP was underestimated in the Coast Range and East Cascades by CLM4, improved for the Coast Range with CLM4_stem, but was then overestimated for the East Cascades. As with stem biomass, there was better performance in wet versus dry stands, except in the Klamath Mountains. Performance was better for both metrics in mature stands. This was especially true for the Coast Range and West Cascades where the x^2 values for both CLM4 and CLM4_stem were close to 1 for the mature age classes, indicating model-data unity.

Results: Evaluation with tower and supplemental plot data

Simulated monthly values for GPP were compared with 4-5 years of eddy-covariance tower data at two sites in the region. At the semi-arid mature ponderosa pine site (Metolius), a reduced x^2 value of 0.53 indicated good overall model performance (values less than 1 indicate good model performance) after accounting for observation uncertainty (Schaefer et al., in press). Observation uncertainty ranged from 12-200% of the observation value for the Metolius site and 13-90% for the Campbell River site. Maximum GPP is lower for modeled results (Figure 3.4a) and peaks one to two months later than observed values in most of the years compared. Model bias was an underestimation of an average of 27 g C m^{-2} yr^{-1} for all years compared. Underestimation was highest in 2005, although this was the only year where timing of maximum GPP was equal to observed. There was no noticeable bias in the fall and spring months. At the mesic mature Douglas-fir site (Campbell River), a reduced x^2 of 1.1 indicated weaker model performance than the Metolius site, although still nearly within the observed range of uncertainty. Model bias resulted in underestimation of 46 g C m^{-2} yr^{-1}. Model data mismatch again occurred primarily in summer, with underestimation of summer GPP, and annual GPP up to 200 g C m^{-2} yr^{-1}. Timing of peak NPP was mostly correct as were fall and spring values.

CLM4 includes direct down-regulation of the photosynthetic rate under nitrogen limitation, which effectively reduces GPP. We also compared GPP before down-regulation (Figure 3.4a and Figure 3.4b; “initial GPP”) with tower data and found similar model performance. However, GPP was overestimated by an average of 40 g C m^{-2} yr^{-1} at the Metolius site, especially in the late summer months. At the Campbell River site (Figure 3.4b), overall model performance did not improve compared with initial GPP, however summer maximum GPP was much closer to observed. We tested both increasing foliage nitrogen content and altered the equation that calculates biological nitrogen fixation. CLM4 nitrogen fixation is controlled by a single equation that determines the rate as a function of NPP. We increased the rate of fixation for the Campbell River site and found improved simulated summer GPP. However, fall and spring values were also increased resulting in overestimation. The overestimation for fall and spring resulted in correct annual sums of GPP, but no improvement to seasonal model performance.

We compared modeled and observed monthly light use efficiency (LUE) with monthly average air temperature at each tower site (Figure 3.5). We define LUE as the monthly GPP as a function of monthly average incident solar radiation (shortwave radiation). At the Metolius site, observed LUE increased with air temperature to about 10 °C, then declines (Figure 3.5a). In other words, higher GPP is attained at lower radiation levels in the 10°C soils. This pattern was also true for the modeled relationship, but occurred at a higher temperature range, LUE peaks at around 15 °C (Figure 3.5b). Generally, simulated LUE is lower than observed LUE, and the slope of the relation indicates that simulated LUE is about half that of the observed. At the Campbell River site, there is a smaller increase in LUE with temperature than the Metolius site without the nitrogen availability modifications (Figure 3.5b, grey surface), and there is much less seasonal variation in temperature. As noticed with model performance metrics, introduction of increased N fixation does not increase LUE (the slope), but simply increases the intercept. There is no increase in LUE with temperature in the modeled results. Again, the modeled LUE is about half the observed LUE.

Annual biometric estimates of NPP were available from the Metolius site and are often used as cross-checks with tower data for consistency (Luyssaert et al. 2009). Modeled annual NPP was underestimated by an average of 24% when compared to biometric estimates of NPP at the Metolius site while modeled GPP was underestimated by an average of 30% compared to the eddy-covariance data (Appendix B, Figure B6). However, the ration of NPP/GPP was nearly identical for both equaling 37% (observed) and 36% (modeled).

We also compared monthly precipitation with both observed and simulated monthly GPP (Appendix B; Figure B2). For both sites, winter precipitation is much higher and summers are generally dry. Again, GPP is correctly estimated for the higher precipitation months (winter and spring), but underestimated in the low precipitation months (summer).

Results: Model improvement and testing

Finally, we also compared regional plot data of foliar chemistry and morphological characteristics with the physiological file constants used for the modeled runs (Figure 3.6). There is significant variation in both foliar carbon to nitrogen ratios and specific leaf area (SLA, projected) between ecoregions according to plot data. The default configuration for CLM4 allows one foliar CN ratio and one SLA value per PFT.

We experimented with physiological parameter spatial variation (Figure 3.3; CLM_eco), and found that for the Blue Mountains, overall mean biomass decreased to 71 Mg C ha^{-1} and mean NPP decreased to 307 g C m^{-2} yr^{-1}, both falling within the observed range of uncertainty. The stem carbon reduced x^2 statistic decreased from 15 to 2 and the NPP x^2 decreased from 5 to 2. Stem carbon bias was reduced from 48 to 9 Mg C ha^{-1} and NPP bias decreased from 112 to a slight underestimation of -3 g C m^{-2} yr^{-1}. We found similar improved relationships in the other ecoregions for NPP with CLM_eco, but stem carbon stocks were subsequently underestimated. CLM4 includes dynamic stem wood allocation, but it is a single equation for all woody PFTs globally. Finally, using CLM_stem, where we also changed the dynamic stem allocation equation to vary by ecoregion, we found an overall improvement in stem carbon stocks compared to CLM4.

Discussions: Modeled results and regional totals

The regional patterns of carbon stocks, NPP, and NEP are similar to the observed values in this study and prior studies. Stem carbon stocks from over 8000 inventory plots and 200 plots in Oregon showed stem carbon stocks range from 60 – 420 Mg C ha^{-1} (Hudiburg et al. 2009, Van Tuyl et al. 2005) in the more mesic ecoregions (Coast Range, Klamath Mountains, West Cascades). Reported densities from the same studies for the drier ecoregions (East Cascades, Blue Mountains) range from 20 to 100 Mg C ha^{-1}. The CLM4_stem estimates in this study range from 10-400 Mg C in agreement with the reported values. Pacific Northwest temperate forests have some of the highest carbon stocks in the world (Keith et al. 2009), with most of the carbon stored in the tree wood. Modeled relationships of biomass accumulation over time and with increasing age classes typically show a decrease in tree wood biomass or it reaches an asymptote. However, observations in the Pacific Northwest suggested otherwise (Hudiburg et al. 2009) and modeled allocation to wood biomass in these regions was modified in CLM4 to reflect these regional stand dynamics (CLM4_stem).

Modeled NPP ranges from 100-1100 g C m^{-2} yr^{-1} (CLM4_stem) across the study region agreeing with the reported regional values of 100-900 g C m^{-2} yr^{-1} (Hudiburg et al. 2009) and falling within the range of 100 to 1600 g C m^{-2} yr^{-1} reported for temperate and boreal forests (Luyssaert et al. 2008). The regional total NPP for forests is 57.6 Tg C yr^{-1}, a value very close to the observed total of 58.2 ± 6.5 Tg C yr^{-1} calculated from inventory data (Law et al. 2012). The regional modeled total NEP for 2001-2006 is also close to the reported value from inventory data (13.2 versus 15.2 ± 1.6 Tg C yr^{-1}; (Law et al. 2012)), and Biome-BGC modeled results (17.0 ± 10 Tg C yr^{-1}; (Turner et al. 2007)), but lower than uncertainty of an inverse modeling estimate (35.4 Tg ± 11 Tg C yr^{-1}; (Göeckede et al. 2010)). The range of NEP reported in a recent study by (Williams et al. 2012) was 0- 270 g C m^{-2} yr^{-1} for the Pacific Northwest and an overall NEP of 18 Tg C yr^{-1}.

Discussion: Spatial evaluation

After modifications were made, stem carbon stocks continued to be underestimated in all ecoregions. Performance was generally better in older age classes, and underestimation of stem biomass was balanced by overestimation of stem biomass in young age classes in some ecoregions. Stem wood allocation is a dynamic function of NPP rather than age in CLM4. In a modeling assessment of US forest NEP following disturbance, the ecosystem model used (CASA) was altered so that live biomass estimates were constrained by age-accumulation trajectories calculated from FIA data (Williams et al. 2012). An approach similar to this could be used in CLM4 to remove the age-related bias in stem biomass and would improve on ecoregion-specific allocation we implemented in this study. In the Pacific Northwest, the age-related biomass accumulation trajectories are known to vary by ecoregion and management regime (Van Tuyl et al. 2005, Hudiburg et al. 2009) with higher potential stem biomass in the more productive ecoregions.

Implementation of ecoregion physiological variation and mortality had a significant impact on NPP performance, with better performance in mature forests for CLM4_eco and CLM4_stem. This is not surprising considering NPP tends to peak early in stand development, decline and then remain at a consistent level as stands age. The age-related variation in this response varies by ecoregion and disturbance regime (Law et al. 2004, Hudiburg et al. 2009) and improvement to age-related allocation may help to correct part of the discrepancies. We found underestimation of NPP by CLM4 in the Coast Range and overestimation in the Blue Mountains was primarily due to the single-value parameterization of foliar CN ratios and specific leaf area (Figure 3.6), which are much higher in mesic versus semi-arid forests (Matson et al. 1994). Maximum rates of carboxylation (V_{cmax}) are determined by SLA and foliar nitrogen content in CLM4. Prior modeling efforts with CLM4 also found significant improvement in GPP estimates by using site-specific parameterization of V_{cmax} (Bonan et al. 2011.)

NPP continued to be overestimated while stem biomass continued to be underestimated in the West Cascades after implementing CLM4_eco and CL4_stem, although both were improved. Foliar nitrogen content in the Cascade Mountain ecoregion is lower than that of the Coast Range and Klamath Mountain ecoregions and has higher specific leaf area. NPP was reduced with ecoregion-specific parameterization, but this also reduced stem biomass. However, observed West Cascade stem biomass is equal to or higher than Coast Range mean biomass. Stem biomass density is affected by removal rates through fire and harvest. The CLM4 input harvest rates are higher than observed values in the West Cascades (1.9 Tg C yr^{-1} vs 1.0 Tg C yr^{-1}; Turner et al. 2007)) effectively reducing stem carbon densities over time. Fortunately, these values can be easily adjusted to the correct rates for future simulations. Total regional modeled fire emissions are also overestimated by 1.0 Tg C yr^{-1} which could also be contributing to the underestimation bias.

Finally, nitrogen availability has recently been shown to significantly impact the NPP to GPP ratio, with higher rates of biomass production sites with higher fertility (Vicca et al., 2012). Our results support this hypothesis, with higher biomass production in the forests with high foliar nitrogen content (Figure 3.2 and Figure 3.6). Thus, the model represents nitrogen influences on allocation and productivity quite well.

Discussion: Seasonal evaluation

Simulating GPP correctly is important because most of the subsequently calculated carbon fluxes are calculated from GPP. In a model-data synthesis activity including 39 flux sites and 26 models (CLM4 was not included) GPP was found to be overestimated in the spring and fall and underestimated in the summer resulting in poor model performance at most flux sites (Schaefer et al, in press). We found CLM4 simulated GPP at the Metolius site to be close to the observed range of uncertainty (reduced x^2 = 0.60) and GPP was not over-predicted in fall and spring resulting in overall fair model performance. However, GPP was under-predicted in the summer months (Figure 3.6a), and it peaked one month later than observed values. LUE was determined as the primary driver of underestimation of GPP in summer months in the model-data synthesis. Our analysis agrees with this as we found LUE to be on average less efficient in the modeled results than the observations. However, this does not necessarily mean the low GPP bias in the model is caused by incorrect representation of LUE. We also found a different range of temperature thresholds for the range of LUE values indicating PFT-specific temperature thresholds may vary, especially in the drier more extreme climates found in the eastern portion of our study region. GPP was also found to be underestimated for months with little to no precipitation (i.e. summer) indicating soil water availability or plant water use efficiency need further investigation. We also noted the “initial GPP” before down-regulation as a result of nitrogen limitation had a positive summer bias, and while down-regulation brought the majority of the simulated GPP monthly values closer to observed, there was too much constraint in the summer months.

At the Campbell River site, model performance was similar with the same tendency to underestimate summer GPP. Foliar nitrogen content and availability are both higher at the Campbell River site than the Metolius site. However, since LUE is underestimated at both sites, V_{cmax} must also be underestimated. V_{cmax} increases with increasing nitrogen availability and fraction of leaf nitrogen in Rubisco which could be calculated from plot data collected in the region to improve parameterization of leaf nitrogen content and Rubisco activity in the Pacific Northwest.

Finally, the tower site simulations were forced with the regional downscaled data for the Metolius site and the NCEP data for the Campbell River site until 1950. While this is typical for point simulations where multiple years of meteorological forcing data are unavailable, there are recent modeling activities where site data are being used for the entire simulation period and initial model results tend to achieve overall better model performance with site data for the duration of the simulation period (P. Thornton, personal communication)

Summary of results and recommendations for model improvement

CLM4 was evaluated against inventory data in PNW forests using the default configuration and regional parameterization. Initial results indicated overall underestimation of stem biomass except in the semi-arid Blue Mountains where it was overestimated by 48 Mg C m^{-2}. There was good general agreement with observed NPP values. However, modeled ecoregion mean NPP was overestimated in the Blue Mountains and mesic West Cascades. Following initial default parameterization, model improvements were made to account for ecoregion differences in the physiological variables, foliar N content and mortality, and this resulted in an overall improvement in NPP estimates (all ecoregions fell within the observed range of uncertainty). Changing the stem wood allocation algorithm further improved the results, however wood carbon stocks were still underestimated in the West Cascades and Klamath Mountains (CLM4_stem). Adjusting stem wood allocation changes with age should improve results. The amount of wood mass harvested was overestimated in the West Cascades compared to observed values which could be causing the reduced modeled stem carbon stocks compared to observations. Harvest values are easily corrected or changed. Fire emissions are a function of the percentage of wood combusted and the burn area. The fire module can be easily modified to reduce the amount of stem biomass combusted during wildfire to match historical rates. The percentage of area burned is a more complicated prediction, a process that was improved by Kloster et al. (2011) but not yet incorporated into public release versions of CLM4.

At 12 km spatial resolution, reduced x^2 statistics indicated adequate model performance *in all ecoregions* for both stem biomass and NPP (reduced x^2 was equal 3 and 2, respectively). This was an improvement from the default configuration by 50% for stem biomass and 30% for NPP. Within ecoregions, there was good performance ($x^2 < 2$) in the Coast Range and West Cascades. There was generally better performance in mature stands and apart from the Klamath Mountains, better performance in wet stands.

Evaluation of CLM4 monthly GPP with eddy-covariance tower data revealed good model-data agreement from October to May at the mesic site (ca1; Figure 3.4b) and August – April at the semi-arid site (me2; Figure 3.4a). Summer GPP was underestimated at both sites due to several possible reasons including variation in seasonal V_{cmax} response to temperature and nitrogen dynamics. We found a different range of temperature thresholds for the range of LUE values indicating PFT-specific temperature thresholds may vary, especially in the drier more extreme climates found in the eastern portion of our study region. Adjustments to V_{cmax} by increasing nitrogen availability improved summer GPP estimates, but reduced model fidelity for the remainder of the months suggesting nitrogen availability alone does not improve seasonality. Improvement to V_{cmax} seasonality in CLM4 will require adjustment to other factors such as response to temperature and soil water in order to improve summer GPP.

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Table 3.1: Ecoregion and tower site characteristics in study region

Ecoregion	**Forest (ha) (% of Total)**	**Number plots Private / Public**	**Stand Age Private / Public**	**Dominant Forest Types**	**MAP (mm yr^{-1})**	**MAT (C°)**
Coast Range (CR)	2043332 (17)	294 / 216	34 / 75	Douglas-fir, Sitka Spruce, Redwood, Western Red Cedar, Fir-hemlock	1742	11.0
West Cascades (WC)	2693263 (22)	168 / 512	50 / 140	Douglas-fir, Hemlock, Mixed Conifer, Red Fir, Western Red Cedar	1688	8.8
Klamath Mountains (KM)	1302111 (10)	121/192	59 / 106	Mixed Conifer, Mixed Evergreen, Red Fir, Douglas-fir, Riparian, Oak	1549	11.5
Willamette Valley (WV)	501793 (4)	93/17	43 / 61	Douglas-fir, Hemlock, Riparian	1280	11.0
East Cascades (EC)	2099866 (17)	155 / 395	64 / 94	Ponderosa Pine, Mixed Conifer, Juniper, Pine, Red Fir	630	9.1
Blue Mountains (BM)	3364151 (27)	243 / 614	71 /100	Mixed Conifer, Ponderosa Pine, Juniper, Spruce-Fir	552	7.3
Columbia Plateau (CP)	88922 (<1)	80 / 47	80 / 47	Mixed Conifer, Ponderosa Pine, Riparian	330	9.7
Northern Basin (NB)	253690 (2)	80 / 130	80 / 130	Juniper, Aspen, Pinyon-Juniper, Ponderosa Pine, Mountain Mahogany	304	9.7
Metolius Mature Site (me2)	--	1	80	Ponderosa Pine (secondary growth, privately owned)	434	7.6
Campbell River Mature Site (ca1)	--	1	56	Douglas Fir (secondary growth, privately owned)	1256	8.7

Table 3.2: Model simulations. Transient CO_2, nitrogen deposition (Ndep), and land cover files are annual files covering the period from 1850-2006. Ndep and land cover are spatially interpolated using the CLM toolkit from a half-degree global dataset while the CO_2 file is a single value for the entire region which changes annually. Simulations marked with and '*' indicate tower/point simulations (ca1 = Campbell River and me2 = Metolius Mature Site). Downscaled regional data was unavailable for the ca1 site.

Name	**Years**	**Climate Forcing (Years)**	**CO_2 / Ndep**	**Land Cover**	**Mortality Rate**	**Physiology**	**Model**
Spinup							
S_Oregon	650	PNW (1900-1949)	1850	1850	2 %	PNW	CLM4
S_ca1[*]	650	NCEP (1948-1972)	1850	1850	1%	Ca1	CLM4
S_me2[*]	650	PNW (1900-1949)	1850	1850	1%	Me2	CLM4
Control and Calibration							
C_Default	1850-2006	PNW (1900-1949)	1850	1850	1 %	PNW	CLM4
C_eco	1850-2006	PNW (1900-1949)	2000	2000	varied	PNW_eco	CLM4_eco
C_eco_stem	1850-2006	PNW(1900-1949)	2000	2000	varied	PNW_eco	CLM4_stem
Transient and Modified							
T_PNW_default	1850-2006	PNW (1900-1949;1900-2006)	transient	transient	1%	PNW	CLM4
T_PNW_ eco	1850-2006	PNW (1900-1949;1900-2006)	transient	transient	varied	PNW_eco	CLM4_eco
T_PNW_eco_stem[1]	1850-2006	PNW (1900-1949;1900-2006)	transient	transient	varied	PNW_eco	CLM4_stem
T_ca1[*]	1850-2010	NCEP (1948-1972); Tower	transient	transient	1.0 %	Ca1	CLM4
T_me2[*]	1850-2010	PNW (1900-1949; Tower	transient	transient	1.0 %	Me2	CLM4
T_ca1_nitrogen[*2]	1850-2010	NCEP (1948-1972); Tower	transient	transient	1.0 %	Ca1	CLM4_nitr

[1] The stem wood to leaf allocation equation was modified to change with ecoregion (location).

[2] The nitrogen dynamics were modified to include increased biological fixation.

Table 3.3. Stem carbon and NPP reduced x^2 statistic and model bias by ecoregion, annual precipitation regime[a], and age group[b]. Values marked with an '*' indicate good model performance. ($x^2 < 2$). Reduced x^2 values close to 1 are within observation uncertainty.

Stem Carbon: x^2 statistics

Eco-region	CLM4 simulations					CLM4_stem simulations				
	Precipitation		Age Group			Precipitation		Age Group		
	Dry	Wet	Y	M	Total	Dry	Wet	Y	M	Total
CR	-	3	4	1^*	2	-	3	4	1^*	2
WC	3	2	14	2	2	2	<2	8	$<2^*$	$<2^*$
KM	1^*	8	2	8	7	1^*	6	1^*	6	6
EC	5	6	15	5	4	5	5	14	5	4
BM	17	6	70	17	15	3	2	14	3	2
Overall	12	4	18	8	7	4	3	7	3	3

NPP: x^2 statistics

Eco-region	CLM4 simulations					CLM4_stem simulations				
	Precipitation		Age Group			Precipitation		Age Group		
	Dry	Wet	Y	M	Total	Dry	Wet	Y	M	Total
CR	-	1^*	2	1^*	1^*	-	$<2^*$	3	1^*	$<2^*$
WC	3	1^*	8	1^*	1^*	4	1^*	6	1^*	1^*
KM	1^*	7	6	7	6	1^*	7	6	6	5
EC	2	$<2^*$	8	$<2^*$	2	3	$<2^*$	14	3	3
BM	5	3	18	5	5	2	1^*	8	2	2
Overall	4	2	7	5	3	3	2	6	4	2

Stem Carbon: Bias

Eco-region	CLM4 simulations					CLM4_stem simulations				
	Precipitation		Age Group			Precipitation		Age Group		
	Dry	Wet	Y	M	Total	Dry	Wet	Y	M	Total
CR	-	-19	32	-100	-19	-	-17	36	-100	-17
WC	13	-11	74	-40	-9	-7	-37	45	-65	-36
KM	-85	-40	3	-53	-41	-77	-51	-7	-63	-50
EC	-4	-49	20	-17	-11	-2	-48	18	-15	-9
BM	54	2	77	45	48	-4	-36	21	-11	-7
Overall	28	-17	46	-16	4	-5	-32	29	-41	-18

NPP: Bias

Eco-region	CLM4 simulations					CLM4_stem simulations				
	Precipitation		Age Group			Precipitation		Age Group		
	Dry	Wet	Y	M	Total	Dry	Wet	Y	M	Total
CR	-	-88	-88	-90	-88		13	20	-2	13
WC	93	94	79	97	96	78	55	24	62	58
KM	-221	105	22	92	85	-140	93	-4	85	81
EC	-30	-132	17	-54	-47	49	-60	87	30	35
BM	133	-66	149	104	112	17	-128	40	-6	2
Overall	69	14	19	50	43	27	25	32	29	31

[a] Dry = < 800 mm/yr, Wet = >800 mm/yr

[b] Young = < 60 years, Mature = > 60years

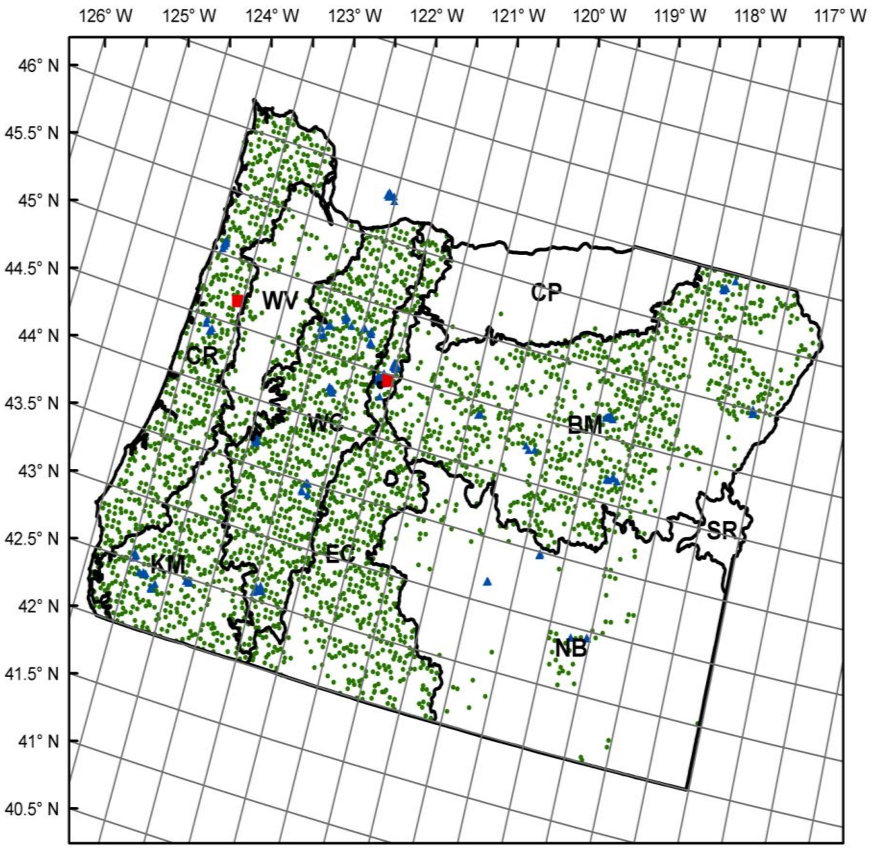

Figure 3.1. Study region area (Oregon) divided by ecoregions (BM = Blue Mountains, CR= Coast Range, CP = Columbia Plateau, EC = East Cascades, KM = Klamath Mountains, NB = Northern Basin, SR = Snake River, WC = West Cascades, WV = Willamette Valley). Green circles represent FIA plots used for evaluating annual model output, blue triangles are the supplemental plots used for parameterization, and red squares are the AmeriFlux tower sites used for seasonal validation (Campbell River site not shown).

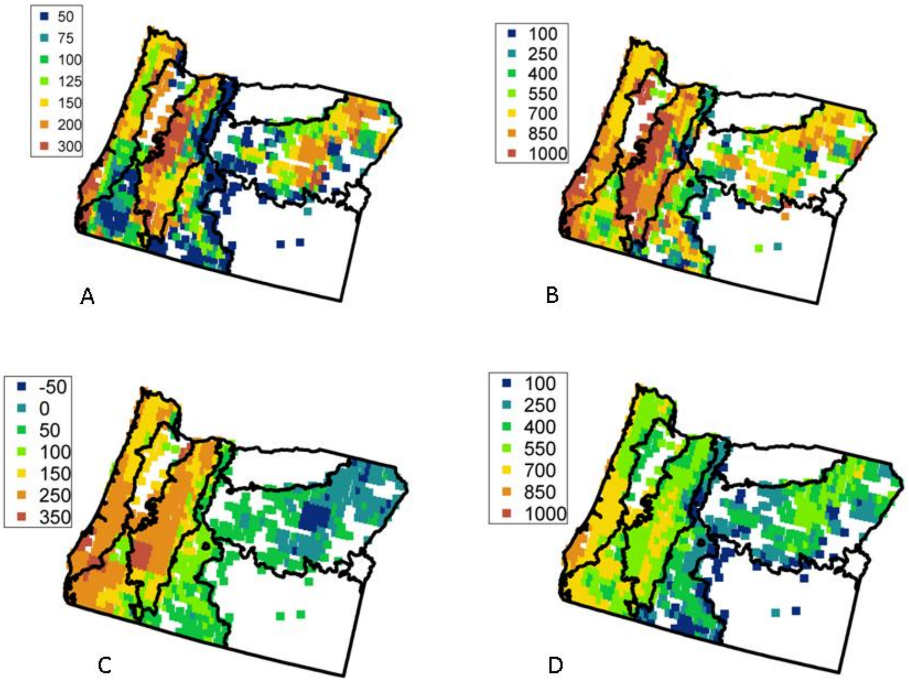

Figure 3.2: Maps of modeled CLM4_stem estimates of a) Stem Biomass, b) NPP, c) NEP, and d) heterotrophic respiration (Rh). Biomass is in units of Mg C ha^{-1} and all others are in units of g C m^{-2} yr^{-1}. Estimates are from the 'all transient' case which is representative of actual historical conditions and includes changing climate, CO_2 and nitrogen deposition levels, and land use and land cover change.

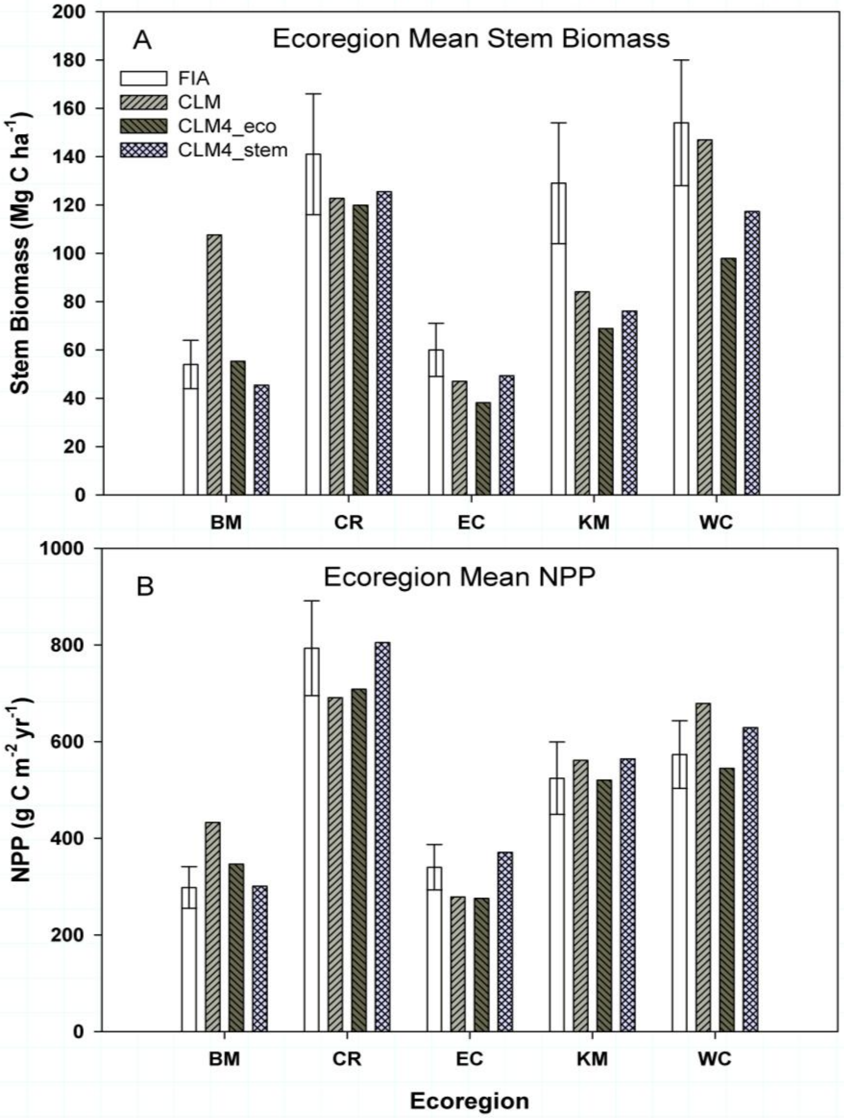

Figure 3.3: Ecoregion means of modeled and observed evergreen needleleaf (ENF) PFT values for the period from 2001-2006. The ENF biome covers 92% of the forested area in the study region. Bar plots show ecoregion ENF means and the associated observation uncertainty. a) Stem Biomass, and b) NPP. Estimates are from the ‘all transient’ case which is representative of actual historical conditions and includes changing climate, CO_2 and Nitrogen levels, and land use and land cover change.

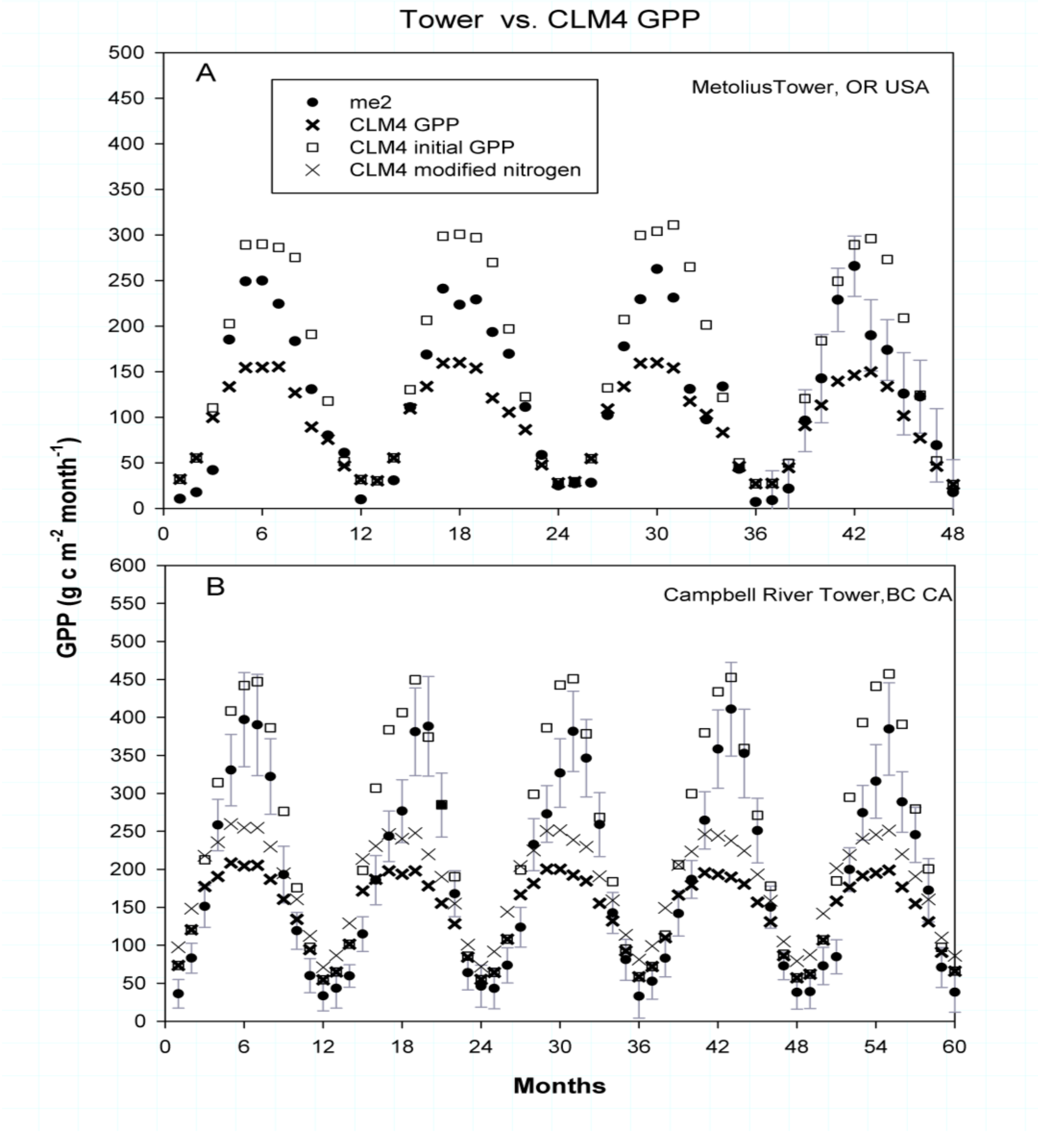

Figure 3.4: Simulated monthly GPP versus observed GPP at two FLUNET eddy-covariance tower sites in the study region. Solid circles represent tower observations, hollow squares are modeled values of GPP before downregulation due to nitrogen limitation, and thick-lined crosses are GPP after downregulation. Grey bars represent observed estimate uncertainty. (A) Metolius tower site in Oregon, USA. (B) Campbell River tower site, British Columbia, Canada. The thin lined crosses represent the model experiment where nitrogen availability was increased.

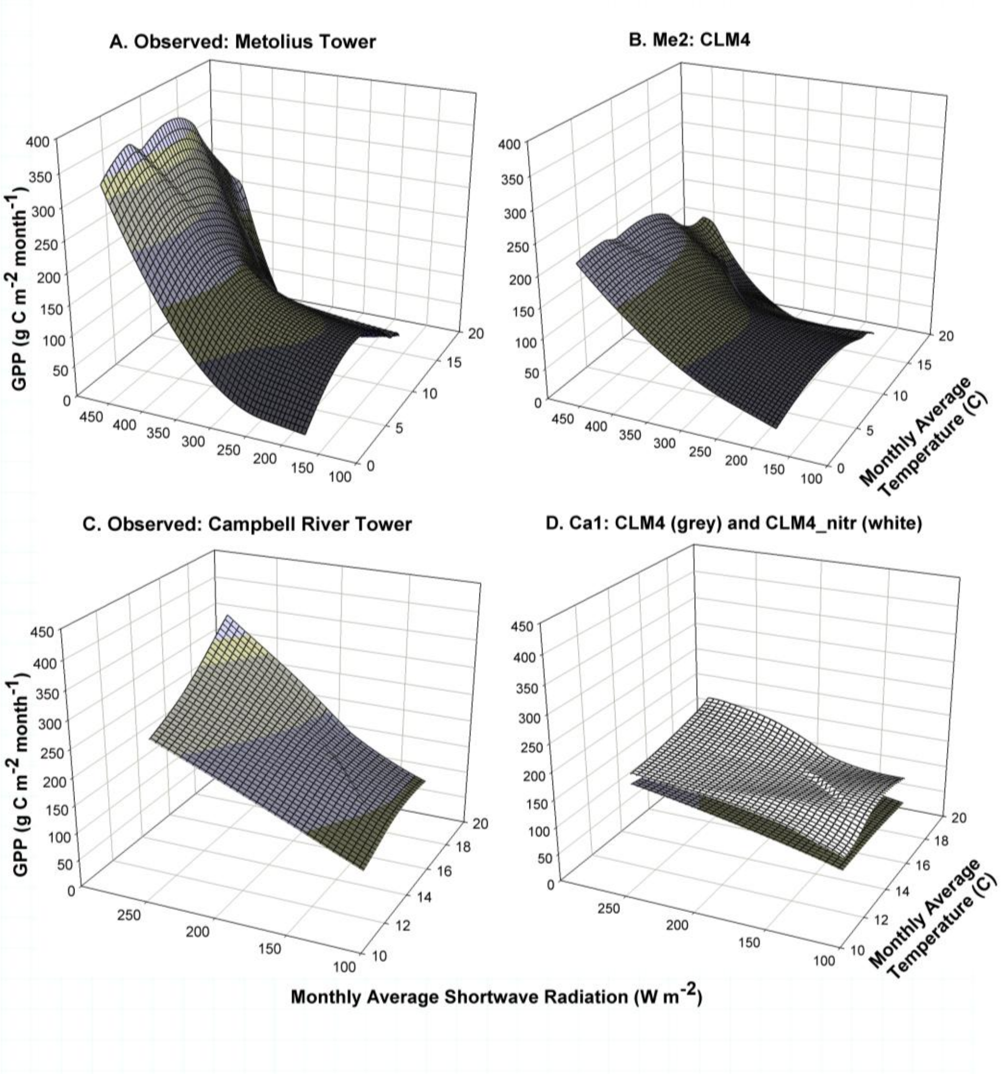

Figure 3.5: 3D surface plots of shortwave radiation versus GPP (LUE) versus monthly average temperature. (A). Observed LUE versus temperature at the Metolius site, (B) Modeled LUE versus temperature at the Metolius site, (C) Observed LUE versus temperature at the Campbell River site, and (D) Modeled LUE versus temperature at the Campbell River site for the CLM4 and the modified nitrogen availability versions of the model code.

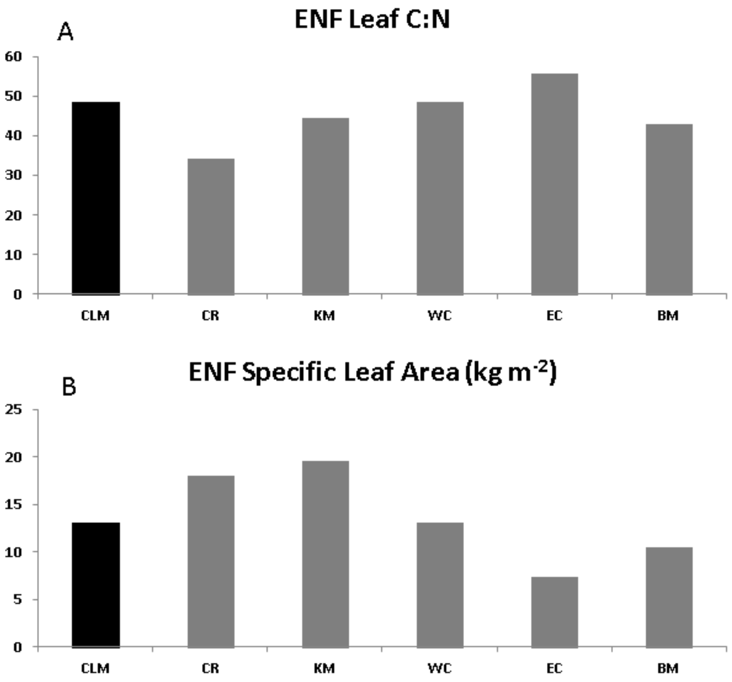

Figure 3.6: Observed values for ENF leaf carbon to nitrogen ratios (A) and specific leaf area (B) from over 100 supplemental plots in the region. Black bar represents the value used for single-value per PFT parameterizations versus the grey bars that were used for CLM_eco and CLM_stem simulations.

Chapter 4: Long-term effects of bioenergy harvest on the carbon balance of Pacific Northwest forests under changing climate and climate-related disturbance

Abstract

Bioenergy is quickly becoming an important fossil fuel replacement source because it can provide energy security, economic development, and is expected to reduce greenhouse gas emissions compared to fossil fuel use. There is continued debate about actual reductions, but recent studies indicate potential areas where CO_2 reductions may be possible where the land based carbon sink has been reduced due to increased mortality from fire, insects, and drought. Here, we examine forest carbon response and life cycle assessment (LCA) of net carbon emissions following varying combinations of bioenergy management scenarios in Pacific Northwest forests for the period from 2010-2100. We use the NCAR CLM4 model combined with a regional atmospheric forcing dataset and account for future environmental change using the moderate IPCC RCP4.5 scenario. At the end of the 21st century, predicted regional net ecosystem production (NEP) is 13.7 Tg C yr^{-1} (107 g C m^{-2} yr^{-1}) for business-as-usual (BAU) conditions compared with the current NEP of 13.2 ± 1.6 Tg (103 g C m^{-2} yr^{-1}). There is no significant influence on NEP by changing climate, nitrogen deposition, and increasing CO_2 concentrations in the long term for the moderate RCP4.5 scenario where CO_2 rises to 550 ppm by 2100. Increases in BAU net primary production (NPP) are accompanied by increases in heterotrophic respiration (R_h) from a warmer climate, resulting in no change in NEP. BAU net biome production (NBP; NEP – harvest removals and fire emissions) averages 38 ± 8 g C m^{-2} yr^{-1}, a decline compared to the current NBP for the study region of 61 ± 14 g C m^{-2} yr^{-1} (Hudiburg et al. 2011). Nitrogen deposition, precipitation, and harvest rates do not change significantly and therefore changes in predicted carbon fluxes are due to climate warming, CO_2 fertilization, and fire. Bioenergy management strategies include a repeated thinning harvest where ~35% of stand biomass was removed in fire prone areas with high stand density or productive areas with high stand density. They also include a repeated clearcut harvest where ~85% of stand biomass was removed in highly productive areas and a single salvage harvest where ~75% of biomass was removed in areas with projected

insect-related mortality. None of the bioenergy management scenarios *reduce* net emissions to the atmosphere compared to BAU by the end of the 21st century. Forest regrowth and reduced fire emissions are not large enough to balance the wood removals from harvest. Moreover, the substitution of wood for fossil fuel energy and .products is not large enough to offset the wood losses through decomposition and combustion. However, in some ecoregions (Blue Mountains and East Cascades), emissions from the thinning harvests are beginning to improve over BAU at the end of the century and could lead to net reductions over a longer time period (> 100 years). For salvage logging, there is no change compared to BAU emissions by the end of the 21st century because the treatment area is minimal compared to the other treatments and only performed once.

Introduction

Wood bioenergy in US Pacific Northwest forests is currently supplied by forest thinnings intended to improve forest health and by forest residues from current harvest. In efforts to improve forest health, create jobs, restore habitat, provide energy security, and reduce greenhouse gas emissions, new management plans have been considered or implemented to increase utilization of forest biomass for wood products and bioenergy.

Recently, there has been a growing interest in integrating wood bioenergy with rotation-based wood product harvest on industrial forestland, similar to some European countries (Routa et al. 2011). Unlike traditional harvest and thinning practices where the non-merchantable wood is slowly decomposed or burned on site, rotation-based harvest removes all of the woody biomass offsite including the residues. Consequently, the natural transfer of live wood to the woody detritus, litter, and eventually the soil carbon and nitrogen pools through mortality will be lessened, decreasing the baseline land-based carbon stocks (Mitchell et al. 2012, Schulze et al. 2012). In turn, nitrogen losses due to detritus removals may limit future carbon uptake potential. Policy and management plans based on current forest condition will influence the extent to which the forest industry utilizes harvest residues, forest thinnings, and rotation-based harvest to meet energy demands for replacement of fossil fuels intended to reduce greenhouse gas (GHG) emissions to the atmosphere.

The basic assumptions, justifying an increased harvest to supply bioenergy, are that forest bioenergy will be carbon neutral, with no additional CO_2 emissions because carbon in wood was recently removed from the atmosphere. It is also assumed to be an effective means for reducing greenhouse gas emissions because the forest will regrow new biomass to replace removed carbon and that bioenergy emits less carbon per unit of energy than fossil fuel-derived energy (Lippke et al. 2011, Malmsheimer et al. 2011). This is contrary to comprehensive studies that account for the baseline carbon sink and show an increase in emissions compared to business-as-usual management in the next several decades. The 'Manumet' study in Massachusetts found that utilizing forest biomass for bioenergy production did not provide enough carbon substitution benefits to replace the reduced forest carbon storage (Walker et al. 2010). Another study in Ontario, showed CO_2 increases for the next 16-38 years for combined heat and power (CHP) use and hundreds of year for ethanol conversion (McKechnie et al. 2011). In addition to the amount of time required for bioenergy substitutions to repay the forest carbon lost due to harvest, it can take hundreds of years for bioenergy production to substitute the amount of carbon that would be stored if the forest were left unharvested (Mitchell et al. 2012).

However, these studies did not examine the expected changes in the baseline carbon sink owing to climate change, which for the western US is predicted and observed to affect species composition (Coops and Waring 2011), lead to increased mortality from drought stress (van Mantgem et al. 2009, Breshears et al. 2008, van Mantgem et al. 2009, McDowell et al. 2010), insect outbreaks (Kurz et al. 2008, Raffa et al. 2008), and fire (Rogers et al. 2011). Forest carbon sinks will change as climate and societal demands change. The change ultimately depends on the interplay of regional conditions such as current sink strength, climate, fire regime, absence of catastrophic disturbances, etc. (Hudiburg et al. 2011, Hudiburg et al. 2009, Zhang et al. 2012).

Here, we go beyond recent studies by simulating the effects of varying bioenergy harvest scenarios on forest carbon and nitrogen dynamics and by accounting for future environmental change (climate, increasing atmospheric CO_2 and nitrogen deposition). We focus on the forests of Oregon, USA, a state characterized by a wide range of climate and productivity. We provide potential bioenergy management solutions that account for carbon and subsequent global change mitigation consequences. The specific questions we answer are:

1. What are the interactive effects of changing climate, increasing atmospheric CO_2, N deposition and land use change on net ecosystem production (NEP)?
2. How do the varying management scenarios affect carbon stocks and fluxes at different spatial scales?
3. Does bioenergy management increase or decrease net CO_2 emissions to the atmosphere compared to BAU by the end of the 21st century?
4. For which ecoregions do net CO_2 emissions decrease compared to BAU for bioenergy management?

Materials and Methods

Ecosystem models provide a means to analyze the multiple interactions of environmental change with management, simulate the effects separately and together, and evaluate the relative importance of each factor. We modeled the interactive effects of environmental change and bioenergy management using a modified version of the NCAR CLM4 model developed for use in the study region (Hudiburg et al., in prep; dissertation Chapter 3) combined with a regional atmospheric forcing dataset. The output of the NCAR CLM4 simulations contain harvested biomass that was used in an off-line LCA model to quantify the net CO_2 emissions of the bioenergy scenarios.

Model description and parameterization

The Intergovernmental Panel for Climate Change (IPCC) synthesizes estimates of future climate change impacts on terrestrial carbon cycling through the use of a specific set of nationally recognized global circulation models. Among them is the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR). The land model component (Community Land Model; CLM4) has been used to evaluate and predict the net carbon uptake and loss from terrestrial biomes, particularly forests (Thornton and Zimmermann 2007, Bonan et al. 2011) and has been scientifically validated with regional observations (Ch.3). We use a modified version of CLM4 described by Hudiburg et al., (in prep; Ch. 3) that accounts for within PFT and ecoregion variation in physiological parameters, mortality, and stem wood allocation. Regional evaluation with this model version found good model agreement in all ecoregions with historical annual net primary production data and slight underestimation of woody biomass in the highly productive ecoregions. Historical regional annual totals of NPP, NEP, and NBP were also within or very close to the observed and/or modeled range of uncertainty from inventory, tower, process model, and atmospheric inversion model estimates in the region suggesting the model should be able to make reasonable predictions about the effects of future land use change on forest carbon and nitrogen fluxes.

Through the combined use of regional climate data, physiological characteristics, and site physical attributes and history, CLM4 estimates the daily carbon, nitrogen, and water fluxes between the atmosphere and the vegetation and soils. Active model components used in this study include biogeophysics, 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. 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 land use change dataset that includes wood harvest (Lawrence et al. 2011). The transient land use dataset has been formatted for use by CLM4 from a global historical transient land use and land cover change dataset (Hurtt et al. 2006) covering the period from 1850–2005. The dataset is not a dynamic vegetation model where PFT changes occur based on climate, stress, and disturbance drivers overtime. This dataset is a prescribed human-induced disturbance history of forests which we can use to test the model’s ability to simulate carbon dynamics following clearcut or thinning harvests. We use this embedded dynamic PFT framework to implement our future land use change scenarios (described below). We use the dataset to prescribe the annual fraction of land that is transformed from one PFT to another and to prescribe the harvest rates for each PFT within a grid cell over the simulation period.

CLM4 includes PFT-specific physiological variables, a constant mortality rate for all forest PFTs, and a single stem wood allocation equation for all woody PFTs. After we evaluated historical simulations with eddy-covariance tower and forest inventory data, we modified CLM4 to enable the physiological parameters and mortality rates to vary within a PFT by ecoregion and to allow the stem wood allocation equation to vary by ecoregion (Ch.3). We use the modified version for all simulations in this study. The modifications and prescribed parameters are provided in Appendix B.

Model simulations of management scenarios

We modeled future carbon and nitrogen dynamics from 2010-2100 for the state of Oregon located in the Pacific Northwest region of the United States (Figure 4.1). Model spin-up, regional and plant functional type calibration, historical simulations and model development were completed for a separate evaluation analysis of the region. After modifications were made to CLM4 to more closely represent the ecoregion-specific variability of a single plant functional type's physiology, mortality, and allocation patterns, we found good model agreement for spatial patterns of NPP and stem biomass with inventory data (Ch 3). Modeled ecoregion means of NPP were not significantly different from observed ecoregion means (two-sided p value = 0.8) and modeled means of stem biomass fell within the observed range of uncertainty for the majority of the ecoregions with better performance in mesic ecoregions and older age classes. There was also overall good model agreement with seasonal GPP at eddy-covariance tower locations in the region (reduced x^2 statistics were close to 1, Ch 3). There was some underestimation of summer GPP (25-100 g C m^{-2} $month^{-1}$), however spring and fall values were within observation uncertainty and the timing of maximum GPP was also correct.

Pacific Northwest climate is characterized by wet springs and dry summers leading to late summer drought. Climate models predict this trend will become more enhanced with warmer and wetter winters followed by drier summers (Mote and Salathé 2010). There has been concern that overestimation of modeled springtime NPP and GPP can lead to overestimation of biomass resulting in overestimation of fire burn area and severity (Rogers et al. 2011) or drought-induced mortality. Prediction of increased fire and mortality is important for land management planning and placement of forest health treatments to reduce risk. Because CLM4 is not overestimating spring GPP, we feel the seasonal dynamics are adequate for making future predictions without the risk of overestimating fire and mortality. Based on the historical evaluation, we are also confident CLM4 is adequately representing spatial carbon biomass and production patterns in order to make predictions about changes to future carbon dynamics following the implementation of varying management scenarios.

Model simulations of the management scenarios are summarized in Table 4.2 and treatment specifications, removals, and the available treatment areas are shown in Figure 4.1 and Table 4.3. We implemented varied combinations of thinning, clearcut, salvage, and no harvest management strategies. Grid cells were identified for treatments 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 (USGS 2009), and potential insect mortality areas were identified using published maps of current insect mortality (Raffa et al. 2008) and predicted potential vulnerability of tree species to climate change (Coops and Waring 2011). Areas with low MFRI (< 40 years) and high stand density due to fire suppression 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 and capable of producing 10 Mg of merchantable wood per hectare per year. Two areas for salvage harvest following insect-related mortality were selected from the East Cascades and the Blue Mountains. These areas represent a sub-set of the current and projected forested area affected by insect-related mortality. Finally, portions of the Coast Range, Klamath Mountains, and West Cascades were selected for clearcut treatments.

Again, 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 not spatial overlap of current harvest rates with BAU conditions. For grid cells not selected, the current harvest rates (BAU) remained the same. BAU harvest rates were prescribed based on harvest since the Pacific Northwest Forest Plan was implemented in 1990.

To implement the harvest treatments, we modified the harvest rates in the dynamic land use file used by CLM4 as the prescribed wood removal rate per year. The harvest rates in CLM4 were designed for much larger grid cell sizes and actual removal rates vary from the annual harvest rate prescribed. The result is an underestimation of harvest removals. For each grid cell treated, clearcut harvests removed 80-90% of the tree biomass for a prescribed 95% harvest rate, salvage harvests removed 65-75% for a prescribed 90% harvest rate, and thinning treatments removed 30-40% for a prescribed 50% harvest rate. While these removals are lower per unit area than what is typical for clearcuts in the region and fuels reduction treatments to reduce the risk of crown fire (Campbell et al. 2012), the total biomass removals are reasonable compared to historical harvest removals. Total thinning, clearcut, and salvage treatment areas amounted to 36, 21, and 5% of total forested area in the region, respectively. Treatment years were staggered so that no more than 2% of the total forested area was treated each year to be consistent with average national and regional harvest rates and current mill capacity in the study region (Table 4.3). For the clearcut and salvage harvests, the plant functional types 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 (Campbell et al. 2009). 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, to simulate insect outbreak and mortality before salvage harvests we ran a single year where the mortality rate was set to 95% in the identified susceptible areas as described by

Edburg et al., (2011). For the No Harvest scenario, all harvest rates were set to zero. Because we include the insect-killed areas in the no harvest scenario, we were also able to calculate the net carbon balance if the dead trees are allowed to decompose versus salvage harvesting for bionenergy and wood products.

Model forcing datasets

Offline simulations of CLM4 are typically forced with the NCEP reanalysis dataset (Qian et al. 2006) provided by NCAR. While this dataset includes the required climate and forcing variables at a sub-daily timestep, the spatial resolution (~2 degrees or 200 km) is not adequate for sub-regional simulations in Oregon, where there are strong climatic and vegetation gradients. For this reason, we forced the model with a 1/8th degree regional dataset assembled by the Climate Impacts Group at the University of Washington (http://www.cses.washington.edu/data/ipccar4/). Daily gridded historical (1900-2000) and future (2000-2100) data are provided from three different models participating in the IPCC assessment reports. The regional downscaled dataset includes daily precipitation, minimum and maximum temperature, and wind speed. Because CLM4 also requires shortwave radiation and relative humidity we calculated values incorporating algorithms from DAYMET (Thornton et al. 1997) and methods for sub-daily calculations as described by (Appendix B; Göeckede et al. 2010).We chose to use the dataset that was downscaled from ECHAM A2 6 hourly simulation output as it presents the ‘middle of the road’ scenario for future projections.

The IPCC requested from the scientific communities new scenarios (representation concentration pathways; RCPs) for modeling future climate change according to the radiative forcing expected based on socioeconomic, technological, and biophysical parameters (IPCC 2007). We chose to use the RCP4.5 pathway that leads to a radiative forcing level of 4.5 W m^{-2} (approx. 550 ppm atmospheric CO_2 concentration) by the end of the century as it represents a ‘middle of the road’ scenario consistent with the climate forcing data and current harvest rates. Because atmospheric CO_2 has almost reached 400ppm already (http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html), a higher scenario (RCP8.5) may turn out to be more realistic, but we chose the moderate level to be consistent with remaining assumptions. Our BAU scenario does not include increases to current harvest rates in the region which declined on publically owned forestland in the early 1990's, but has remained relatively stable since 2000 (Turner et al. 2012). NCAR supplies half degree gridded aerosol, land cover change, and nitrogen deposition forcing datasets for future simulations according to the RCP4.5 scenario. We used the NCAR spatial interpolation tools to re-grid the datasets to our regional 1/8th degree resolution and constructed a global (single value per year) CO_2 forcing dataset per the RCP4.5 trajectory where CO_2 increases to ~550 ppm.

Life cycle assessment (LCA)

In Chapter 2 and Hudiburg et al. (2011), we developed the LCA approach to quantifying net CO_2 emissions from wood use. It is detailed in Appendix A. Net CO_2 emissions to the atmosphere are determined using life cycle assessment (LCA) of wood use. Studies have identified ranges of efficiencies and energy inputs for realistic LCAs that also consider technological advances for future wood bioenergy (e.g. Mitchell et al. 2012, Winford and Gaither Jr. In Press). 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 (Appendix A).

Life-cycle assessment of forest carbon removals includes forestry-related sinks and sources of carbon to and from the atmosphere and the associated impact on total fossil fuel emissions (FFE). For each scenario, the net flux of carbon from or to the atmosphere (net carbon emissions; Net C_e) over 90 years (2010-2100) was calculated as the difference between the sources and the sinks following this process:

Net carbon emissions (Net C_e) = NBP + Total Harvest – WD1 – WD2 – Wood Industry FFE – Bioenergy Emissions + Bioenergy Substitution + FF Well-To-Tank Emissions displacement + Wood Substitution (Eq. 1)

Where, WD1 is the wood lost during manufacturing processes, WD2 is the wood decomposed over time from product use and wood substitution is included with the assumption that there is an increased demand for wood supply. Total harvest is added back to NBP to represent the theoretical amount of wood that could be stored in a wood product or converted to bioenergy if the process was 100% efficient. The WD1 variable accounts for the wood losses because wood product conversion is not 100% efficient although up to 25% of harvest and mill residues are used internally at some processing facilities for bioenergy offsetting a portion of the losses (Lippke et al. 2011). We incorporated potential mill use of current harvest residues as part of the BAU scenario. This is different from the LCA described in Hudiburg et al. (2011) where current use of forest residues for bioenergy were not included as part of the BAU net emissions calculations. This does not reduce the WD1 term in the equation (the wood is still combusted and emissions still occur), but it increases the bioenergy substitution for fossil fuel emissions. Net C_e (net emissions from LCA equation) values are positive for carbon sinks and negative for carbon sources. In the figures and tables, 'delta Net C_e' refers to the difference between the management scenario Net C_e values and the BAU value. Net C_e can be positive in both cases, but negative 'delta Net C_e' values indicate increased emissions (or decreased uptake) compared to BAU. In other words, the sink strength is weakened.

To quantify the change in Net C_e for each scenario, we calculate the difference between each scenario and the BAU Net C_e. The physical sinks are forest net uptake (NBP) and wood products (Harvest) and the added virtual sinks of bioenergy and wood product substitution (FF Substitution). We exclude imports and exports from the study region since we are only interested in quantifying domestic wood production emissions and exports are less than 1% of harvested merchantable wood (http://www.fs.fed.us/pnw/ppet/). FFE and 'Emissions' variables in the equation include release of carbon from woody biomass combustion and FFE associated with harvest (Sonne 2006), transport of both harvested material and end-use products (Evans and Finkral 2009, Heath et al. 2010), and processing and manufacturing of wood products (Heath et al. 2010) and bioenergy (Winford and Gaither Jr. In Press). 'Decomposition' includes loss of material through decomposition or combustion during the manufacturing of wood products (Smith et al. 2006), and the percentage of wood products that are expected to no longer be in-use at the end of the treatment period (Smith et al. 2006).

Biomass utilized for wood products can end up in a long term storage product (structural wood) or a short term product (paper). Some wood product carbon reenters the atmosphere through rapid (paper) or slow (wood) decomposition or combustion while some is eventually disposed in landfills where it is very slowly decomposed. West Coast harvests generate merchantable bole wood at rates of 50-60% of the total wood harvested (Harmon et al. 1996) and decay at a net rate of 1% per year (Harmon and Marks 2002, Smith et al. 2006) after accounting for the portion stored in landfills. Using values provided by (Smith et al. 2006), we determined the amounts of long and short term wood products that could be generated by the merchantable wood harvested accounting for the losses along the way using the net decay rate. The remaining non-merchantable wood from harvest was used for combined heat and power (CHP) bioenergy. We also accounted for the associated emissions for both conversion to wood chips and the combustion emissions.

Fossil fuel substitution with bioenergy was calculated as biomass combustion for CHP compared to fossil fuel sources. Woody biomass provides less energy per unit of carbon emitted than fossil fuels (i.e. wood has an energy content of 20 GJ per ton versus 35.5 GJ per ton in coal and 58 GJ per ton in natural gas) because fossil fuels have a lower heating value (Wright et al. 2006). The conversion efficiency of biomass to CHP compared to the reference fossil fuel source ranges from 20-80% depending on the power plant and the fossil fuel source being replaced (Mitchell et al. 2012). The US average conversion efficiency is 51% given a combination of low to highly efficient plants and the US mix of fossil fuel CHP production (coal, natural gas and petroleum/oil). State annual fossil fuel emissions, energy sources, and consumption were acquired from the Oregon Department of Energy (http://www.oregon.gov/energy/pages/oregons_electric_power_mix.aspx). The Oregon average conversion efficiency given the state energy mix is very close to the US average at 50%. This was also an improvement over the LCA used in Hudiburg et al. (2011) where the fossil fuel source replaced was petroleum/oil only.

There are also emissions associated with crude extraction and manufacturing, sometimes called the wells-to-tank emissions (WTT). Fossil fuel LCA total emissions (wells to wheels; WTW) include both WTT and tank-to-wheels (TTW) emissions. The amount of carbon emitted per unit of fossil fuel energy varies widely by source fuel, but average WTT emissions are approximately 15% (ICCT 2010) of total emissions (WTW), or 12 g CO_2 per MJ of energy. We have included these emissions in the Wood Industry FFE and we have added a WTT displacement benefit along with the bioenergy substitution benefit.

Finally, we add potential wood product substitution benefits for replacement of fossil fuel derived products. Wood product substitution for a 50/50 mix of aluminum and steel used in residential American housing generates a 36% reduction in fossil fuel emissions (Upton et al. 2008) and 26% for concrete (Lippke et al. 2010). We assumed these rates will continue into the future for new residential housing and applied a 36% wood substitution benefit of the final structural wood product pool to represent optimal substitution rates.

Results and Discussion

What are the interactive effects of changing climate, increasing atmospheric CO_2, and land use change on net ecosystem production (NEP)?

At the end of the 21st century, predicted regional mean annual air temperature is 11.5 °C, an increase of 3.5 °C over the mean annual temperature in 2010 (Figure 4.2a). Annual precipitation averages 1050 mm in the last five years of the century, increasing only 25 mm over early century averages. However, the predicted precipitation patterns vary by ecoregion with a decline in precipitation of about 40 mm yr^{-1} in the mesic Coast Range, West Cascades, and Klamath Mountains versus a 115 mm yr^{-1} increase in the drier East Cascades and Blue Mountains. Interannual variability in precipitation is high for the entire simulation period. Seasonal variation of precipitation on monthly GPP revealed slightly increased GPP in summers following wet winters in the semi-arid Blue Mountains and East Cascades, but no change in the mesic ecoregions (Appendix B Figure B6).

Regional relative humidity remains constant overtime (Appendix B, Figure B5). Predicted atmospheric CO_2 concentrations are 550 ppm and nitrogen deposition varies from 2.2 kg N ha^{-1} yr^{-1} in the Coast Range, West Cascades, and Klamath Mountains to 3.3 kg N ha^{-1} yr^{-1} in the East Cascades and Blue Mountains. This is a change of < 1 kg N ha^{-1} yr^{-1} for the study region and it is less than typical values for temperate forests receiving high levels of nitrogen deposition from industrial and agricultural sources (> 5.5 kg N ha^{-1} yr^{-1}; Janssens et al. 2010).

Predicted regional net ecosystem production (NEP) in 2100 is 13.7 Tg C yr^{-1} (107 g C m^{-2} yr^{-1}) for BAU conditions compared with the current NEP of 13.2 ± 1.6 (103 g C m^{-2} yr^{-1}) indicating that the effects of changing climate, nitrogen deposition, and increasing CO_2 concentrations offset each other after the 90 year period (bright green line scenario in Figure 4.2 and Table 4.4). Nitrogen deposition, precipitation patterns, and relative humidity do not change significantly and therefore changes in predicted carbon fluxes are due to climate warming ((Figure 4.2a), CO_2 fertilization, and/or disturbance. Increases in BAU NPP (Figure 4.2b) are accompanied by increases to heterotrophic respiration (R_h), resulting in no change in NEP (Figure 4.2c).

The modeled response to warming and rising CO_2 is not surprising and is in line with previous work (Thornton et al. 2009). Net carbon uptake has been shown to increase in response to elevated CO_2 concentrations in laboratory-grown tree seedlings (Curtis and Wang 1998) and experiments on whole forest canopies (DeLucia et al. 2005). Warming has been shown to increase decomposition which increases nitrogen mineralization, followed by increases in NPP. However, eventually nitrogen availability limits carbon assimilation (Thornton et al. 2007). Predicted soil mineral nitrogen is maintained for the first 40-50 years and then declines (Figure 4.2d). Finally, a simulation where only climate was allowed to vary (black lines in Figure 4.2), shows increases in NPP followed by decline, but R_h only increases over time. In Pacific Northwest forests, our results support the hypothesis that increases in NPP and R_h due to climate warming are enhanced by CO_2 fertilization and warming until nitrogen limitation occurs and carbon uptake declines following a peak in 2030 and then drops below its current value (Fig 4.2c, red line).

As expected, the thinning and clearcut strategies that increase harvest compared to BAU, result in consistently higher regional NEP (Figure 4.4) although they follow the same general pattern as BAU over time (Figure 4.3). This is primarily due to reductions in heterotrophic respiration (R_h) because of a declining woody detritus pool creating an imbalance between NPP and R_h (Figure 4.3). The predicted decline in R_h compared to BAU is due to decreases in decomposable material (i.e. woody detritus; Table 4.4) because the bioenergy harvests remove harvest residues that would have otherwise decomposed onsite and reduce inputs to the woody detritus pool by removing a portion of the standing biomass. However, the wood removed is either combusted, stored in a wood product, or decomposed offsite adding to carbon emissions in the life cycle assessment.

NBP averages 5.5 Tg C yr^{-1} (38 ± 8 g C m^{-2} yr^{-1}) under a BAU management scenario that maintains present harvest rates over the next 90 years. NBP declines from an average of 6.2 Tg C yr^{-1} in the first half of the century to 4.5 Tg C yr^{-1} in the last part of the century. NBP changes with increases or decreases to NEP, fire, or harvest. For the BAU scenario, we find no significant change to NEP over time and harvest rates are purposely held constant. However, projected burn area doubles by the end of the century increasing fire emissions from an average of 2.5 to 3.5 Tg C yr^{-1} (Appendix B, Figure B4) compensating for most of the decline in NBP. Historical comparisons of CLM4 simulated burn area (Appendix B, Figure B3) with other datasets (MTBS; Eidenshink, J. et al. 2007 and GFED; van der Werf, G. et al. 2010) show both over- and underestimation by CLM4. The Global Fire Emissions database (GFED) underestimated burn area by 15% for the Oregon Biscuit fire in 2002 and was consistently the lowest burn area estimate compared other models in a synthesis done by French et al. (2011). However, the predicted increase in burn area over the 21st century is consistent with other studies (Rogers et al. 2011, Westerling et al. 2006).

The majority of the management scenarios cause NBP to decline by 2- 4 Tg C yr^{-1} because harvest is increased removing more wood compared to BAU. For the treatments intended to prevent fire-related emissions, the reduction in predicted fire emissions is not enough to compensate for the harvest losses (Figure 4.4). The overall increases in treatment NEP compared to BAU (Table 4.4) are not sufficiently large enough to balance the wood removals from harvest, although some of these losses are recouped offsite in wood products and substitution of fossil fuels with bioenergy. The state level results indicate that the effects of changing climate, nitrogen deposition, and increasing CO_2 concentrations offset each other after the 90 year period, resulting in nearly equal NEP at the beginning and end of the 21st century for BAU conditions. For BAU management where harvest rates are held constant, statewide NBP still declines over the 90 year period compared to the first part of the century. This is primarily due to increased fire emissions from an increase in predicted burn area by CLM4 consistent with other studies. The only scenario that does not reduce NBP is the No Harvest scenario where NBP increased by approximately 4 Tg C yr^{-1} (30 g C m^{-2} yr^{-1}) despite increases in fire because harvest removals are stopped.

The thinning and clearcut bioenergy scenarios result in increased NEP compared to BAU at the end of the 21st century because of a decline in heterotrophic respiration (R_h). The decline in R_h is most likely due to a decreasing woody detritus pool because bioenergy management removes the harvest residues that would otherwise decompose onsite. However, NBP is still reduced for the bioenergy management scenarios compared to BAU emphasizing that the increase in NEP and treatment reductions in predicted fire emissions do not compensate for the wood removals. The opposite is true for the No Harvest scenario where NBP and total forest carbon are increased despite a decline in NEP and increase in fire emissions.

How do the varying management scenarios affect carbon stocks and fluxes at different spatial scales?

For all ecoregions, NPP generally decreased for several years following the bioenergy management scenarios compared to BAU. NPP recovered between 5 – 30 years following each treatment depending on the intensity of the harvest (thinning vs. clearcut) and the ecoregion where the treatment was performed. Recovery times were generally longer for both the first thinning and the first clearcut treatments because more biomass was available for removal. Subsequent removals were less because aboveground stem biomass had not fully recovered to BAU levels (Figure 4.4e-4.8e), resulting in less biomass available for harvest (Figure 4.4f-4.8f). This is consistent with research in Pacific Northwest showing a decline in baseline carbon stocks over time with either increased harvest removals or decreased rotation time (Harmon and Marks 2002).

A study of a thinning chronosequence in a mixed conifer forest of the Sierra Nevada region of California found stand level NPP recovery rates of about 80% for shrubs and trees combined and almost complete recovery of NEP after 16 years, with shrubs compensating for lost NPP due to thinning (Campbell et al. 2009). Modeled shrub NPP increased following the thinning treatments as expected because the transfer of tree NPP to shrub NPP was prescribed in the simulations by transferring a percentage of the grid cell from the tree PFT to the shrub PFT in the dynamic PFT input file. Shrub NPP declined as the percentage was slowly transferred back to the tree PFT in accordance with the observed data.

Simulated recovery after clearcut management was followed by increases in NPP compared to BAU, as expected, from a combination of the positive effect of climate and CO_2 fertilization and young stand development following harvest in the more productive ecoregions (Coast Range and Klamath Mountains; Figure 4.5a and 4.7a) and salvage logging management in the insect-kill areas (Figure 4.4a and 4.6a). Thinning treatments are known to increase the biomass production of remaining individuals, but have little to no effect on stand level NPP because ultimately site resources limit total production (Law et al. 2012), i.e. the Law of Constant Final Yield. We found this to be true in the East Cascade thinning treatments where NPP following the first thinning harvest returned to BAU levels after 30 years and did not appreciably surpass BAU. The increases beyond BAU NPP in the latter thinning treatments are associated with the regional climate and CO_2 fertilization trends. This was not the case in the Blue Mountains where NPP in the thinning treatment exceeds BAU NPP following each disturbance. Although, there was no change in regional mean annual precipitation, precipitation in the Blue Mountains increased by 130 mm by the end of the study period suggesting that drought stress impacts on NPP were alleviated by the additional precipitation. There is some evidence from other studies that thinning relief of drought stress could result in higher stand level NPP (McDowell et al. 2003, Kolb et al. 2007).

There is an increasing trend in NEP and NBP over time compared to BAU for the thinning and clearcut bioenergy management scenarios in the Blue Mountains and East Cascades. Reasons for this again include the positive effects of CO_2 and warming, but also because of a decline in R_h due to declines in detritus pools because of removals for bioenergy use. Since NEP is the balance between NPP and R_h, as respiration declines without concurrent declines in NPP, NEP increases in all management scenarios compared to BAU. Another reason for increases in NBP overtime is the decline in subsequent harvest removals (Figures 4f-8f) following the initial harvest. Prescribed harvest rates were the same for each harvest (~85% of stem biomass for clearcuts and ~35% of stem biomass for thinning), however because stem biomass carbon had not recovered to initial conditions before the second treatment, harvest removals declined. This is important because the rotation lengths will be determined by both fire prevention measures and wood supply demands for products and energy. The rotation lengths suggested here are sustainable over time and under this climate projection and CO_2 scenario, as indicated by the recovery of NBP. However, the initial carbon debt will take longer to recoup because the carbon lost in the first treatment is not fully re-sequestered in forest biomass over the next century.

In summary, the ecoregion trends in R_h and NEP are similar to the statewide results for the management scenarios, R_h declines and NEP increases. NPP is increased above BAU in the Blue Mountains for the thinning scenario, as did precipitation, suggesting Blue Mountain NPP was limited by drought stress. NBP declines compared to BAU over the 90 year period for each of the bioenergy scenarios, but the recovery rates vary by harvest intensity. 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 an increase in NBP compared to BAU at the end of the 21st century.

Does bioenergy management increase or decrease net CO_2 emissions to the atmosphere compared to BAU by the end of the 21st century? Where do net CO_2 emissions decrease compared to BAU for bioenergy management?

After complete life cycle assessment of the removed wood, we find that none of the bioenergy management scenarios *reduce* emissions to the atmosphere by the end of the 21st century. Overall, the more intensive thinning and clearcut scenarios increase state-wide emissions to the atmosphere compared to BAU over the 90 year period whereas the less intensive salvage logging scenario results in no change.

The bioenergy management scenarios increase landscape level net CO_2 emissions (Net C_e in equation 1 is decreased) to the atmosphere over the next century compared to BAU, especially in the Coast Range and West Cascades (Figure 4.9) compared to BAU. The No Harvest scenario is the only scenario that significantly decreased overall emissions by 2100 except for in the Klamath Mountains. For the No Harvest scenario, Net C_e is equivalent to NBP because there are no associated wood product or bioenergy emissions or substitutions. In the Coast Range and West Cascades ecoregions, the decline in harvest rates between BAU and No Harvest result in large increases in NBP compared to BAU and the offsite wood product sinks and bioenergy substitutions are not large enough to compensate for the difference. However this is not the case in the Klamath Mountains where a relatively small BAU harvest exits; the small harvest rate combined with offsite wood product and bioenergy substitutions amounts to lower carbon emissions for BAU compared to a No Harvest scenario with no offsite wood product sink or bioenergy substitutions. These results suggest that for the Klamath Mountains, there exist specific combinations of harvest, wood products, and bioenergy management that reduce emissions compared to management plans with no harvest at all. However, at the state-level, a No Harvest scenario results in overall emissions reductions despite the increase in the Klamath Mountains.

Given the simulated extent and low intensity, salvage harvesting has almost no significant effect on emissions in the treated ecoregions and at the state level, indicating this management strategy is an acceptable bioenergy management strategy from an emissions perspective as long as this low intensity of salvage is applied. Simulated salvage harvests are small, not repeated, and the combined increase in NEP (reduced R_h) and offsite sinks and substitutions *do* compensate for the harvest losses in this experiment overtime. In reality, for those regions where insect- and disease-related mortality are occurring or predicted to increase, the salvage logging treatment would probably have to be repeated after forest regrowth and subsequent mortality. This would change the salvage logging treatment impact and increase the amount of time required to reduce emissions. However, these results do support the hypothesis that bioenergy management should target those areas already experiencing large decrease in net carbon uptake.For the west coast region, net uptake would have to decline by 40% for short-term emissions reductions, but by as little as 10-15% in the Blue Mountains and East Cascades (Hudiburg et al. 2011; Ch. 2).

In the Blue Mountains, the thinning scenario decreases net emissions (positive values for Net C_e) compared to BAU at the end of the 21st century, indicating the long-term effects of bioenergy management combined with environmental change will decrease CO_2 emissions to the atmosphere. The Blue Mountains are a semi-arid ecoregion where productivity is much lower than the mesic ecoregions. However it takes nearly 60 years for the Net C_e trend to become mostly positive, primarily because of the subsequent thinning removals. This trend is not as evident in the East Cascades (Figure 4.13a) and West Cascades (Figure 4.15a) where the change in Net C_e does not become positive until after the second thinning rotation (Figure 4.13b and Figure 4.15b). These results suggest that it will take longer in both the East and West Cascades to realize overall net reductions in CO_2 emissions, however the amount of time cannot be determined because is it longer than the simulation period.

Net carbon emissions in the clearcut scenario are increased in the Coast Range and Klamath Mountains (Figure 4.12a and 4.14a) for about 35 years after the first clearcut, with less impact after the second harvest because the second harvest is smaller.

Net C_e in the No Harvest scenario is greater than BAU for the majority of the simulation period for the three mesic ecoregions resulting in less cumulative emissions compared to BAU after 90 years, except in the Klamath Mountains. The reason for the increase in the Coast Range and West Cascades is because of reduced harvest compared to BAU. However, Net C_e declines (Figure 4.12b, 4.14b, and 4.15b) and is no longer reducing CO_2 emissions compared to BAU after 50 – 60 years in the three mesic ecoregions. NEP declines over time for these ecoregions in the No Harvest scenario because of increases in R_h and eventually the reductions in harvest do not compensate for the reductions in NEP. However, there is evidence that NEP can remain positive (Luyssaert et al. 2008) in old-growth temperate forests and with no harvest or large increases in fire, Net C_u would also remain positive in the absence of catastrophic disturbance.

Overall, the more intensive thinning and clearcut scenarios increase state-wide emissions to the atmosphere compared to BAU over the 90 year period whereas the less intensive salvage logging scenario does not. In the semi-arid Blue Mountains ecoregion, net uptake is greater than BAU *at the end* of the 21st century indicating the long-term effects of bioenergy management combined with environmental change will decrease CO_2 emissions to the atmosphere. In all ecoregions except for the Klamath Mountains, the No Harvest scenario reduced CO_2 emissions compared to BAU over the 90 year period. In the Klamath Mountains, small BAU harvest rates combined with offsite wood product and bioenergy substitutions amounted to lower carbon emissions for BAU compared to a No Harvest scenario with no offsite wood product sink or bioenergy substitutions. These results suggest that for the Klamath Mountains, there exists a specific combination of harvest, wood products, and bioenergy management that reduce emissions compared to management plans with no harvest at all.

Conclusions

At the end of the 21st century, predicted regional net ecosystem production (BAU NEP) does not change compared with the current NEP indicating compensating effects of changing climate, nitrogen deposition, and increasing CO_2 concentrations over the next 90 years. In other words, statewide rates of net carbon uptake under business-as-usual conditions are not reduced compared to current conditions. Despite no change to NEP or harvest rates, BAU NBP still declines by ~2 Tg C yr^{-1} by the end of the 21st century, primarily due to increases in fire emissions and fire related mortality predicted by CLM4 under future climate conditions.

Implementation of bioenergy management strategies that increase harvest compared to BAU (thinning and clearcut scenarios), do not result in net reductions to carbon emissions over the next 90 years despite inclusion of *all* wood product and bioenergy substitutions. 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 from product acquisition, conversion, decomposition, and combustion for energy by the end of the 21st century.

The dominant trend at the regional level varies at different spatial resolutions and in some ecoregions (Blue Mountains and East Cascades), net carbon uptake is beginning to improve over BAU at the end of the 90 year period suggesting bioenergy management could lead to net reductions over a longer time period (> 100 years). If the bioenergy treatments were only implemented in these two ecoregions total state-wide emissions would still increase by 10 Tg C by the end of the 21st century compared to 140 Tg C if all ecoregions are treated. Salvage logging has almost no significant effect on emissions in the treated ecoregions and at the state level, however the salvage logging treatments are small compared to the other treatments (<4% increase in removals compared to BAU harvest). Finally, in the Klamath Mountains, there is evidence that the current level of harvest, wood products, and bioenergy management reduces emissions compared to management plans with no harvest at all.

Longer simulations and better fire and insect related mortality prediction will be required to identify areas where long term bioenergy management strategies will be most effective. Also, the simulations do not include a mechanism for PFTs to change overtime (i.e. dynamic vegetation model) due to stress caused by disturbance factors such as insects, disease and fire or drought. Also, the annual scenario harvest rates presented here are not necessarily reflective of industry operations, which would require a steady supply of wood over space and time. Current mill capacity in Oregon is capable of processing the suggested harvest increases in merchantable wood, but there are only a few wood biomass CHP facilities in operation in Oregon although construction is planned for more (Siemers 2011). Finally, inclusion of carbon removals in runoff and flood events (DOC; dissolved organic carbon) also needs to be incorporated in the CLM4 carbon budget as they can increase by 50-200% in the years following harvest (Morris 2009).

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, none of the scenarios reduce CO_2 emissions and there is only one treatment where bioenergy management results in no change in emissions. This is another example of "slow in and fast out" where consumption (increased emissions from bioenergy) exceeds growth (Schultz et al. 2012). In other words, forest carbon that took decades to centuries to accumulate is rapidly lost to the atmosphere through harvest for bioenergy.

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Table 4.1. Ecoregion characteristics including forested area, mean stand ages by ownership, dominant forest types, mean annual precipitation (MAP), mean annual temperature (MAT), and proposed bioenergy management scenarios. Ecoregions are listed from high to low MAP.

Ecoregion	**Forest Hectares (% total)**	**Stand Age Private/public**	**Dominant Forest Types**	**MAP (mm yr^{-1})**	**MAT (C°)**	**Proposed Bioenergy Management**
Coast Range (CR)	2043332 (17)	34 / 75	Douglas-fir, Sitka Spruce, Redwood, Western Red Cedar, Fir-hemlock	1742	11.0	45 year clearcut rotations on non-reserved secondary forestland
West Cascades (WC)	2693263 (22)	50 / 140	Douglas-fir, Hemlock, Mixed Conifer, Red Fir, Western Red Cedar	1688	8.8	45 year clearcut rotations on non-reserved secondary forestland ; 30 year thinning rotations in high density stands
Klamath Mountains (KM)	1302111 (11)	59 / 106	Mixed Conifer, Mixed Evergreen, Red Fir, Douglas-fir, Riparian, Oak	1549	11.5	45 year clearcut rotations on non-reserved secondary forestland
Willamette Valley (WV)	501793 (4)	43 / 61	Douglas-fir, Hemlock, Riparian	1280	11.0	None
East Cascades (EC)	2099866 (17)	64 / 94	Ponderosa Pine, Mixed Conifer, Juniper, Pine, Red Fir	630	9.1	30 year thinning rotations on high fire return interval forestland; Salvage harvest of insect-killed forests
Blue Mountains (BM)	3364151 (27)	71 /100	Mixed Conifer, Ponderosa Pine, Juniper, Spruce-Fir	552	7.3	30 year thinning rotations on high fire return interval forestland; Salvage harvest of insect-killed forests
Columbia Plateau (CP)	88922 (<1)	80 / 47	Mixed Conifer, Ponderosa Pine, Riparian	330	9.7	None
Northern Basin (NB)	253690 (2)	80 / 130	Juniper, Aspen, Pinyon-Juniper, Ponderosa Pine, Mountain Mahogany	304	9.7	None

Table 4.2. CLM4 future simulations for control, baseline, and bioenergy management scenarios. Transient CO_2, nitrogen deposition (Ndep), and land cover files are annual files covering the period from 2010-2100. Ndep and land cover are spatially interpolated using the CLM toolkit from a half-degree global dataset while the CO_2 file is a single value for the entire region which changes annually according to the IPCC representative concentration pathway RCP4.5.

Name	**Description**	**Climate**	**CO_2 / Ndep**	**Land Cover**	**Harvest Rate (%)**	**Insect Mortality**	**Fire**
Baseline							
BAU	Business-as-Usual	2010-2100	rcp 4.5	rcp 4.5	BAU	Yes	Yes
NO_HARV	No harvest	2010-2100	rcp 4.5	2000	None	Yes	Yes
Bioenergy Management							
THIN	Thin at risk forests	2010-2100	rcp 4.5	rcp 4.5	50	No	Yes
SALV	Salvage dead	2010-2100	rcp 4.5	rcp 4.5	90	Yes	Yes
CC	Clearcut secondary mesic forests	2010-2100	rcp 4.5	rcp 4.5	100	No	Yes
TS	Thin + salvage	2010-2100	rcp 4.5	rcp 4.5	50, 90	Yes	Yes
TSC	Thin + salvage + clearcut	2010-2100	rcp 4.5	rcp 4.5	50, 90, 100	Yes	Yes
Control							
CLIM	Vary climate	2010-2100	constant*	constant	none	No	No
CLIM_CN	Vary climate, CO_2, Ndep	2010-2100	rcp 4.5**	constant	none	No	No

* constant level is based on the value from the year 2000

** RCP4.5 refers to the IPPCC representative concentration pathway where CO_2 rises to 550ppm by the end of the century

Table 4.3. Ecoregion forested hectares percent of total study region forested area, mean stand ages by ownership, dominant forest types, mean annual precipitation (MAP), mean annual temperature (MAT), and proposed bioenergy management scenarios.

Simulated Management Strategy	Description	Proposed treatable area (hectares)	Forest area treated (%)	Harvest Rate (%), Actual Removal (%)	Restrictions
No Harvest	BAU harvest is stopped. This strategy allows for determination of the potential carbon uptake and storage in the absence of harvest.	12,800,000	0	0	none
Salvage	Single harvest of biomass from an area susceptible to insect-related mortality. This scenario is hypothetical and intended to test the difference between allowing insect-killed trees to decompose on the land versus using the biomass for products and energy.	596,026	0.7 to 1.4 % per year	90%, ~65	Non-reserved forestland, no roadless area
Thin	Three 30 year thinning rotations. Areas with a mean fire return interval of < 40 years and a portion of the West Cascades were selected. This scenario is intended to test the effectiveness of fire emissions reduction while producing a continuous supply of bioenergy biomass.	4578689	1.5 to 1.7 % per year	50%, ~35%	Non-reserved forestland, no roadless area, current stand densities must be > 300 trees per hectare
Clearcut	Two 45 year clearcut rotations from productive ecoregions with historical clearcut history and forestland capable of 10 Mg of merchantable wood per hectare per year	2642941	0.1 to 0.8 % per year	95%, ~85	Non-reserved, no roadless areas
Thin + Salvage	Application of both Thin and Salvage scenarios above	5174715	1 to 2% per year	50%, ~35 90%, ~65	Same as above for both
Thin + Clearcut + Salvage	Application of both Thin and Clearcut scenarios above	7817656	1 to 2% per year	50%, ~35 95%, ~85 90%, ~65	Same as above for all three

Table 4.4. Business-as-Usual (BAU) regional carbon stocks and fluxes and soil mineralized nitrogen (Smin) summed over the treatment period (90 years) and the difference compared to BAU for each of the management scenarios. Positive numbers indicate increases over BAU values and negative numbers indicate decreases. A '±' symbol indicates estimate uncertainty where available.

Carbon stocks

Scenario	Wood (Tg C)	Soil (Tg C)	CWD (Tg C)	Leaf C (Tg C)	Lit C (Tg C)	Tot C (Tg C)	Smin (Tg N)
BAU (BAU)	1436	998	199	55.5	19.8	2709	0.078
Climate (CLIM)	73	2	22	-7	-1	89	0.058
Climate + CN (CLMCN)	336	10	20	0	1	367	0.078
Salvage (SALV)	-1	-1	0	0	0	-2	0.078
Thin (THIN)	-214	-14	-19	-2	0	-249	0.083
Clearcut (CC)	-174	-13	-21	0	-1	-208	0.085
Thin + Salvage (TS)	-215	-15	-20	-2	-1	-252	0.083
Thin + Salvage + Clearcut (TSC)	-436	-5	-24	-7	-1	-473	0.090
No harvest (NOHARV)	336	10	20	0	1	367	0.078

Carbon fluxes

Scenario	NPP (Tg C)	AgNPP (TgC)	R_h (Tg C)	NEP (Tg C)	Fire (Tg C)	Harvest (Tg C)	NBP (Tg C)
BAU (BAU)	5568	3504	4311	1257 ± 138	264	524	469 ± 103
Climate (CLIM)	-578	-381	-170	-409	30	-472	33
Climate + CN (CLMCN)	-66	-39	20	-86	30	-472	356
Salvage (SALV)	2	4	-13	15	4	48	-37
Thin (THIN)	-67	-41	-102	35	-14	208	-160
Clearcut (CC)	26	19	-72	98	-19	339	-212
Thin + Salvage (TS)	-62	-38	-129	67	-14	267	-187
Thin + Salvage + Clearcut (TSC)	5	-1	-137	142	-37	550	-372
No harvest (NOHARV)	-62	-42	47	-109	25	-472	390

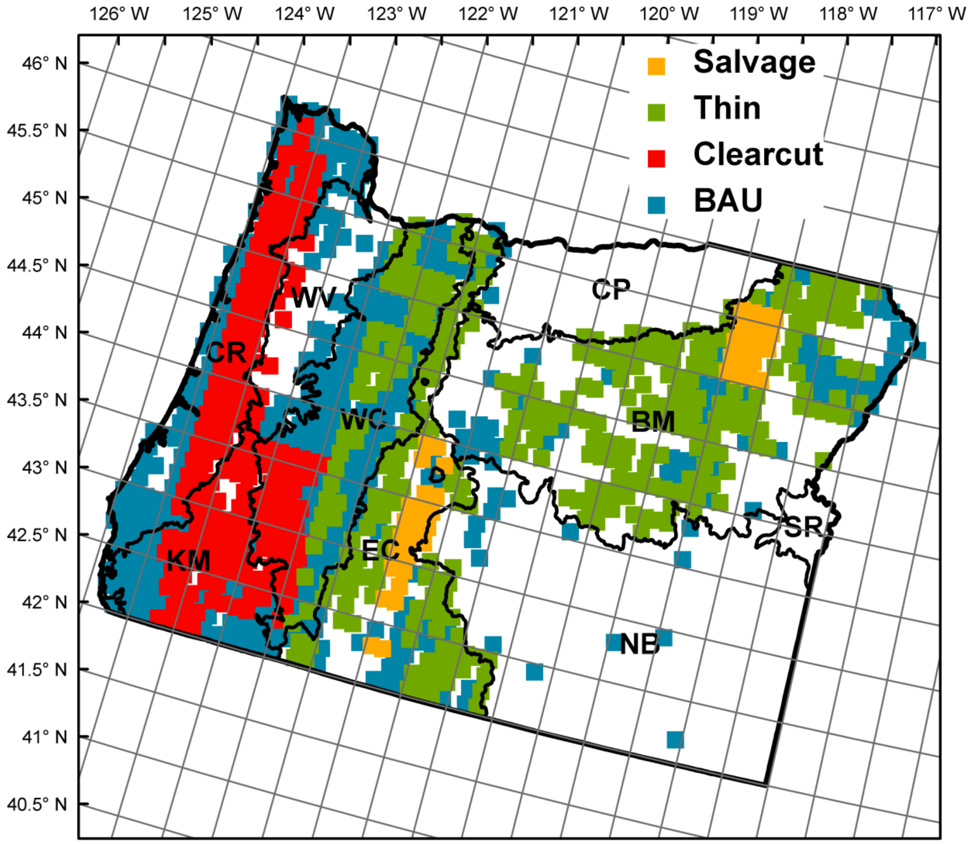

Figure 4.1. Study region area (Oregon, USA) divided by ecoregions and coded according to potential management plans (BM = Blue Mountains, CR= Coast Range, CP = Columbia Plateau, EC = East Cascades, KM = Klamath Mountains, NB = Northern Basin, SR = Snake River, WC = West Cascades, WV = Willamette Valley). Blue areas indicate no treatment change to BAU, green areas indicate thinning, orange areas are salvaged, and red areas are clearcut harvest. Old-growth reserves were excluded from any proposed harvest in the analysis.

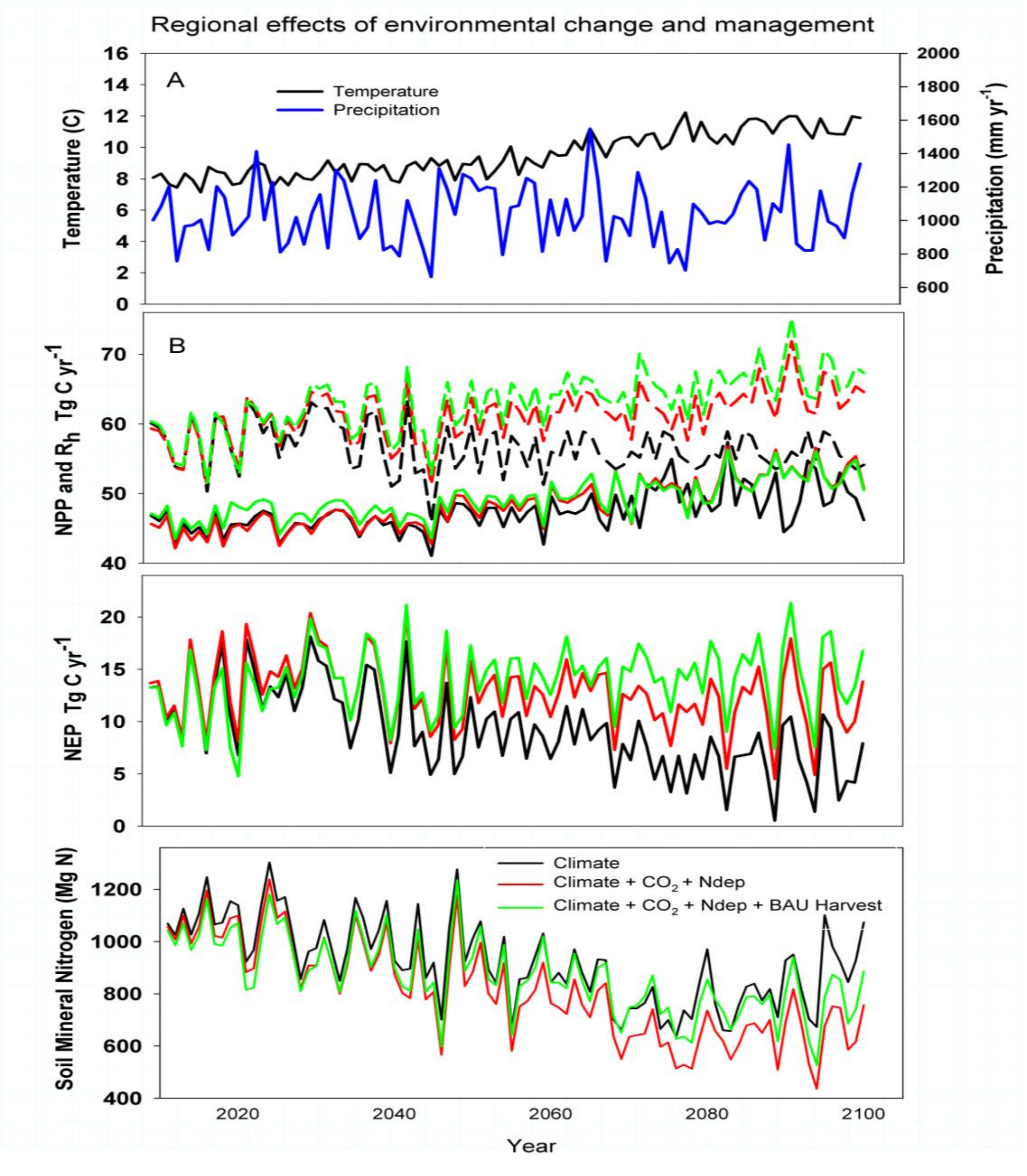

Figure 4.2. Predicted regional change in: (A) annual temperature and precipitation from 2010 to 2100, (B) NPP (dashed lines) and R_h (solid lines), (C) NEP, and (D) mineralized soil nitrogen for each of the factors tested (climate, CO_2 and N deposition, BAU harvest). The x-axis is years and the y-axis is in T g C yr^{-1} for NPP, R_h, and NEP and Mg N for mineralized N content. Black line = climate only effects, red line = climate + CO_2 + N deposition effects, and the green line = BAU.

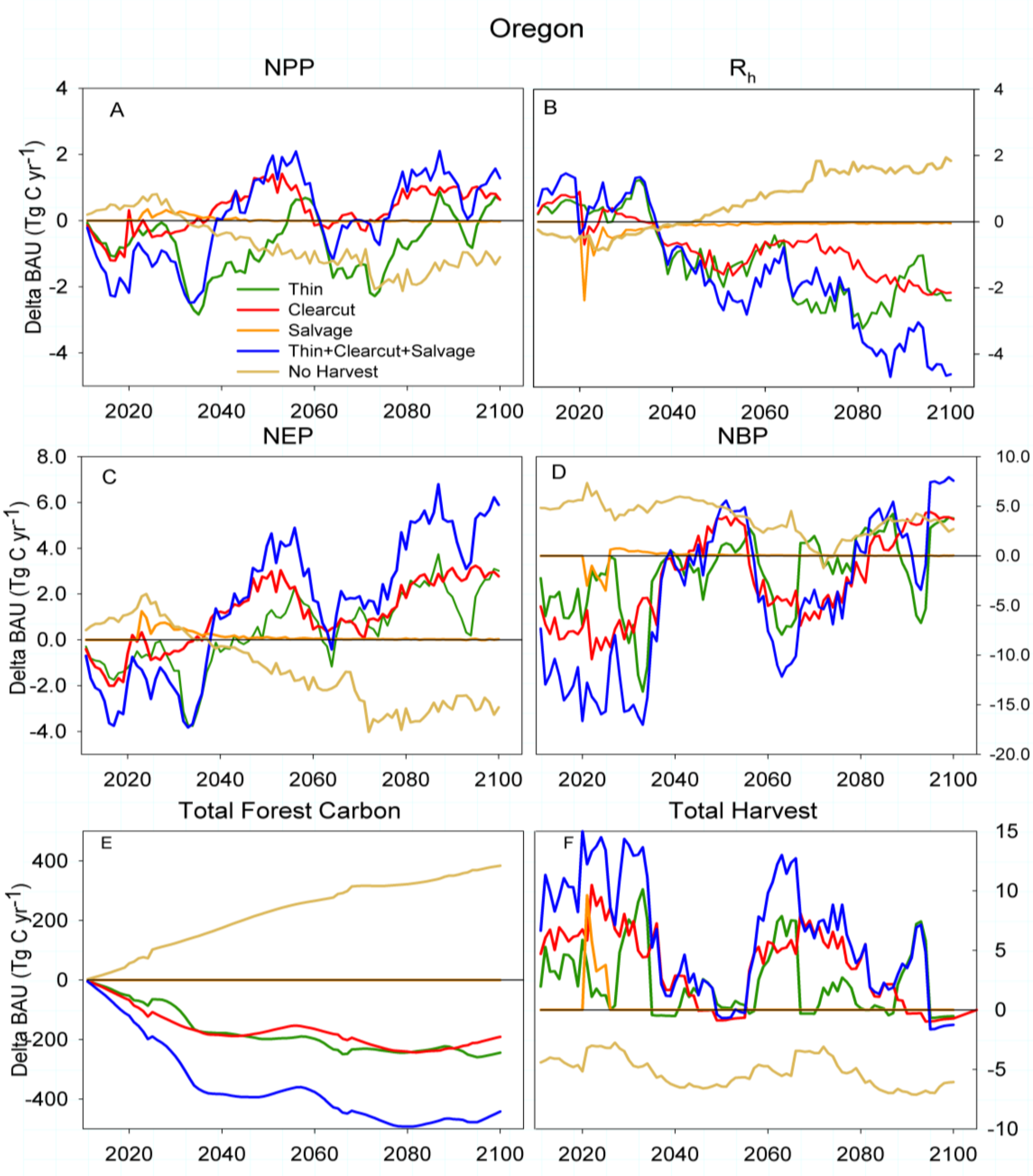

Figure 4.3. The change (delta) for each management scenario compared to BAU in the state of Oregon for a) NPP, b) Rh, c) NEP, d) NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}.Orange lines = Salvage harvest, Red lines = clearcut harvest, Green lines = thinning harvest, Blue lines = thinning + salvage harvest, and Yellow lines = No Harvest. There were no grid cells in the Blue Mountains under the clearcut scenario and no significant changes to BAU in the No Harvest scenario (excluded from figure). The black line indicates the ‘zero’ change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

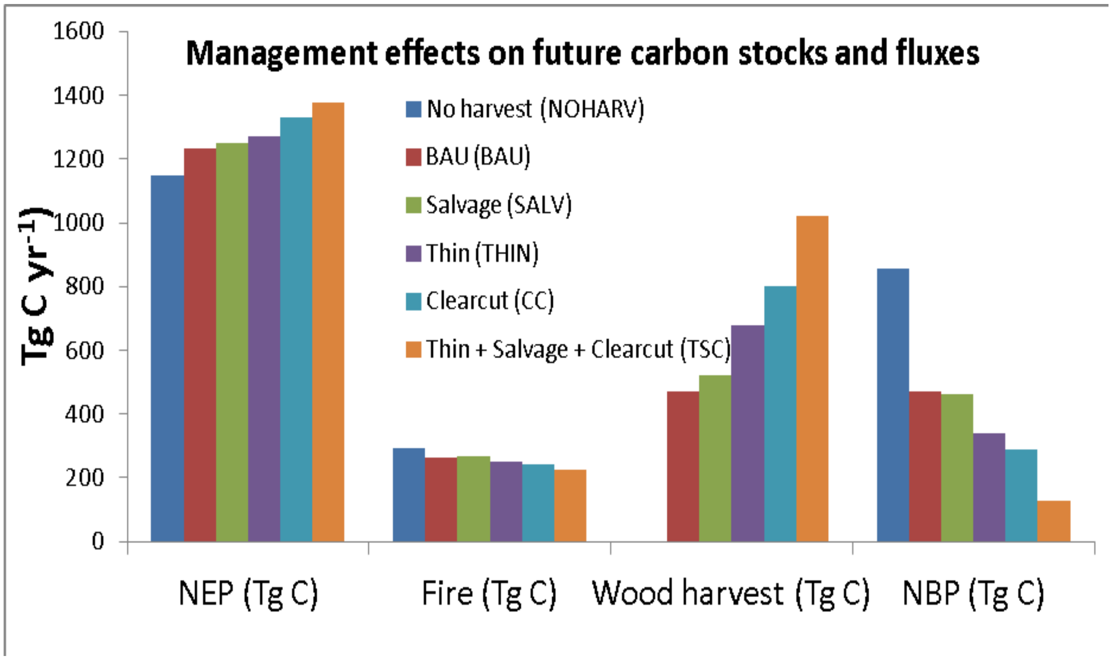

Figure 4.4. Oregon total net ecosystem production (NEP), fire emissions, wood harvest removals, and net biome production (NBP) in Tg C per year. Each management scenario is included and all scenarios account for future environmental change.

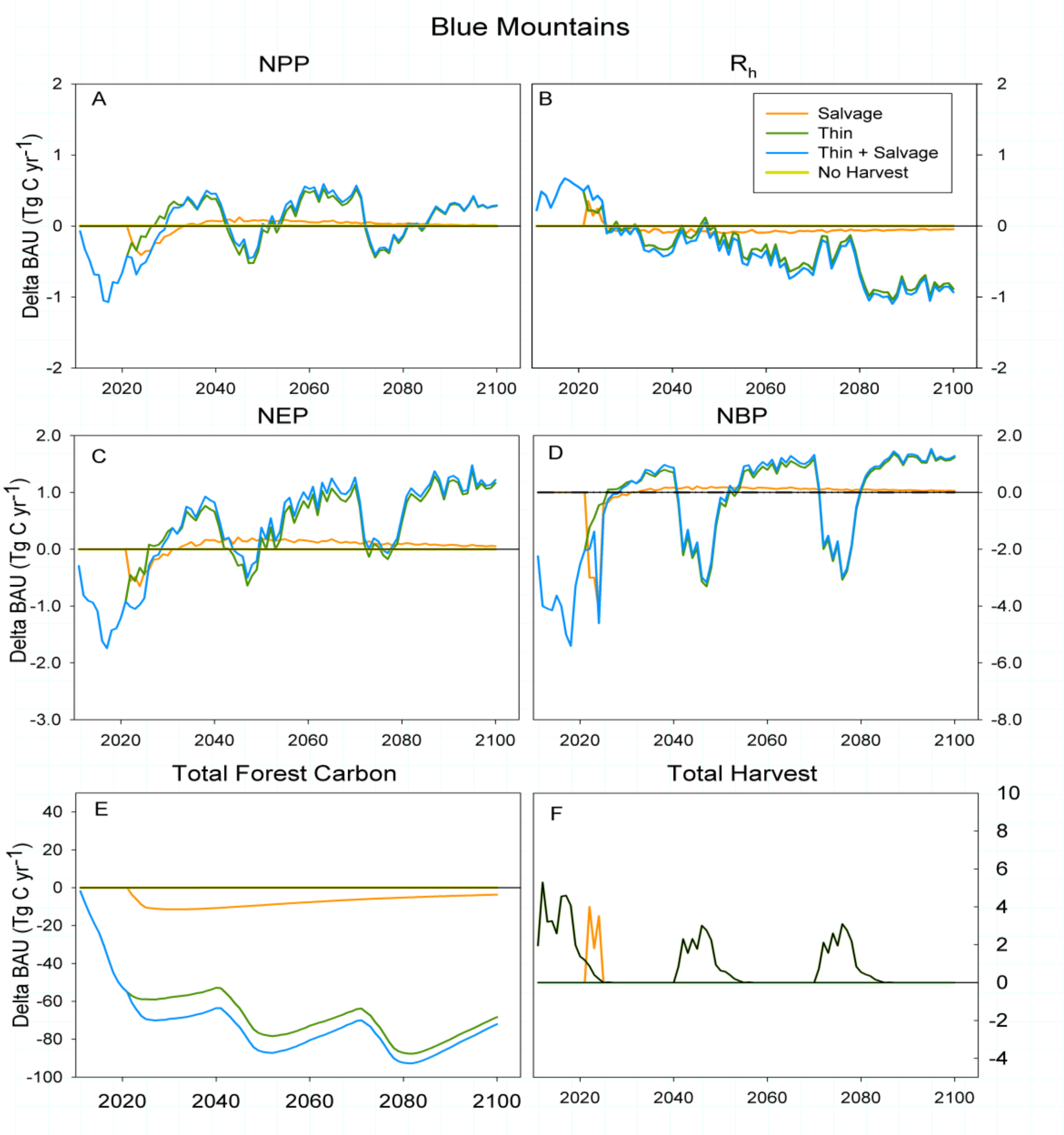

Figure 4.5: The change (delta) for each management scenario compared to BAU in the Blue Mountains for a) NPP, b) Rh, c) NEP, d) NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}. Orange lines = Salvage harvest, Green lines = thinning harvest, and blue lines = thinning + salvage harvest. There were no grid cells in the Blue Mountains under the clearcut scenario and no significant changes to BAU in the No Harvest scenario (excluded from figure). The black line indicates the 'zero' change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

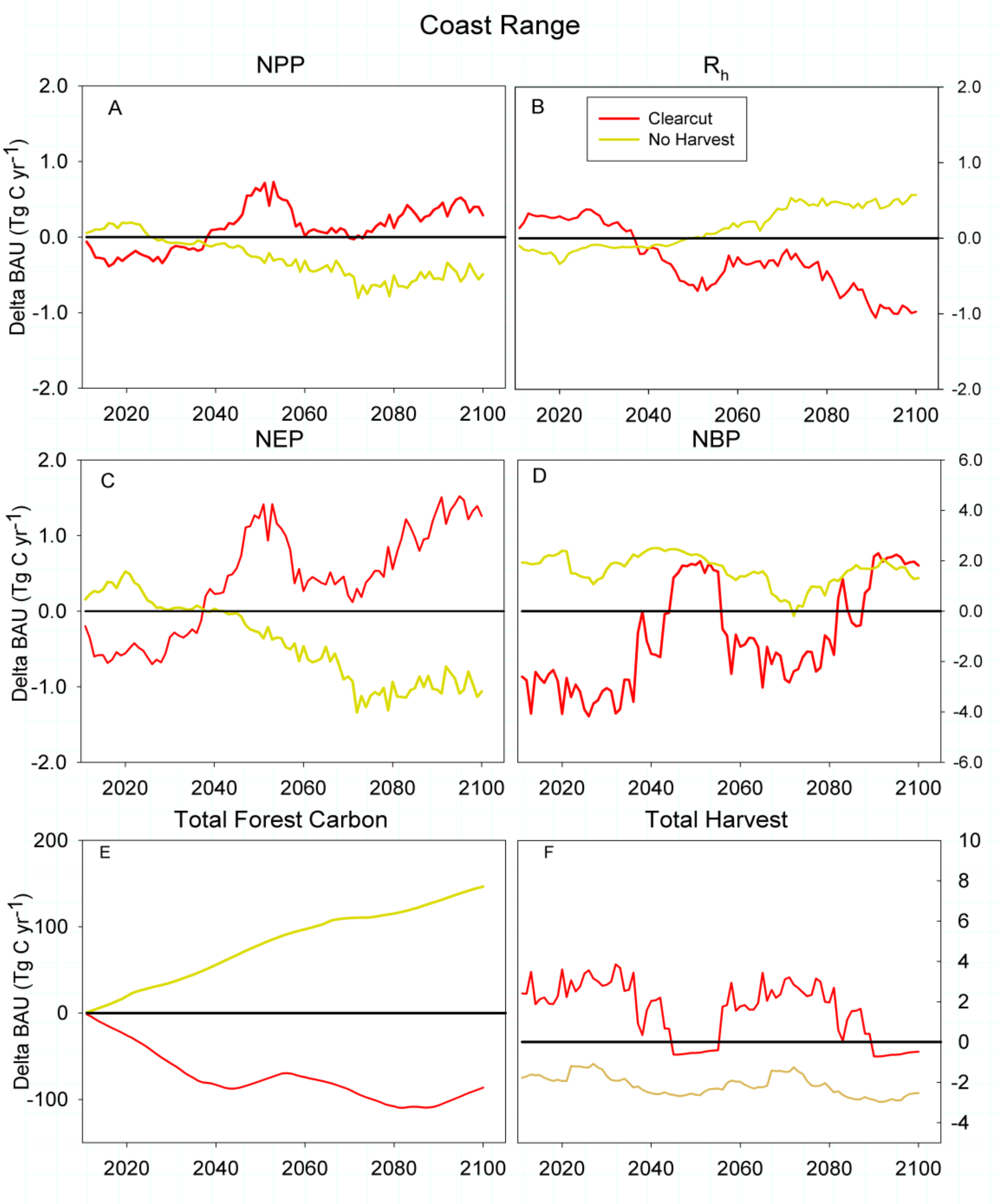

Figure 4.6: The change (delta) for each management scenario compared to BAU in the Coast Range for a) NPP, b) Rh, c) NEP, d)NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}. Red lines = Clearcut harvest, Yellow lines = No harvest. There were no grid cells in the Coast Range under the thinning and salvage scenarios. The black line indicates the ‘zero’ change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

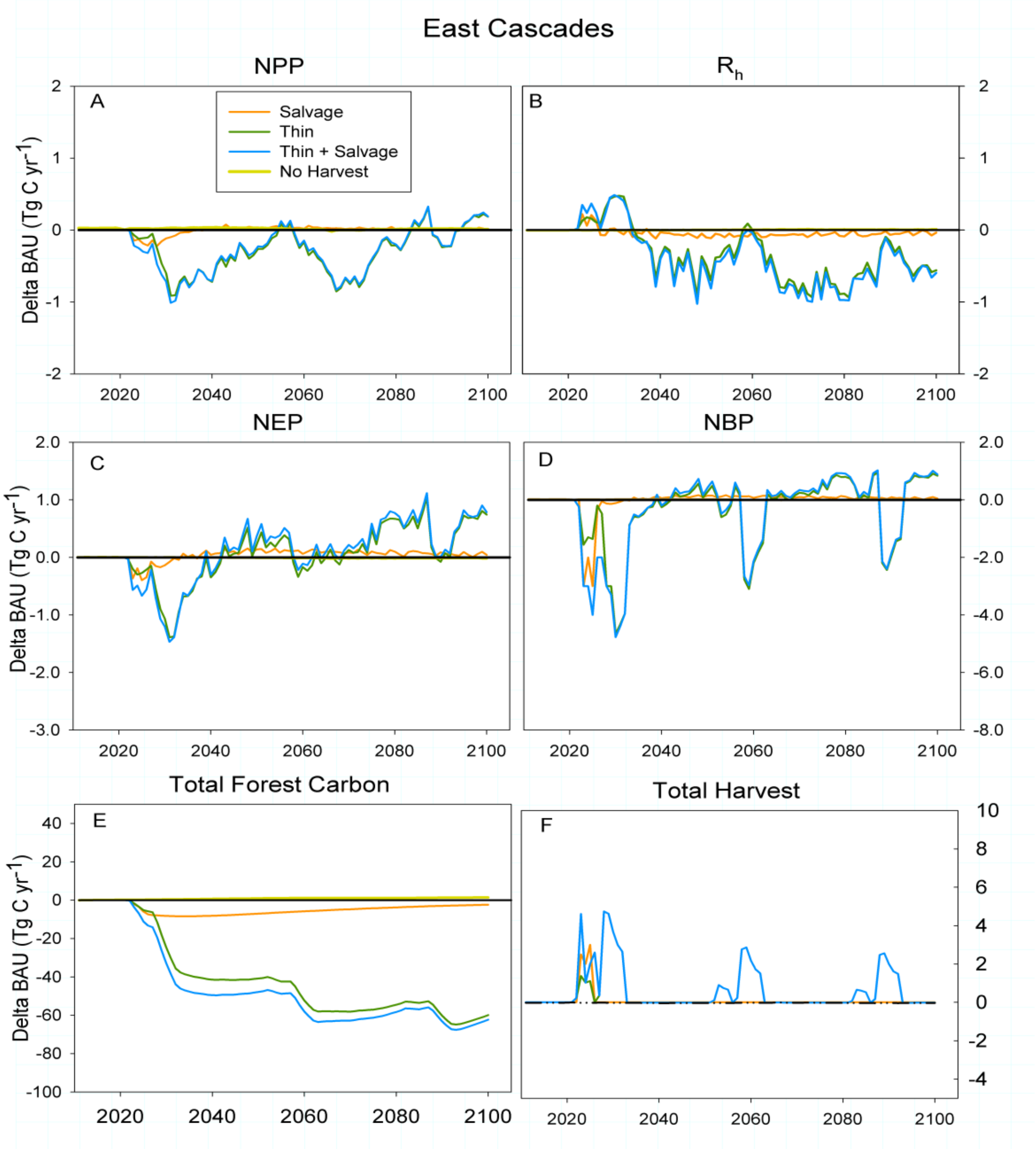

Figure 4.7: The change (delta) for each management scenario compared to BAU in the East Cascades for a) NPP, b) Rh, c) NEP, d) NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}. Orange lines = Salvage harvest, Green lines = thinning harvest, Light Blue = thinning + salvage and Yellow lines = no harvest. There were no grid cells in the East Cascades under the clearcut scenario and no significant changes to BAU in the No Harvest scenario. The black line indicates the 'zero' change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

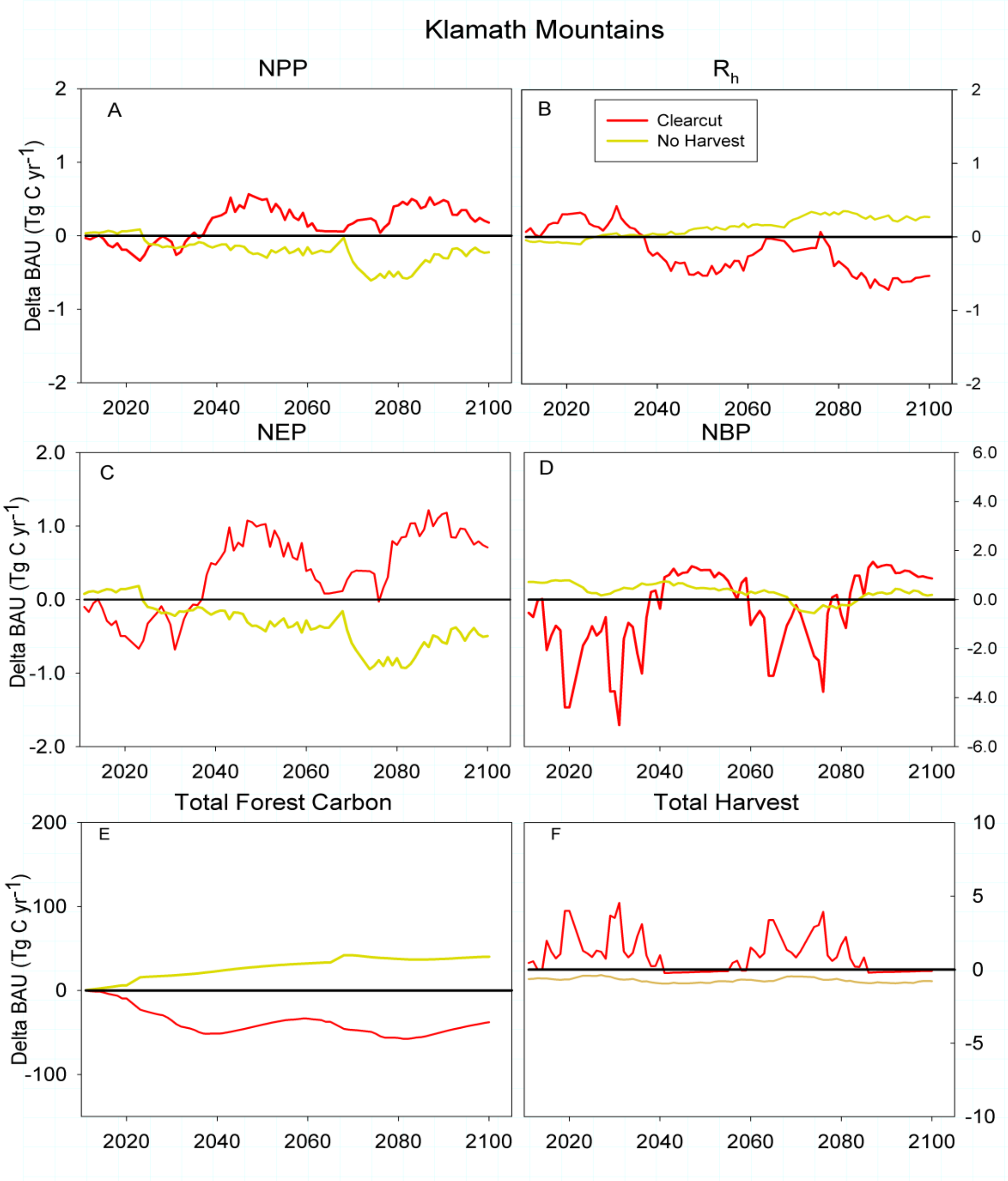

Figure 4.8: The change (delta) for management scenario compared to BAU in the Klamath Mountains for a) NPP, b) Rh, c) NEP, d) NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}. Red lines = Clearcut harvest, Yellow lines = No harvest. There were no grid cells in the Coast Range under the thinning and salvage scenarios. The black line indicates the ‘zero’ change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

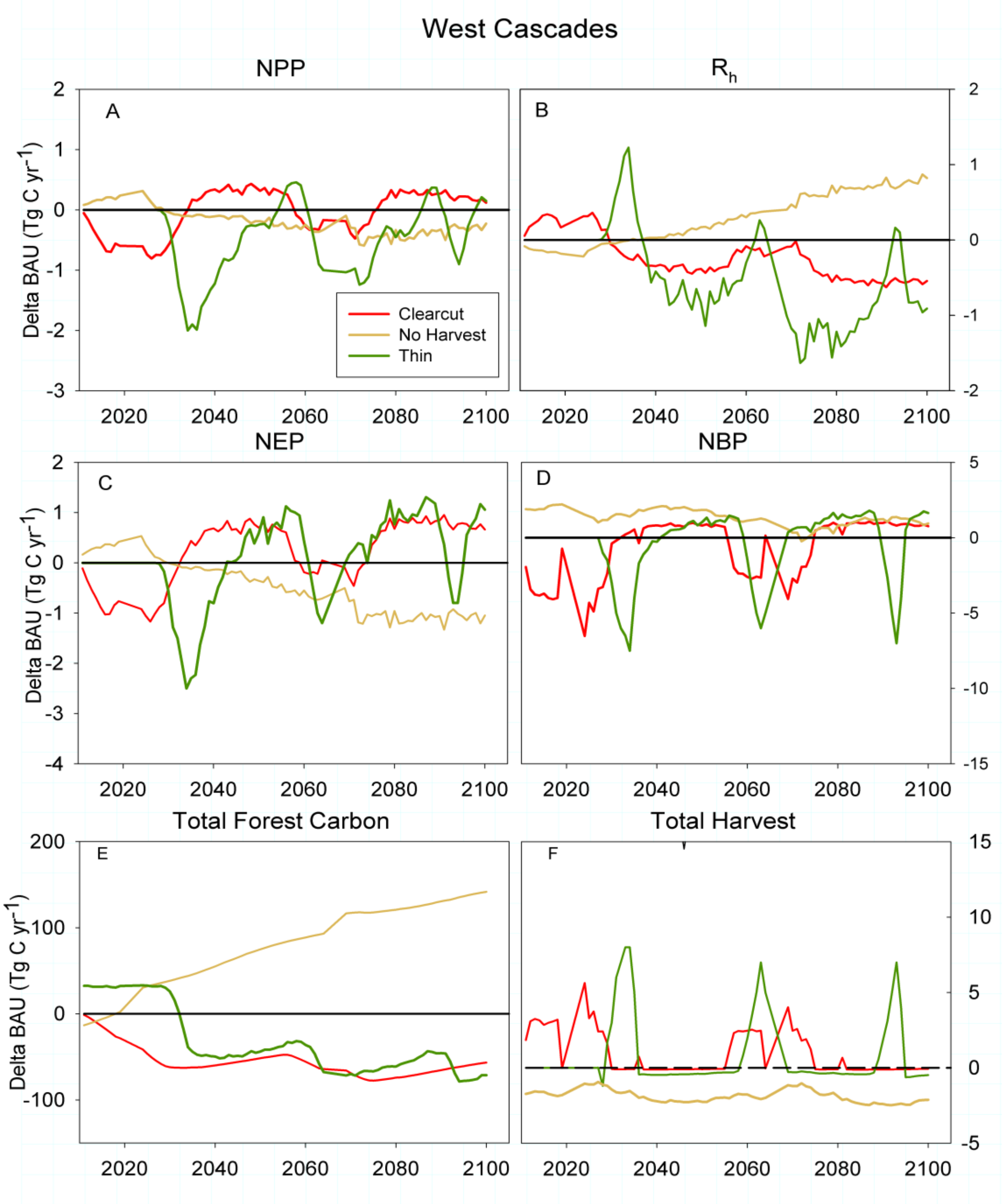

Figure 4.9: The change (delta) for each management scenario compared to BAU in the West Cascades for a) NPP, b) Rh, c) NEP, d)NBP, e) Total Carbon, and f) Harvest. The x-axis is in years and the y-axis is in Tg C yr^{-1}. Re lines = Clearcut harvest, Yellow lines = No harvest and Green lines = thinning harvest. There were no grid cells in the West Cascades for the salvage scenario. The black line indicates the ‘zero’ change. Positive values indicate increases to BAU carbon stocks and fluxes while negative values indicate decreases.

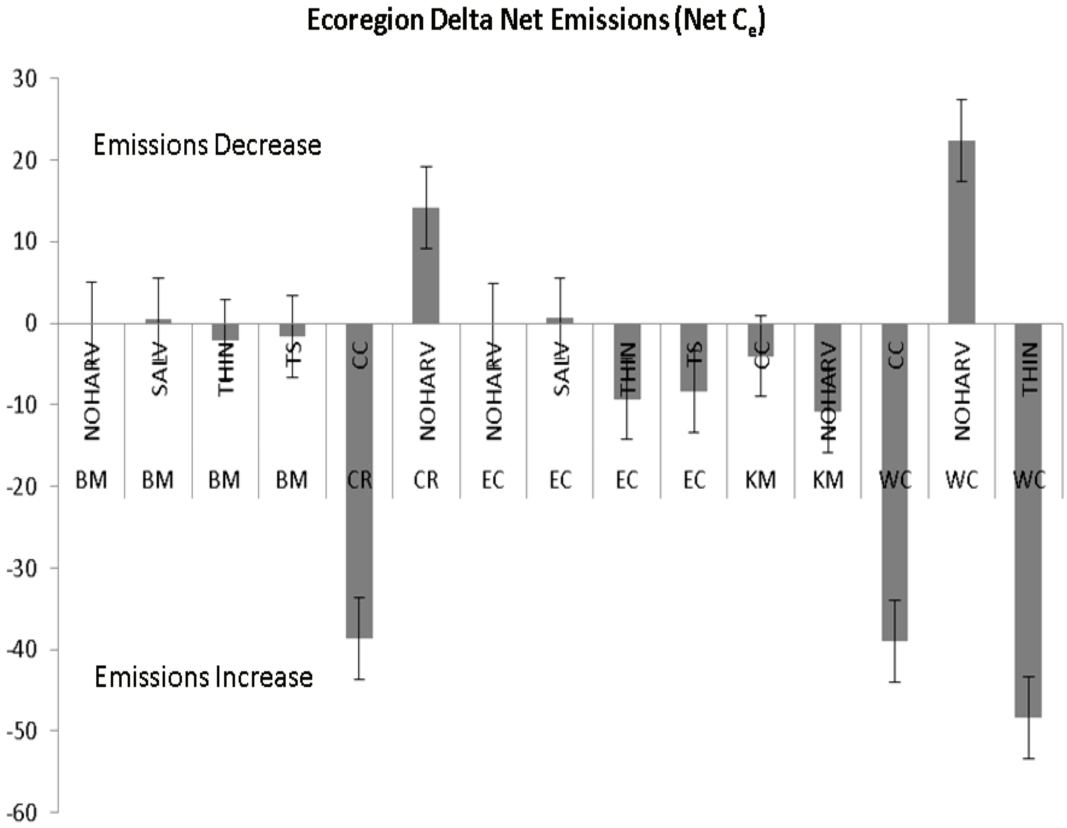

Figure 4.10. Total change in Net C_e to the atmosphere summed over the 90 year period compared to BAU for each management scenario in each ecoregion in Tg C. Error bars indicate the estimate uncertainty (± 5 Tg C) based on the uncertainty in current regional Net C_e.

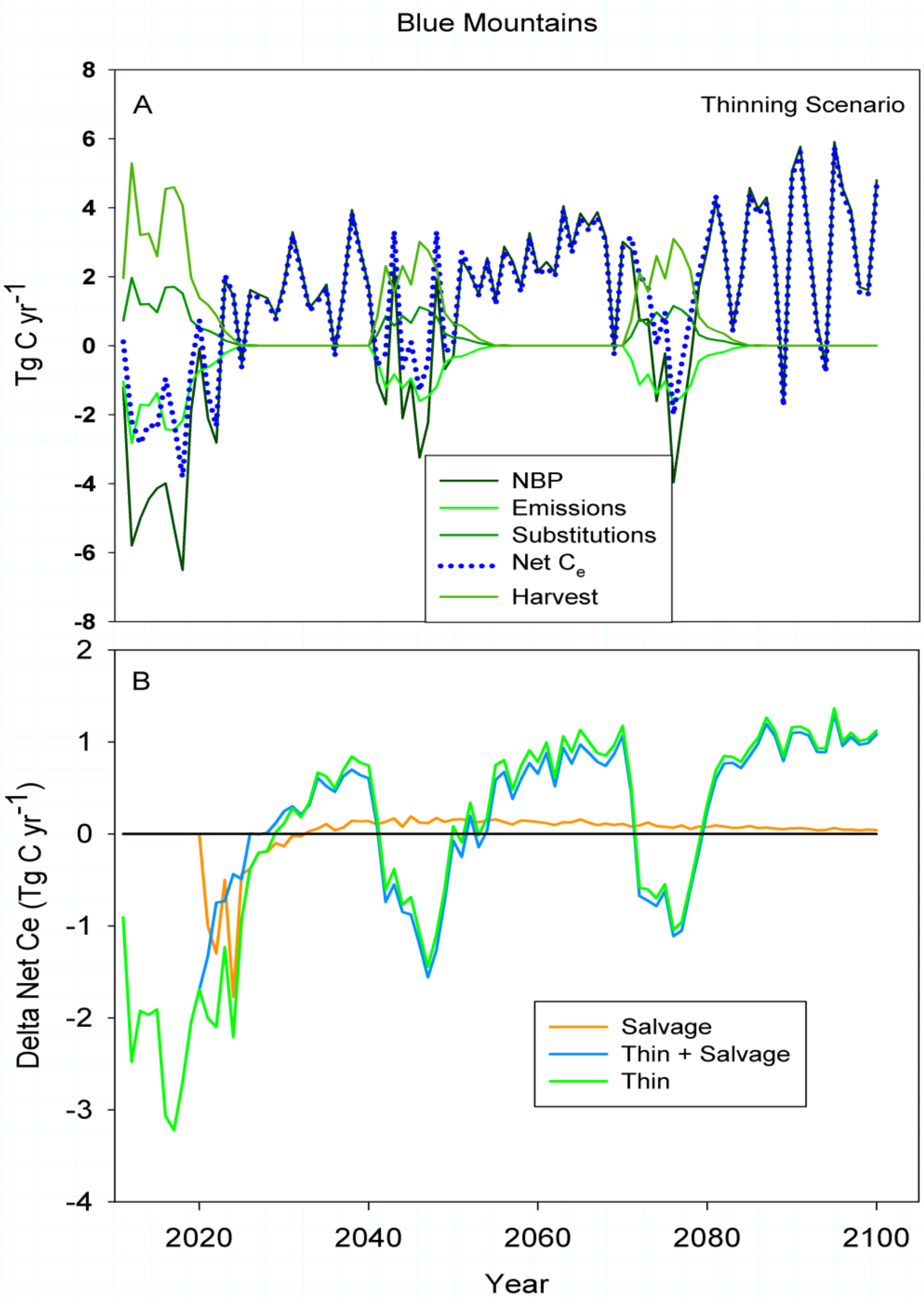

Figure 4.11. Blue Mountains LCA by component for a) the Thinning Scenario only and b) All scenarios Net C_e compared to BAU (Delta Net C_e). All units are in Tg C yr^{-1}.

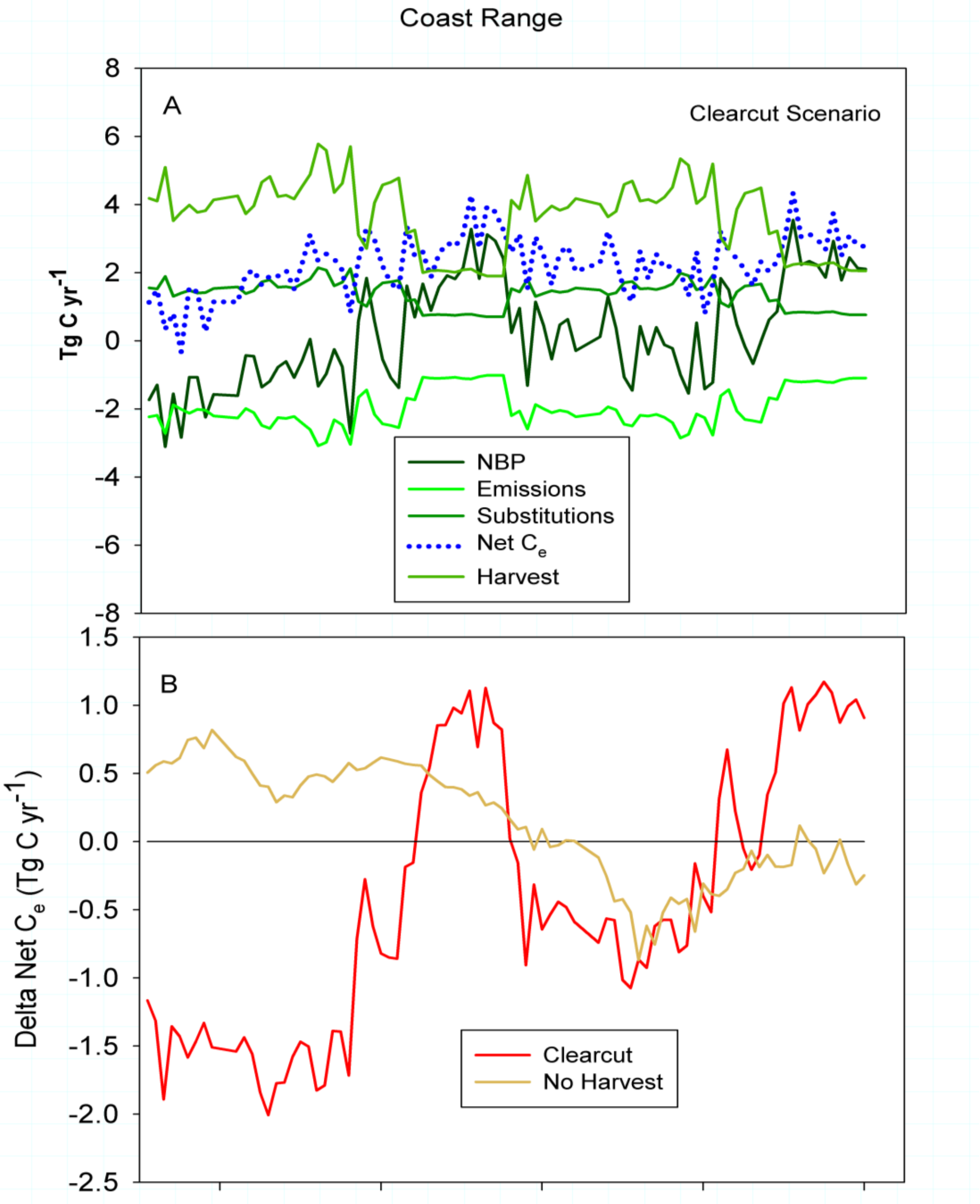

Figure 4.12. Coast Range LCA by component for a) the Clearcut Scenario only and b) All scenarios Net C_e compared to BAU (Delta Net C_e). All units are in Tg C yr^{-1}.

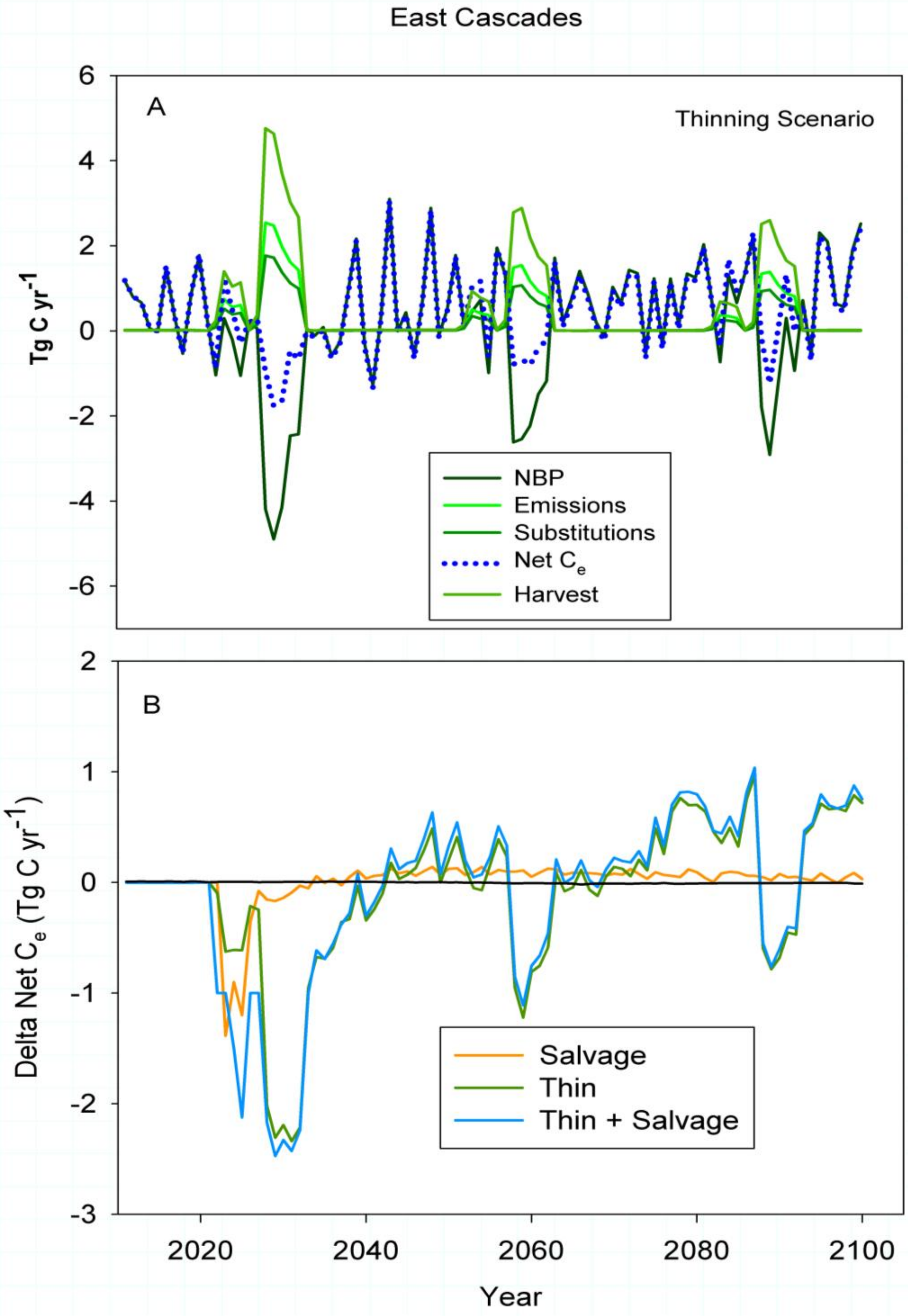

Figure 4.13. East Cascade LCA by component for a) the Thinning Scenario only and b) All scenarios Net C_e compared to BAU (Delta Net C_e). All units are in Tg C yr^{-1}.

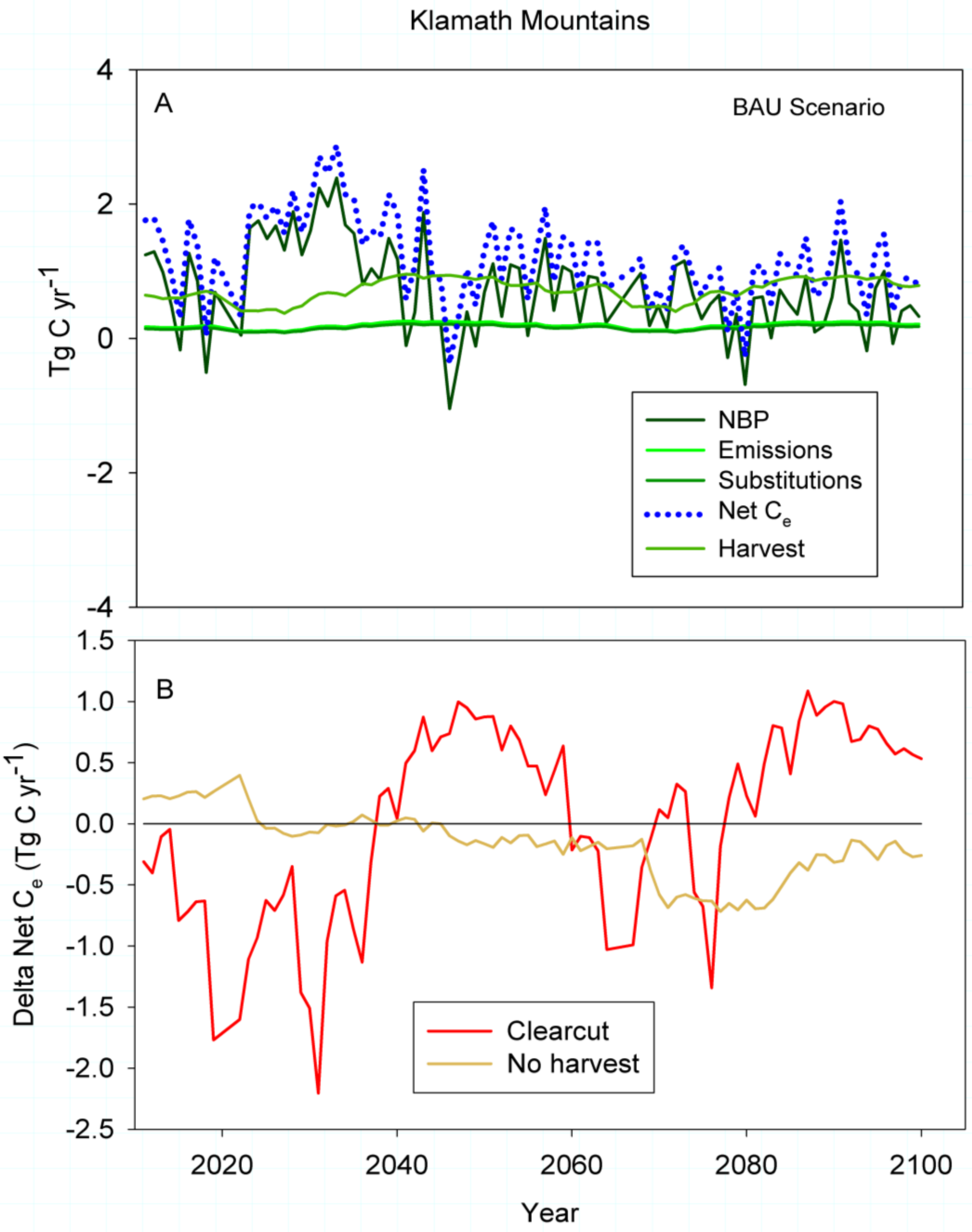

Figure 4.14. Klamath Mountains LCA by component for a) the BAU Scenario only and b) All scenarios Net C_e compared to BAU (Delta Net C_e). All units are in Tg C yr^{-1}.

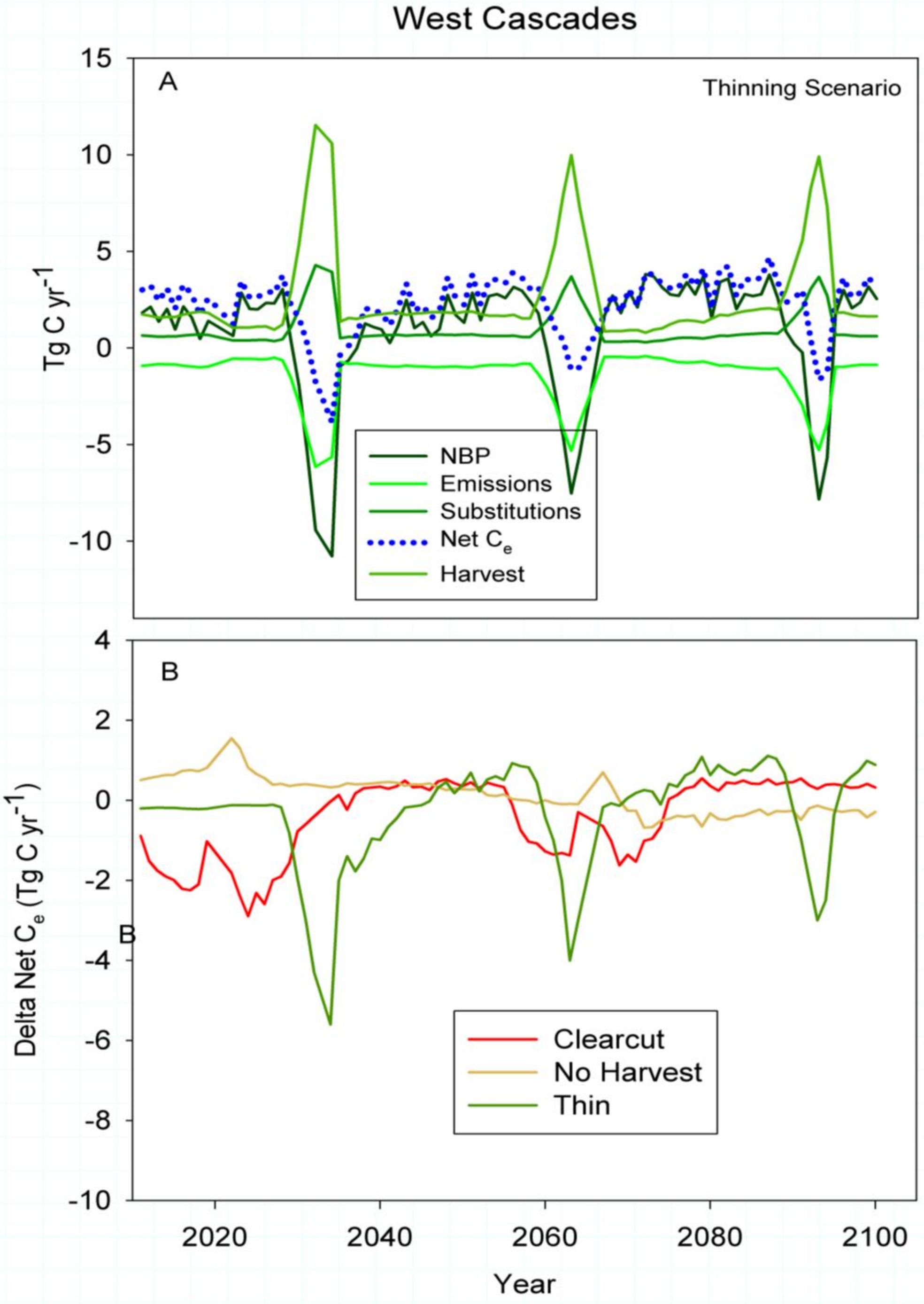

Figure 4.15. West Cascade LCA by component for a) the Thinning Scenario only and b) All scenarios Net C$_e$ compared to BAU (Delta Net C$_e$). All units are in Tg C yr^{-1}.

Chapter 5: Conclusions

Mitigation of climate change with forests requires a thorough understanding of forest carbon uptake and storage and the ability to make predictions about how uptake and storage will change as climate and management change. Policy aimed at reducing greenhouse gases (GHGs), particularly carbon dioxide (CO_2), through the use of forest biomass as bioenergy must consider the land-based forest carbon dynamics (*in-situ* carbon) as well as the off-site wood product sinks and sources. Because climate, natural disturbance, and management affect the rate at which forests store and release CO_2 to the atmosphere (Law et al. 2004, Williams et al. 2012), careful consideration of all of the factors involved is necessary in order to make predictions about net reductions or increases to emissions following proposed bioenergy management strategies. The strength in our predictive ability lies in our ability to reproduce current observed patterns with models. Through a combined approach using observational datasets and terrestrial ecosystem process models, this study analyzed the impacts of proposed forest management for bioenergy on short- and long-term regional carbon dynamics in the US west coast states.

Observations with forest inventory and supplemental plot indicated that the US West Coast forests are strong carbon sinks under business-as-usual and current environmental conditions (Chapter 2). Current uptake after accounting for removals (NBP) is 26±3 Tg C yr^{-1} (76±9 g C m^2 yr^{-1}) for Washington, Oregon, and California combined. This is equivalent to 18% of the total fossil fuel emissions for the region. Forests cover approximately 50% of the land area on the West Coast.

Using the observed data, we calculated the net carbon emissions to the atmosphere over the next 20 years *assuming constant environmental conditions* following implementation of low to high intensity bioenergy management. We found that forest thinning for fire prevention measures and large-scale bioenergy harvest in US West Coast forests leads to 2-14% higher emissions compared to current management practices over the next 20 years (Chapter 2; Hudiburg et al. 2011).. However, this was not true for all ecoregions within the study area. In ecoregions where the current sink has been weakened by insect-related mortality, increased fire emissions, or reduced net primary production, management schemes including bioenergy production may succeed in jointly reducing fire risk and carbon emissions. Hence, forest policy should not be a one-size-fits-all approach.

While the short-term implications of bioenergy are important for policy timelines which call for emissions reductions in the next 20 years, we recognize that changing environmental conditions will affect the current forest carbon sink and therefore the net carbon emissions over longer timeframes. Terrestrial ecosystem models provide the means to integrate changing environmental conditions, disturbance, and management on carbon dynamics and make predictions about future carbon dynamics as climate and management change. The uncertainty in the predictions depends on the model's ability to duplicate historical and current conditions. We evaluated the NCAR C*ommunity Land Model* (CLM4), the land model portion of the Community Earth System Model (CESM1.0.4) in the region (Lawrence et al. 2011) with existing datasets and identified model deficiencies (Chapter 3).

CLM4 was evaluated against inventory data in PNW forests using the default configuration and regional parameterization. Initial results indicated overall underestimation of stem biomass except in the semi-arid Blue Mountains where it was overestimated by 48 Mg C

m^{-2}. Modeled ecoregion mean NPP was also overestimated in the Blue Mountains and mesic West Cascades. Following initial default parameterization, model improvements were made to account for ecoregion differences in the physiological variables, foliar N content and mortality, and this resulted in an overall improvement in NPP estimates (all ecoregions fell within the observed range of uncertainty). Changing the stem wood allocation algorithm further improved the results, however wood carbon stocks were still underestimated in the West Cascades and Klamath Mountains (CLM4_stem).

After modifications, model estimates of NPP fell within the observed range of uncertainty in all ecoregions and the underestimation of stem biomass was reduced. At 12 km spatial resolution, reduced x^2 statistics indicated adequate model performance *in all ecoregions* for both stem biomass and NPP (reduced x^2 was equal 3 and 2, respectively).

This was an improvement from the default configuration by 50% for stem biomass and 30% for NPP. Within ecoregions, there was good performance ($x^2 < 2$) in the Coast Range and West Cascades, ecoregions that account for ~40% of the forested area. There was generally better performance in mature stands and apart from the Klamath Mountains, better performance in wet stands.

At the tower sites, modeled annual GPP fell within the observed range of uncertainty (reduced x^2 statistic < 1.2) at both sites. Fall, winter, and spring values followed seasonal patterns, however, summer GPP was consistently underestimated and did not fall within the observed range of uncertainty. Modeled LUE was too low suggesting better estimation of seasonal V_{cmax} would improve summer GPP estimates. We found improved parameterization of foliar nitrogen content and nitrogen availability increased monthly GPP in all months and therefore did not improve seasonal dynamics. This indicates that the model code controlling V_{cmax} response to either temperature and / or soil water content should be revised.

Following evaluation, a series of modeling experiments were performed to determine the long term impacts of varying management strategies on net carbon emissions compared to BAU (Chapter 4). Simulations of future conditions in Oregon indicate no change to the current sink strength as long as BAU management is maintained. At the end of the 21st century, predicted regional net ecosystem production (BAU NEP) did not change compared with the current NEP indicating no significant influence by changing climate, nitrogen deposition, and increasing CO_2 concentrations over the next 90 years. In other words, statewide rates of net carbon uptake under business-as-usual conditions were not reduced compared to current conditions. However, simulated BAU NBP did decline by ~2 Tg C yr^{-1} by the end of the century compared to the beginning primarily due to increases in fire emissions.

For the state of Oregon, implementation of bioenergy management strategies which increase harvest compared to BAU (thinning and clearcut scenarios), did not result in net reductions to carbon emissions over the next 90 years despite inclusion of *all* wood product and bioenergy substitutions. 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 from product acquisition, conversion, decomposition, and combustion for energy by the end of the 21st century.

There were some cases where the dominant trend at the regional level varied at different spatial resolutions. In the semi-arid ecoregions (Blue Mountains and East Cascades), net carbon uptake following thinning began to improve over BAU at the end of the 90 year period suggesting bioenergy management could lead to net reductions over a longer time period (> 100 years). For salvage logging, there was no change in emissions compared to BAU by the end of the 21st century in all cases. Finally, in the Klamath Mountains, there was evidence that the current level of harvest, wood products, and bioenergy management reduces emissions compared to management plans with no harvest at all.

Management and policy implications

Regional bioenergy management strategies utilizing forest biomass will not reduce GHGs, particularly carbon dioxide, over the next 90 years given the results of this study. The specific situations where emissions were not increased (i.e. Salvage logging) are limited to single harvests that do not increase BAU harvest by more than 4%. In the majority of the ecoregions and at the state-level, policy that reduces harvest would decrease emissions over the 90 year period. This is particularly important for policy makers as this reemphasizes that a ‘one-size-fits-all’ approach will not help to mitigate climate change. Management plans will need to be written accounting for local conditions, especially where predicted future local climate deviates from regional climate (i.e. precipitation in the Blue Mountains). Bioenergy from forest biomass by thinning in the Blue Mountains was beginning to reduce emissions compared to BAU at the end of the 21s century. Based on this analysis, the challenge for policy makers and land managers will be to balance wood harvest for local economies and forest health while *maintaining* carbon emissions relative to BAU management as significant *reductions* do not seem possible.

Suggestions for future research

The short- and long-term experiments could still be improved to determine the net carbon emissions from bioenergy management strategies that will provide a continuous bioenergy supply (i.e. rotation based thinning and clearcut harvest). Longer simulations and better fire and insect related mortality prediction will be required to identify areas where long term bioenergy management strategies will be most effective. Also, the simulations do not include a mechanism for PFTs to change overtime (i.e. dynamic vegetation model) due to stress caused by disturbance factors such as insects, disease and fire or drought. The annual scenario harvest rates presented here are not necessarily reflective of industry operations, which would require a steady supply of wood over space and time. The temporal and spatial distribution of the harvests will ultimately need to be planned with mill and facility location and capacity in mind. Finally, more climate and RCP scenarios should be investigated to provide a range of responses to policy makers and land managers.

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APPENDICES

Appendix A: Supporting information for Chapters 2 and 4

Methods

General Approach: We combined data from the Forest Inventory and Analysis National Program (FIA) for Oregon, Washington and California (~34 million hectares) with LandFire satellite remote sensing products (USGS 2009), 200 Appendix plots (Hudiburg et al. 2009), and a global wood decomposition database(Wirth et al. 2010) to provide new estimates of US West Coast forest biomass carbon stocks, net ecosystem production (NEP, the net of photosynthesis and respiration), net biome production (NBP, the net forest carbon-sink accounting for removals) and their uncertainties. We include all forestland in our analysis. These forests range across all age classes (0-1000 years old), are on rotation management or may have never been harvested, and are both public and privately owned. Plot values were aggregated by climatic region (ecoregion), age class (succession class), and forest type and the mean values were used to assign a value to each associated 30 meter pixel. Thinning treatments were applied to each plot according to a specific set of criteria (Figure A1b) of removed forest carbon. Life cycle assessment (LCA) was calculated at the ecoregion, state, and regional level using published values for associated fossil fuel emissions, energy conversion efficiencies, wood product pool ratios and decomposition, and fossil fuel inputs (Table A4).

Database: Federal forest inventory data (FIA) are now being collected on an annual basis, statewide on all types of forestland in all regions. The inventory design consists of 0.404 hectare (one-acre) plots systematically placed across the landscape, encompassing a representative range of stand ages, disturbance histories, ownerships, and land cover types. The study area includes all forested land in Washington, Oregon and California for the period from 2001-2006. In addition to the traditional tree surveys, new measurements include woody detritus, understory shrubs, and litter allowing for a more complete quantification of land-based carbon stocks (excluding stocks in soils). As of 2006, there were 8889 measured plots (Table A7) with accessible forestland (Plot Status code = 2), of which 8659 with tree increment data recorded which is required for our methods of estimating NPP. Of these 8659, only 6840 had the necessary detritus measurements to calculate NEP (Phase 3 plots). These remaining 6840 plots are still distributed across the landscape in all forest types and ecoregions with about 20% of the plots excluded. Plot means of biomass, NPP, NEP, and NBP were scaled to state totals using spatially explicit forest cover, forest type and productivity, and succession class data products available in 30 x 30 meter resolution from LandFire Landsat satellite remote sensing derived products (USGS 2009). Finally, state carbon budgets were estimated using datasets containing annual harvest removals and wood densities, fire emissions, and fossil fuel emissions (Table 5).

Biomass stock and flux estimates: Tree and shrub carbon stocks and NPP were calculated with a combination of species-specific allometric equations, tree increment data, and supplemental plot data using methods (Table A8) described in (Hudiburg et al. 2009). Wood cores collected from a subsample of trees on each plot were used to estimate plot NPP from 10 year diameter growth increment and thus the annual mean NPP is averaged over a 10 year period of growth conditions. Woody detritus carbon was calculated using the line intersect method and species- and decay class-specific wood densities (Hudiburg et al. 2009). Foliage litter and duff depth measurements were converted to biomass as the product of the depth and the material density. Foliage NPP was calculated by dividing foliage biomass per tree by the average foliage retention time (average number of years of foliage that a stand carries). Herb mass was estimated using a biomass conversion factor and percent cover on each plot.

We define NEP as the difference between annual NPP and heterotrophic respiration. While direct measurements of soil respiration are not available on FIA plots, we were able to calculate NEP using a mass-balance approach and Appendix plot data (Giardina and Ryan 2002, Campbell et al. 2009):

$$\text{NEP} = \text{Aboveground NPP} - \text{dead wood decomposition} - \text{litterfall} + \Delta\ \text{root} + \Delta\ \text{soil C.} \quad (1)$$

The basic assumption is that annual soil respiration is balanced with litterfall, belowground carbon allocation and change in carbon of the roots and soils. Aboveground NPP from tree increment cores and dead wood species, diameter, and decay class are available from West Coast FIA observations. Deadwood decomposition was estimated based on a global dataset of wood decomposition rates of tree species (http://www.bgc-jena.mpg.de/bgc-organisms/pmwiki.php/Research/FET). Predictive models used genus-specific baseline rates modified by coefficients describing the sensitivity to mean annual temperature, annual precipitation sum, stem diameter and position (downed versus standing). Litterfall was estimated as foliage NPP minus an average mass retention of 21 percent (Table A9). We assumed change in soil and fine root carbon were zero for plots older than 150 years (old growth) and used the difference between values found at our supplemental plots for younger and mature age classes and the old growth plots to calculate a delta soil carbon (Law et al. 2003, Campbell et al. 2009).

Net Biome Production (NBP): We followed (Chapin et al. 2006) and defined net biome production (NBP) as NEP minus any losses due to fire or harvest. Average annual state timber harvest volumes provided by the respective state Departments of Forestry were converted to biomass removals using known wood densities (Turner et al. 2007). Actual fire emissions were calculated using burn area and severity (Eidenshink et al. 2007) and biomass specific combustion factors for the region (Table A9). Estimates of fire emissions vary greatly depending on the approach (Ottmar et al. 2006, Campbell et al. 2007, Meigs et al. 2009, Wiedinmyer and Hurteau 2010) and combustion factors used. We use biomass specific combustion factors from studies in our region (Campbell et al. 2007, Meigs et al. 2009) which include several of the dominant forest types in our region covering 67% of the forested area. For woody detritus, these factors range from 3 – 100% combustion depending on fire severity and the type of biomass. Emissions estimates using these factors compare well with modeled estimates which also distinguish between biomass components (Ottmar et al. 2006). Other studies use a single combustion factor (30%) for all above ground woody biomass (Wiedinmyer et al. 2006, Wiedinmyer and Hurteau 2010) including the standing dead trees. Since the majority of the woody biomass is in standing tree boles, this results in an overestimation of fire emissions. Nevertheless, we have included additional estimates of NBP for both current and treatment emissions using the single combustion factor to determine the sensitivity of this parameter on our results (Table A6).

Treatment Design: To test the effect of biomass thinning on land-based carbon stocks and NBP, we chose three different management scenarios designed to meet varying objectives (Figure A1a). Basal area removals, maximum tree bole size, and areas treated were varied by the following strategies: 1) Fire Prevention: Thinning targets smaller trees (Stephens et al. 2009a) and is limited to areas with frequent fires or short mean fire return intervals (the latter being derived from LandFire (USGS 2009) Landsat remote sensing derived data product). This scenario is unlikely to be economically feasible due to low value of the extracted biomass. 2) Economically Feasible: Thinning targets larger trees followed by smaller trees providing at least 9 Mg of dry biomass per hectare (4.5 Mg C ha^{-1}) of merchantable biomass (Skog et al. 2008). Merchantable biomass would help pay for removing fuel ladders (understory trees that allow fire to access and ignite the canopy). Hence, this treatment is limited to areas with short mean fire return interval. 3) Bioenergy Production: Thinning targets all regions and trees to maximize biomass available for energy production (Perlack et al. 2005). This scenario is also expected to be economically feasible because merchantable wood is removed. 4) Business-as-usual (BAU): forest management remains the same as current practices (14.7 Tg C harvested annually) with no additional thinning or harvest treatments. The biomass removal targets were defined by current or proposed practices (USDA 2010). Treatments were all designed to produce stands capable of resisting crown fire by reducing canopy bulk density and removal of understory ladder fuel (Stephens et al. 2009a). Synthesis of existing fuel reduction treatment studies found that stand basal area was reduced by an average of 48% (Evans and Finkral 2009). We chose to use a range of basal area reductions, 30% for the Fire Prevention treatment, 40% for Economically Feasible, and 50% for the Bioenergy treatment based on current and proposed practices (Finkral and Evans 2008, Skog et al. 2008, Harrod et al. 2009, Stephens et al. 2009a, Stephens et al. 2009b). These practices are designed to follow a general standard which is to alter stand conditions so that projected fire severity would result in at least 80% of the dominant and codominant residual trees surviving a wildfire under the 80th percentile fire weather conditions known as the ”80-80” rule (Stephens et al. 2009a).

The main difference between the Fire Prevention and the Economic Production scenario is the basal area reduction allowed and the size of the trees removed. For Economic Production, larger trees are targeted first and then smaller trees are removed to meet the basal area reduction requirements. We did not intend to predict or analyze the economic cost of any of the treatments and simply allowed for higher DBH removals to help offset the cost. There have been several studies that investigate the economic potential of forest bioenergy (OFRI 2006, Skog et al. 2008, Evans and Finkral 2009), with mixed results (see http://www.eenews.net/climatewire/2011/07/22/5). In the Fire Prevention scenario, trees are removed from smaller DBH classes first and then larger trees are removed until basil area reduction requirements are met. The main difference between the Economic and the Bioenergy scenario is the basal area reduction and the land area treated. Bioenergy Production treats all land regardless of fire risk or return interval while the Economic scenario only treats land with a fire return interval of less than 40 years.

Thinning prescriptions: Thinning prescriptions were applied to the FIA plots for each of the three treatments (Fire Prevention, Economically Feasible, and Bioenergy Production) according to the management scenarios. The primary objective in each scenario was to reduce stand density in order to reduce the risk of wildfire. The actual fuel reduction thinning treatments applied across different forest types and ownerships vary from stand to stand and are therefore prescribed on a stand-by-stand basis. In order to prevent wildfire, removal of ladder fuels and reduction in crown density are necessary (Agee and Skinner 2005, Huggett Jr et al. 2008, Harrod et al. 2009). Stand prescriptions usually involve a vegetation model simulation which takes inputs of stand characteristics such as height, species composition, understory structure, canopy bulk density, ground fuels, wind speed, temperature, and moisture conditions. While most of the necessary inputs are available for a given FIA plot at a given time, some of these conditions change over time (weather) and are too stand specific (structure) to be extrapolated to other stands spatially and temporally. We chose to use the average basal area reduction (30-50%) found in a synthesis of studies (Skog et al. 2008, Evans and Finkral 2009)to insure adequate reduction in crown density and prevent removal of too much biomass.

To simulate effective removal of ladder fuels, FIA plots were treated by removing the understory non-merchantable small trees (< 12.7 cm) in all three scenarios. Thinning of overstory trees was varied by scenario. All trees on the plot were grouped into small, medium, and large DBH classes. In the Fire Prevention scenario, the majority of the trees removed were in the small DBH class and less trees were removed from the medium and large classes to a maximum of 30% basal area reduction. An upper DBH limit of 45 cm was set. In the Economically Feasible scenario, the majority of trees were removed from the medium and large DBH class followed by a smaller percentage in the smaller class to a maximum of 40% basal area reduction. In the Bioenergy Production scenario, trees were removed similar to the Fire Prevention scenario but the maximum basal area reduction was 50%. For both the Economically Feasible and the Bioenergy Production scenarios, the DBH limit was set to 60 cm. This upper limit on DBH is currently stated in active forest policy in Oregon and California (ORSenate 2005) and the smaller one was proposed to retain larger trees (Harrod et al. 2009). Bole, branch and bark biomass were considered ‘removed’ from the site and separated into merchantable and bioenergy pools. Total plot removals were aggregated and mapped by ecoregion, forest type, and age class. State and regional totals include only non-reserved, productive forestland in accessible areas (http://www.fs.fed.us/r1/gis/thematic_data/ira_us_dd.htm). Productive forestland must be capable of producing 10 Mg/ha of merchantable wood annually.

All scenarios exclude public forest reserves and remove all non-merchantable wood (diameter at breast height or DBH < 12.7 cm). A treatment period of 20 years was assumed to be the amount of time required to treat the entire landscape or 5% of the treatable forested area per year (Bowyer 2006). We chose the 40-year mean fire return interval because a plot that is at least half-way through a 40 year mean fire return interval could burn during a 20-year treatment period. FIA plots on forestland capable of producing 10 Mg of merchantable wood per hectare per year were thinned according to each treatment and new plot mean biomass values were scaled to state and ecoregion boundaries to determine the removal totals. The treatment removals were treated as additional harvest (harvest in addition to Business-as-Usual harvest) in further calculations accounting for the portion of biomass utilized for energy and the portion used as merchantable biomass.

Treatments were assumed to be 75% effective at reducing fire emissions (Raymond and Peterson 2005). Because only 5% of the landscape is treated each year, associated reductions in fire emissions increase as more forestland is treated. If treatments are 75% effective, then emissions are reduced by 3.75% each year with 75% reduction in the final treatment year. This results in reducing fire emissions by half when integrated over the whole treatment period. We also assume there is no increase in fire frequency (or probability) over the study period due to other factors such as climate change. Fire frequency and intensity are expected to increase in the western US due to climate change (Westerling et al. 2006, Littell et al. 2009), but the extent is highly unknown and limited by the capability of the climate-fire models.

Post-treatment NEP: While increased growth of the remaining trees following thinning is well documented, stand-level NPP is reduced (Law of Constant Final Yield, (Shinozaki and Kira 1956)) because ultimately resources limit growth not density (Campbell et al. 2009). Thinning effects on NEP are not well documented and response is variable (Campbell et al. 2009). However, we needed to account for regrowth, either due to the increased growth of remaining trees or the growth of the understory over the treatment period. Since we could not estimate regrowth NEP using the plot data, we decided to use the NEP associated with young-aged plots since this might most mimic the conditions following release from competition. The thinned plots were assigned an NEP equal to the observed mean NEP of stands aged between 1 and 20 years over the treatment period resulting in an overall higher NEP for thinned stands, biasing our results towards beneficial effects on the carbon-sink for forest treatments.

Given the large uncertainty associated with predicting future fire (Rogers et al., 2011), we assume that in BAU, fire will occur with variability that has been observed in the past (no increases in fire). Since FIA plots include those that have within fire perimeters, post-fire NEP is part of the current flux estimates. However, because we assume no increase in fire, we do not predict a new post-fire NEP, which would beyond the appropriate use of the data. In a recent study by (Raffa et al. 2008), post-fire NEP for the 5 years prior to the Oregon Biscuit fire averaged the same as the five years after the fire. In this study, we have shown that a doubling of fire emissions by using different combustion coefficients still does not compensate for the emissions associated with bioenergy production (Supplemental discussion of sensitivity analysis).

Life-cycle assessment (Figure A1b; Tables 4 and 5): Life-cycle assessment of forest carbon removals includes forestry related sinks and sources of carbon to and from the atmosphere and the associated impact on total fossil fuel emissions (FFE). The C emissions to the atmosphere for each scenario (FCO_2) over 20 years were calculated as the difference between the sources and the sinks following this process:

FCO2 = NBP + Total Harvest – WD1 – WD2 – Wood Industry FFE – Bioenergy Emissions + Bioenergy Substitution + FF Well-To-Tank Emissions displacement+ (Wood Substitution) (2)

Where, WD1 is the wood lost during manufacturing processes, WD2 is the wood decomposed over time from product use and wood substitution is included with the assumption that there is an increased demand for wood supply.

To quantify the change in FCO_2 for each scenario we calculate the difference between each scenario and the BAU FCO_2 emissions. The physical sinks are forest net uptake (NBP) and wood products (Harvest) and the added virtual sinks of bioenergy and wood product substitution (FF Substitution). Because the benefits of wood substitution require an increase in wood use and this saturates quickly, we calculate the change in CO_2 with and without a wood substitution benefit (Law and Harmon 2011). We exclude imports and exports from the study region since we are only interested in quantifying domestic wood production emissions and exports are less than 1% of harvested merchantable wood (http://www.fs.fed.us/pnw/ppet/). ‘Emissions’ include release of carbon from woody biomass combustion, and FFE associated with harvest (Sonne 2006), transport of both harvested material and end-use products (Evans and Finkral 2009, Heath et al. 2010), and processing and manufacturing of wood products (Heath et al. 2010) and bioenergy (Jaeger et al. 2007, Whitaker et al. 2010). ‘Decomposition’ includes loss of material through decomposition or combustion during the manufacturing of wood products (Smith et al. 2006), and the percentage of wood products that are expected to no longer be in-use at the end of the treatment period (Smith et al. 2006).

Biomass utilized for wood products can end up in a long term storage product (structural wood) or a short term product (paper). Some wood product carbon reenters the atmosphere through rapid (paper) or slow (wood) decomposition or combustion while some is eventually disposed in landfills where it is very slowly decomposed. West Coast harvests generate merchantable bole wood at rates of 50-60% of the total wood harvested (Harmon et al. 1996) and an average of 54% of this wood remains in use or is in landfills after 20 years (Smith et al. 2006). Using tables provided by (Smith et al. 2006) we determined the amounts of long and short term wood products that could be generated by the merchantable wood harvested accounting for the losses along the way and multiplied this by 54% to determine the wood product storage (Smith et al. 2006). Because this ratio could increase or decrease due to changes in manufacturing efficiency, product use, or recycling, we allowed for a 10% increase and decrease of this percentage for the additional harvest *only* as part of the sensitivity analysis (Heath et al. 2010, Lippke et al. 2010). The remaining non-merchantable wood (including understory trees) from harvest was used for biofuel biomass and associated emissions.

Fossil fuel substitution with bioenergy was calculated as a 50/50 energy mix of ethanol conversion and biomass combustion compared to fossil fuel derived automotive gasoline. Woody biomass provides less energy per unit of carbon emitted than fossil fuels (i.e. wood has an energy content of 20 GJ per ton versus 43.5 GJ per ton in automotive gasoline because fossil fuels have a lower heating value (Wright et al. 2006)). Under maximum yield conditions, the potential energy of woody biomass is 78% of fossil fuel if combusted and 36% if converted to cellulosic ethanol (Mitchell et al. 2009). These maximum values are highly unrealistic as they have yet to be obtained (Mitchell et al. 2009) and ratios up to 30% lower have been suggested (Galbe and Zacchi 2002). Nevertheless, we use the maximum values in our estimates under optimum conditions and reduce the ratios by 10 and 20% to provide a range of conditions in the sensitivity analysis (Table 7). State annual fossil fuel emissions were acquired from the Vulcan Project Database (http://www.purdue.edu/eas/carbon/vulcan/index.php) and from the

Oregon Department of Energy (http://www.oregon.gov/ENERGY/GBLWRM/CCIG.shtml, Appendix A).

There are also emissions associated with crude extraction and manufacturing, sometimes called the wells-to-tank emissions (WTT). Fossil fuel LCA total emissions (wells to wheels; WTW) include both WTT and tank-to-wheels (TTW) emissions. The amount of C emitted per unit of fossil fuel energy varies widely by oil field, but generally WTT emissions are about 15%(ICCT 2010) of total emissions (WTW), or 12 g CO_2 per MJ of energy. We have included theses emissions in the Wood Industry FFE and we have added a WTT displacement benefit along with the bioenergy substitution benefit.

An additional estimate of the LCA was calculated for a wood product substitution benefit. Wood product substitution for a 50/50 mix of aluminum and steel used in residential American housing generates a 36% reduction in fossil fuel emissions assuming a maintained rate in new residential housing (Upton et al. 2008). We applied a wood substitution benefit as 36% of the final structural wood product pool.

Uncertainty Analysis: Monte Carlo simulations were used to conduct an uncertainty analysis using the mean and standard deviations for NPP and Rh calculated using several approaches. For NPP, three alternative sets of allometric equations were used to estimate the uncertainty due to variation in region and/or species-specific allometry. The full suite of species-specific equations that use tree diameter (DBH) and height (preferred) were compared to a DBH-only national set (Jenkins et al. 2003) and to a grouped forest type set. For, Rh, the variation in the calculated decomposition rate was used to quantify the uncertainty. A species-specific lookup table of decay constants was compared to decay constants that were allowed to vary by genus, precipitation, and temperature or by class, precipitation and temperature. Finally, uncertainty in NBP was calculated as the combined uncertainty of NEP, fire emissions (10%) (Campbell et al. 2007), harvest emissions (7%) (Heath and Smith 2000), and land cover estimates (10%) using the propagation of error approach (NRC 2010). Uncertainty estimates are represented in the Figures by the grey error bars and in tables with '±'.

Sensitivity analysis of most of the LCA parameters is summarized below (Table A6). The most sensitive parameters in this study that affect net emissions and NBP are land area treated, allowable removals (DBH limit and basal area reductions) per unit area, and to some extent, fire emissions. First, we present a range of scenarios that vary by land area and allowable removals. Removals are varied by basal area reduction limits of 30, 40, and 50% for the FP, EC, and BP scenarios respectively. These reductions equate to removal rates of 25-53% of live biomass. To test the sensitivity of the reduction in fire emissions, we also calculated NBP and net emissions assuming 50% and 75% effectiveness of the treatments. Additional parameters that affect only net emissions is the ratio of wood products that are in use at the end of the treatment period, the efficiency of the conversion to energy, and the fossil fuel inputs required for energy conversion. For the in-use product ratio, we calculated net emissions for a 10% increase and decrease to the ratio. For the conversion efficiencies, we varied each of these factors by 100, 90 and 80% of the maximum possible values to present a range of results reflecting the most optimum conditions (100% efficiency) to the least optimum (80% efficiency) (Table A6). Values for the most optimum conditions are represented in the Figures unless otherwise noted.

In addition to evaluating the sensitivity of the proposed treatments to the parameter estimates, we also explored the effect of varying the range of harvest to NEP ratios, wood product to bioenergy biomass ratios, percent combusted versus converted to cellulosic ethanol, fossil fuel inputs required, and amount of wood product in the short-term product pool with subsequent recapture as bioenergy. We determined the hypothetical ratios where the forest net carbon flux was zero (neutral) or greater than or equal to the current flux (BAU) and compared the net carbon flux for each scenario with the range of ratios (Figure A6).

Discussion

State-level Estimates: Forest carbon stocks (excluding soil carbon) for the entire region are 5.0 ± 0.8 Pg C with 31% in Washington, 36% in Oregon, and 33% in California (Table A2). NPP ranges from 100 to 900 g C m^{-2} across the region and falls within the range of 100 to 1600 g C m^{-2} yr^{-1} reported for temperate and boreal forests (Luyssaert et al. 2008) and Rh ranges from 100 to 600 g C m^{-2}. Our estimates are in line with previous work: Our mean NEP ranges from -50 to 400 g C m^{-2} yr^{-1} similar to the range of -50 to 800 g C m^{-2} yr^{-1} reported for temperate forests (Luyssaert et al. 2008). Using a simulation model, the total NEP of Oregon in the late 1990's was estimated to be 17 ± 11 Tg C yr^{-1} (vs. 15.3 ± 1.6 Tg C yr^{-1} in this study) most of which was attributed to forests (Turner et al. 2007). Furthermore, recent estimates from (Raffa et al. 2008) predict an NEP of 25.5 Tg C yr^{-1} (vs. 29.2 Tg C yr^{-1} for the same area in this study) in the northwest forest plan area of Washington, Oregon, and California. Also using a simulation model, the total NEP of California (Potter 2010) for 2001-2004 ranged from 14-24 Tg C yr^{-1} (vs.18.1 Tg C yr^{-1} in this study). Previous regional estimates of NEP were not found for Washington.

We explored four scenarios, three treatments and business-as-usual (Figure A1a). The removal limits of 30-50% of stand basal area resulted in 25– 53 % removal of aboveground live tree biomass per plot which is typical for fuel reduction treatments (Skog et al. 2008, Harrod et al. 2009). These treatments do not replace current management practices. They result in additional harvest above the current harvest in the region. Statewide removals were much lower (by 5-10 Tg C yr^{-1}) in Washington than the other two states for the Fire Prevention and Economically Feasible scenarios due to a higher median MFRI (91-100 years versus less than 60 years) resulting in a reduced treatment area (Table A2). The Bioenergy Production scenario results in 264, 220, and 92% reductions in NBP in Washington, Oregon, and California respectively with Washington and Oregon forests becoming a carbon source (Table A2). The Fire Prevention and Economically Feasible scenario had the most impact on California NBP compared to Oregon and Washington (decreased from 13.6 Tg C yr^{-1} to 5.6 and 9.4 Tg C yr^{-1} respectively). Furthermore, at the state level, Washington NBP was not significantly different from BAU for either the Fire Prevention or the Economically Feasible scenario because a smaller percentage of the forested area is in a high fire risk area compared to the other two states resulting in lower harvest levels. Washington removals were balanced by the assumed reduction in fire emissions and increased NEP from regrowth. These findings suggest that in regions where proposed harvest is low there may be little effect on NBP compared with BAU.

Comparing California and Oregon, the area-weighted state level differences in NEP, fire and harvest, are respectively 20, 3.1 and 30 g C m^{-2} y^{-1} summing to a difference in NBP of 46.4 g C m^{-2} y^{-1} (Table A3), indicating the largest differences were in NEP and harvest removals. Coastal Redwood forests in California, for example, contribute 16.5 g C m^{-2} y^{-1} more to the state-wide NBP per unit area than the same forest type in Oregon. However, the opposite was observed in, for example, North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest. This forest type has a 19.9 g C m^{-2} y^{-1} higher NBP in Oregon than in California. Although there are considerable differences in fire emissions between Oregon and California (1.3 and 1.8 Tg C in OR vs CA), the difference in NEP and harvest between similar forest types within the same ecoregions appears to be the dominant reason of the observed differences in NBP between the two states. Some of the possible causes of the difference in NBP are: (1) A productive forest type is present in California but absent in Oregon (i.e. Lower Montane Blue Oak-Foothill Pine Woodland and Savanna), (2) A forest type with an above-average NBP is managed similarly in California and Oregon but is more abundant and productive in California (i.e. Coastal Redwood Forest and Mediterranean (Dry-)Mesic Mixed Conifer Forest and Woodland) and (3) The losses through harvest are lower in California than Oregon in forest types that cover a large area (North Pacific Sitka Spruce, Dry-Mesic and Wet-Mesic Douglas-fir-Western Hemlock Forests). Additionally, our estimates of NBP rely on our estimates of NEP using the mass balance approach. For stands older than 150 years, we have assumed a steady-state for the soil carbon pool (i.e. delta soil carbon is zero). For stands younger than 150 years, we used the best available data to estimate a delta soil carbon value for each plot depending on the age. We may be overestimating by a larger amount if the loss of soil carbon due to disturbance is higher (or gain is slower) in ecoregions (i.e California) not represented in our soils dataset. If we are overestimating NEP and subsequently overestimating NBP, the biomass removal impact on NBP is underestimated.

Previous estimates of forest biomass potentially available for energy supply in Oregon and California vary widely, from 0.4 – 14 Tg C yr^{-1}, depending on assumptions of area needing treatment, volume removed per hectare, and the number of years over which treatments are conducted (Bowyer 2006, Williams 2007, Strittholt and Tutak 2009). While these estimates are in general agreement with our estimates from all three treatments (3.8 – 17 Tg C yr^{-1} for Oregon and California combined), they only addressed a portion of the potential biomass removals i.e. that used for energy production. In our scenario analysis, we go beyond previous approaches by accounting for the fate of all biomass removals and assess their effect on forest NBP. The thinning treatments result in additional biomass removals of 11- 44 Tg C yr^{-1} from current inventory biomass levels for the entire region (Table A5) of which only 7 – 24 Tg C yr^{-1} would be used for energy supply. Since current harvest levels are half of what they were in 1980s, three times current harvest rates are possible in this region as has been suggested in government and industry reports and given the current level of effort that is going into developing a biomass industry (Perlack et al. 2005, OFRI 2006). The proposed harvest intensities are simply scenarios that are being considered in one region, and the application of such scenarios over other regions or subregions may not be appropriate given the forest type, climate, and management history. For example, in fire prone or beetle killed areas, it may be necessary to apply moderate harvest levels. Our approach lends itself to testing the carbon consequences of location-specific management activities.

Additional LCA analysis: Proper accounting of the *in-situ* NBP in LCA reveals the effects of forest management on atmospheric CO_2 when considering mitigation options for reducing CO_2 emissions. Towards this aim, we developed a conceptual model to determine the outcomes of mitigation options which may include different ratios of wood product to energy mixes, higher or lower BAU harvest to NEP ratios, or efficiency of fossil fuel usage. The conceptual LCA model addresses the main determinants of the forest sector carbon budget i.e. forest management and wood processing. This conceptual model reveals that the largest decreases in the forest sector emissions are accomplished by reducing the harvest to NEP ratio (Figure A3, red line).

We analyzed the sink-strength of the forest sector for varying management intensities where intensity was expressed as the ratio of harvest to net ecosystem productivity (H/NEP), the latter including forest growth and regrowth. The current H/NEP ratio is about 0.3. Wood processing was described by the ratio of wood products to total harvest (P/H). We then investigated the combinations of P/H ratios varying from 0 to 1 with different combinations of bioenergy (combustion versus ethanol), 0-100% reduction in fossil fuel inputs, and recycling of manufactured waste for bioenergy production to determine if biomass end-use affected the forest sector CO_2 emissions. Changing the ratios for the percentage used in wood products versus bioenergy (Figure A3a), the mix of energy used for combustion versus cellulosic ethanol (Figure A3b), the efficiency of fossil fuel inputs (Figure A3c), and the reduction of the short-term product pool (Figure A3d) has very little impact compared to the increase in removals.

Furthermore, this analysis suggests that a reduction of net CO_2 emissions compared to BAU can only be realized if harvest remains at current levels or increases to a maximum of 20% more than BAU, but this requires that either all bioenergy is produced by means of combined heat and power rather than ethanol (Figure A3b), or wood-use results in 100% reduction of fossil fuel emissions from this process (Figure A3c), or 100% of waste wood is used for bioenergy production (Figure A3d). These measures are definitely unlikely to take place within the proposed 20-year time-frame.

Sensitivity Analysis: The differences in NBP and emissions due to land area treated and allowable removals are shown in Table 2. The amount of land area treated has a significant impact on NBP. In the life-cycle assessment, the range in efficiencies changed the impact of the scenarios by 3-28% (Table A6). For example, if the amount of wood products in use are reduced by 10%, bioenergy production is at 80% of optimum conditions (least effective), and fire emissions are reduced by 50%, net emissions to the atmosphere increase by a larger amount: 101, 251, and 579 Tg C for the Fire Prevention, Economically Feasible, and Bioenergy Production scenarios respectively (compared with 44, 175, and 421 Tg C for 100% of optimum conditions; Table A5). Using the alternative combustion estimates reduces the impact of the FP and EC scenarios by 6-9%, and increases the impact in the BP scenario. This increase in initial fire emissions eliminates the net increases in emissions for the FP scenario (very small annual increase), but only under optimum conditions. The impact is greatest in the Klamath Mountains. Inclusion of wood substitution reduces atmospheric emissions by 2-10% across the scenarios, but only under optimum conditions and assuming there is a demand for the wood use.

Finally, our estimates of BAU harvest practices may decrease in the future, in which case, we could be overestimating removals over the next 20 years. However, this is unlikely because harvest declined significantly since 1990 due to restrictions placed on harvest on federal lands as part of the Northwest Forest Plan.

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Table A1. Ecoregion characteristics including dominant forest types, mean annual temperature (MAT), mean annual precipitation (MAP), and area weighted mean fire return interval (MFRI).

Eco-region[1]	Forest (ha)	Dominant Forest Types	MAT	MAP	MFRI
BM	3312268	Mixed Conifer, Ponderosa Pine, Juniper, Spruce-Fir	7.3	552	41 to 45
CB	352650	Pinyon-Juniper, Jeffrey-Ponderosa Pine, Limber-Bristlecone Pine	6.0	445	51 to 60
CO	2688165	Blue Oak-Foothill Pine, Mixed Evergreen, Mixed Conifer, Redwood, Oak Woodland and Savanna, Black Oak-Conifer	14.8	652	26 to 30
CP	253667	Mixed Conifer, Ponderosa Pine, Riparian	9.7	330	51 to 60
CR	4812627	Douglas-fir-Western Hemlock, Sitka Spruce, Redwood, Mixed Evergreen, Riparian, Western Red Cedar, Western Hemlock-Silver Fir	11.0	1742	91 to 100
CV	170243	Blue Oak-Foothill Pine, Riparian, Salt Desert Scrub, Mixed Oak Savanna	17.2	412	36 to 40
EC	3545116	Ponderosa Pine, Mixed Conifer, Montane Riparian, Juniper, Jeffrey Pine-Ponderosa Pine, Lodgepole Pine, Red Fir, Mountain Hemlock	9.1	630	36 to 40
KM	3748465	Mixed Conifer, Mixed Evergreen, Red Fir, Douglas-fir-Western Hemlock, Riparian, Black Oak-Conifer, Redwood, Mixed Oak Woodland	11.5	1549	16 to 20
MB	93889	Pinyon-Juniper, Montane Riparian, Mixed Oak Woodland	18.4	185	41 to 45
NB	478106	Juniper, Aspen, Pinyon-Juniper, Montane Riparian, Jeffrey-Ponderosa Pine, Mountain Mahogany	9.7	304	51 to 60
NC	2311424	Western Hemlock-Silver Fir, Mixed Conifer, Mountain Hemlock, Spruce-Fir, Western Red Cedar, Riparian, Subalpine Woodland	5.6	1548	101 to 125
NR	1514359	Mixed conifer, Riparian, Spruce-Fir, Ponderosa Pine	7.5	613	51 to 60
PL	1102015	Douglas-fir-Western Hemlock, Riparian, Western Red Cedar, Sitka Spruce	10.6	1304	151 to 200
SB	2175	Pinyon-Juniper	22.0	110	41 to 45
SM	730051	Mixed Evergreen, Mixed Conifer, Mixed Oak, Blue Oak-Foothill Pine, Oak Woodland, Riparian	12.3	1064	26 to 30
SN	1022645	Mixed Conifer, Red Fir, Jeffrey-Ponderosa Pine, Riparian, Mixed Oak, Subalpine Woodland, Blue Oak-Foothill Pine, Black Oak-Conifer, Lodgepole Pine	8.2	915	21 to 25
SR	8613	Montane Riparian	9.7	303	101 to 125
WC	4329871	Douglas-fir-Western Hemlock, Silver Fir-Western Hemlock, Mountain Hemlock, Mixed Conifer, Red Fir, Riparian, Western Red Cedar	8.8	1688	101 to 125
WV	538681	Douglas-fir-Western Hemlock, Riparian	11.0	1280	46 to 50

[1] BM, Blue Mountains; CB, Central Basin; CO, California Chaparral and Oak Woodlands; CP, Columbia Plateau; CR, Coast Range; CV, Central California Valley; EC, East Cascades; KM, Klamath Mountains; MB, Mohave Basin; NB, North Basin and Range; NC, North Cascades; NR, Northern Rockies; PL, Puget Lowlands; SB, Sonoran Basin; SM, Southern California Mountains; SN, Sierra Nevada; SR, Snake River; WC, West Cascades; WV, Willamette Valley.

Table A2. State total and mean carbon fluxes for Business-As-Usual (BAU) and treatments. Net biome production (NBP) calculated for 75% treatment efficiency (possible fire emission reductions). Uncertainty is noted by the '±' symbol.

State (forested hectares)	**Washington 9.0×10^6**	**Oregon 12.2×10^6**	**California 12.8×10^6**
Annual Fossil Fuel Emissions (Tg C yr^{-1})	**21**	**15**	**105**
Carbon density (Mg C ha^{-1})	**172 ± 25**	**150 ± 22**	**130 ± 18**
Net Primary Production (NPP)			
(Tg C yr^{-1})	**46.7 ± 4.7**	**60.0 ± 6.0**	**61.0 ± 6.2**
(g C m^{-2} yr^{-1})	**518 ± 52**	**488 ± 49**	**477 ± 48**
Net Ecosystem Production (NEP)			
(Tg C yr^{-1})	**11.3 ± 1.2**	**15.2 ± 1.6**	**18.1 ± 2.1**
(g C m^{-2} yr^{-1})	**125 ± 13**	**125 ± 13**	**142 ± 16**
Harvest emissions (Tg C yr^{-1})	**5.5 ± 0.4**	**6.4 ± 0.5**	**2.7 ± 0.2**
Fire emissions (Tg C yr^{-1})	**0.9 ± 0.1**	**1.3 ± 0.2**	**1.8 ± 0.3**
Net Biome Production (NBP)			
(Tg C yr^{-1})	**4.8 ± 1.3**	**7.5 ± 1.7**	**13.6 ± 2.1**
(g C 2^{-2} yr^{-1})	**53 ± 14**	**61 ± 14**	**107 ± 16**
Area Treated (hectares)			
• **Fire Prevention**	**0.8×10^6**	**4.0×10^6**	**6.8×10^6**
• **Economically Feasible**	**0.8×10^6**	**4.0×10^6**	**6.8×10^6**
• **Bioenergy Production**	**7.2×10^6**	**9.8×10^6**	**7.9×10^6**
Additional Removals (Tg C yr^{-1})			
• **Fire Prevention**	**0.6 ± 0.02**	**3.8 ± 0.2**	**6.7 ± 0.4**
• **Economically Feasible**	**0.9 ± 0.04**	**5.7 ± 0.3**	**10.5 ± 0.7**
• **Bioenergy Production**	**13.2 ± 0.4**	**17.2 ± 0.7**	**13.4 ± 0.9**
Scenario NBP (Tg C yr^{-1})			
• **Fire Prevention**	**4.8 ± 1.3**	**5.2 ± 1.7**	**9.4 ± 2.1**
• **Economically Feasible**	**4.5 ± 1.3**	**3.3 ± 1.7**	**5.6 ± 2.2**
• **Bioenergy Production**	**-6.1 ± 1.3**	**-6.6 ± 1.9**	**2.9 ± 2.3**

Table A3. Forest types that contribute more than 1 g C m^{-2} y^{-1} to the observed area-weighted difference of 46.4 g C m^{-2} y^{-1} (see also Table 2) in net biome production (NBP) between California and Oregon for shared forest types. For example, this difference in NBP is partially due to an area-weighted difference in net ecosystem production (NEP) and harvest of 19.2 and 2.7 g C m^{-2} y^{-1} for the California Coastal Redwood forest type (see example calculation in footnote). Units are in g C m^{-2} y^{-1} unless otherwise noted.

Forest Type	State	NEP	Fire	Harvest	Area (ha)	ΔNEP	ΔFire	ΔHarvest	Weighted NBP	ΔNBP
North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest	**CA**	**189**	**4**	**0**	**3488**	**-44.9**	**-0.1**	**-24.9**	**0.1**	**-19.9**
	OR	**205**	**0**	**113**	**2684324**				**19.9**	
California Coastal Redwood Forest	**CA**	**296**	**1**	**41**	**832912**	**19.2**	**0.1**	**2.7**	**16.6**	**16.5**
	OR	**238**	**0**	**26**	**2983**				**0.1**	
California Lower Montane Blue Oak-Foothill Pine Woodland and Savanna	**CA**	**120**	**7**	**17**	**1636673**	**15.4**	**0.9**	**2.2**	**12.3**	**12.3**
	OR	**0**	**0**	**0**	**0**				**0.0**	
Mediterranean California Mesic Mixed Conifer Forest and Woodland	**CA**	**111**	**13**	**27**	**2748963**	**17.6**	**1.9**	**4.1**	**15.4**	**11.6**
	OR	**107**	**14**	**29**	**721488**				**3.8**	
Central and Southern California Mixed Evergreen Woodland	**CA**	**186**	**28**	**2**	**643670**	**9.4**	**1.4**	**0.1**	**7.9**	**7.9**
	OR	**0**	**0**	**0**	**0**				**0.0**	
California Montane Riparian Systems	**CA**	**165**	**14**	**0**	**667775**	**8.1**	**0.7**	**0.0**	**7.9**	**7.4**
	OR	**163**	**18**	**0**	**42589**				**0.5**	
Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland	**CA**	**153**	**20**	**27**	**1559888**	**10.1**	**2.0**	**1.2**	**13.0**	**6.8**
	OR	**158**	**8**	**37**	**671005**				**6.2**	
Mediterranean California Mixed Evergreen Forest	**CA**	**308**	**11**	**62**	**581798**	**3.6**	**-3.0**	**1.1**	**10.7**	**5.5**
	OR	**228**	**76**	**38**	**562982**				**5.2**	
North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest	**CA**	**166**	**0**	**0**	**3184**	**-11.1**	**-0.7**	**-5.4**	**0.0**	**-5.0**
	OR	**163**	**11**	**78**	**838685**				**5.1**	
Great Basin Pinyon-Juniper Woodland	**CA**	**208**	**23**	**0**	**343308**	**5.4**	**0.6**	**0.0**	**5.0**	**4.8**
	OR	**221**	**16**	**0**	**8570**				**0.1**	
Mediterranean California Mixed Oak Woodland	**CA**	**155**	**27**	**0**	**455384**	**5.4**	**1.0**	**0.0**	**4.5**	**4.4**
	OR	**151**	**7**	**0**	**9823**				**0.1**	

Forest Type	State	NEP	Fire	Harvest	Area (ha)	ΔNEP	ΔFire	ΔHarvest	Weighted NBP	ΔNBP
Mediterranean California Red Fir Forest	CA	91	13	20	1087841	6.7	1.1	1.3	4.9	4.3
	OR	90	2	38	147570				0.6	
North Pacific Hypermaritime Sitka Spruce Forest	CA	0	0	0	0	-7.2	0.0	-3.8	0.0	-3.4
	OR	275	0	145	321231				3.4	
Northern Rocky Mountain Ponderosa Pine Woodland and Savanna	CA	59	3	21	104182	-5.8	-0.9	-1.9	0.3	-3.0
	OR	63	10	20	1225805				3.3	
North Pacific Montane Riparian Woodland and Shrubland	CA	178	3	0	2846	-2.7	-0.1	0.0	0.0	-2.7
	OR	175	3	0	192321				2.7	
Mediterranean California Lower Montane Black Oak-Conifer Forest	CA	158	13	27	320462	3.6	0.3	0.6	2.9	2.6
	OR	159	9	23	28108				0.3	
Southern California Oak Woodland and Savanna	CA	158	51	0	261241	3.2	1.0	0.0	2.2	2.2
	OR	0	0	0	0				0.0	
Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest	CA	41	4	20	4468	-5.6	-1.0	-2.4	0.0	-2.2
	OR	40	7	17	1737309				2.2	
California Montane Jeffrey Pine(-Ponderosa Pine) Woodland	CA	71	11	22	601572	3.3	0.4	1.0	1.8	1.9
	OR	71	89	22	13831				0.0	
North Pacific Dry-Mesic Silver Fir-Western Hemlock-Douglas-fir Forest	CA	122	0	0	9	-4.1	-0.2	-2.1	0.0	-1.8
	OR	142	7	73	350817				1.8	
North Pacific Swamp Systems	CA	190	0	0	71	-1.7	0.0	0.0	0.0	-1.7
	OR	190	5	0	112087				1.7	
North Pacific Mountain Hemlock Forest	CA	105	2	33	9232	-2.9	-0.4	-1.4	0.1	-1.1
	OR	99	14	48	372207				1.1	

[1] Weighted NBP = ((NEP – Fire – Harvest) * Forest Type Area) / Total Forest Area of State; Total forest areas are 12.2 and 12.8 million hectares for Oregon and California, respectively (Table 2)

Table A4. Life Cycle Assessment coefficients. Each coefficient is multiplied by a biomass pool (Tg C yr^{-1}). Processing efficiencies vary by state (PNW = Pacific Northwest or Oregon and Washington; CA = California)

Life-Cycle Factor	**Coefficient**	**Biomass Pool**	**Description and source**
Sawlog (SL)	0.80	Merchantable wood	Sawlog fraction of merchantable portion of harvest(Smith et al. 2006)
Pulpwood (PW)	0.11	Merchantable wood	Pulpwood fraction of merchantable portion of harvest(Smith et al. 2006)
WD1a	0.09	Merchantable Wood	Portion of wood lost in initial manufacturing process(Smith et al. 2006)
Sawlog Wood (PNW) Sawlog Wood (CA)	0.56 0.53	Sawlog (SL)	Wood product fraction of sawlog (Smith et al. 2006)
Sawlog Paper (PNW) Sawlog Paper (CA)	0.25 0.145	Sawlog (SL)	Paper product fraction of sawlog (Smith et al. 2006)
Pulpwood Paper (PNW) Pulpwood Paper (CA)	0.50 0.145	Pulpwood (PW)	Paper product fraction of pulpwood (Smith et al. 2006)
WD1b	na	(SL+PW)- (Wood + Paper)	Portion of wood lost in conversion to products (Smith et al. 2006)
WD2	0.46	(Wood + Paper)	10yr Decomposition (no longer in use or in a landfill) (Smith et al. 2006)
Wood Industry FFE[2] Harvest Harvest Transport Manufacturing Wood Paper Product Transport FF WTT[3]	 .009 .003 0.004 0.57 0.009 0.1675	 Merchantable Wood Merchantable Wood Wood Paper (Wood + Paper) Wood Industry FFE	 Harvest FFE (Sonne 2006) Transport FFE (Heath et al. 2010) for average 75 km distance(Evans and Finkral 2009) Wood FFE (Heath et al. 2010) Paper FFE (Heath et al. 2010) Transport FFE (Heath et al. 2010) for average 250 km distance(Evans and Finkral 2009) Fossil Fuel extraction and production (ICCT 2010)

Bioenergy FFE Combustion (CHP) Cellulosic Ethanol (CE)	 0.05 0.35	 Non-Merchantable Wood Non-Merchantable Wood	 Harvest, Transport, Chip manufacturing(Heath et al. 2010) Harvest, Transport, Conversion to Ethanol(Jaeger et al. 2007, Whitaker et al. 2010)
Bioenergy Substitution Combustion (CHP) Cellulosic Ethanol (CE)	 0.78 0.36	 Non-Merchantable Wood Non-Merchantable Wood	 FFE reduction for the energy potential of wood energy compared to fossil fuel (Mitchell et al. 2009)
FF WTT Displacement	0.1675	Bioenergy Substitution	Displaced FF emissions from crude oil extraction
Bioenergy Emissions	1.00	Non-Merchantable Wood	C released from bioenergy use
Wood Substitution	0.36	Sawlog Wood	FFE reduction with 50:50 mix of aluminum/steel substitution(Upton et al. 2008)

[1] LCA = FCO_2 = NBP + Total Harvest – WD1a – WD1b – WD2 – Wood Industry FFE - Bioenergy Emissions + Bioenergy Substitution + FF WTT displacement + (Wood Substitution); WTT = Well to tank emissions; WD = Wood decomposition; Wood Substitution is dependent on increase in wood use

[2] FFE = Fossil Fuel Emissions

[3] WTT = Well to Tank emissions from crude oil extraction are approximately 15% of total well to wheels (extraction plus use) emissions.

Table A5. Life cycle assessment of forest derived bioenergy for the West Coast region assuming a 50:50 mix of combustion for combined heat and power (CHP) and conversion to cellulosic ethanol (CE). All values are in Tg C yr^{-1} unless otherwise noted. Numbers in bold represent optimum conditions, biomass pool specific combustion factors, and no wood substitution.

LCA Parameter	**Business-as-Usual (BAU) Opt | Alt | Low[1]**	**Fire Prevention Opt | Alt | Low**	**Economically Feasible Opt | Alt | Low**	**Bioenergy Production Opt | Alt | Low**
NEP	**44.5**	**38.0**	**38.0**	**30.5**
Regrowth [2]	**0.00**	**9.6**	**9.6**	**20.6**
Fire emissions	**4.1 | 8.1 | na**	**2.5 | 3.9 | 3.0**	**2.5 | 3.9 | 3.0**	**2.5 | 3.9 | 3.0**
Total harvest [3]				
Current	**14.6**	**14.6**	**14.6**	**14.6**
Additional	**0.00**	**11.1**	**17.1**	**43.8**
NBP [4]	**25.8 | 21.8 | na**	**19.4 | 18.0 | 18.9**	**13.4 | 12.0 | 12.9**	**-9.7 | -11.1 | -10.3**
Wood Product FFE (fossil fuel emissions)	**1.06**	**2.74**	**6.69**	**8.07**
Wood Decomposition (WD1)	**4.7**	**9.34**	**10.46**	**16.82**
Wood Decomposition (WD2)	**4.5**	**4.25 | 4.25 | 4.68**	**4.64 | 4.64 | 4.96**	**7.12 | 7.12 | 9.16**
Bioenergy emissions	**0.00**	**6.80**	**10.65**	**24.12**
FF Substitution	**0.00**	**3.9 | 3.9 | 2.5**	**6.1 | 6.1 | 3.9**	**13.7 | 13.7 | 8.9**
FF WTT Displaced[5]	**0.00**	**0.65 | 0.65 | 0.42**	**1.01 | 1.01 | 0.67**	**2.30 | 2.30 | 1.49**
Wood Substitution	**0.00**	**0.7**	**1.0**	**3.1**
FCO_2 [6]				
No Wood Sub	**28.9 | 24.8 | na**	**26.6 | 25.1 | 24.0**	**19.8 | 18.4 | 16.1**	**8.6 | 7.2 | 0.4**
With Wood Sub	**na**	**27.2**	**20.8**	**11.6**
Uncertainty	**3.0**	**3.1**	**3.3**	**3.5**
Σ Tg C added to atmosphere (20 yrs)				
No Wood Sub	**0.00**	**46.0 | -7.0 | 97.3**	**174.6 | 127.7 | 254.4**	**420.7 | 352.0 | 569.1**
With Wood Sub	**0.00**	**32.9**	**161.1**	**344.5**

Table Footnotes (continued)

[1] Opt = Optimum efficiency parameters, Alt = Alternative combustion coefficients, not pool specific, Low = Low efficiency parameters

[2] Thinned plot total NEP is the sum of the NEP and Regrowth rows

[3] Total harvest includes the continued harvest for wood products plus an additional harvest for bioenergy resulting in harvest increases compared to BAU for each scenario

[4] NBP = Scenario NEP + Scenario Regrowth – Scenario Total harvest – Scenario Fire emissions

[5] FF WTT = Fossil fuel well-to-tank emissions from extraction and refining of crude oil

[6] FCO_2 = NEP + Regrowth – Fire –Wood Product FFE (includes associated FF WTT) – WD1 – WD2 – Bioenergy Emissions + FF Substitution + FF WTT displacement + (Wood Substitution)

Table A6. Sensitivity Analysis parameters and relative impact on results (CHP = biomass used as combined heat and power; FP = Fire Prevention scenario; EC = Economically Feasible scenario; BP = Bioenergy Production scenario).

Efficiency	**Parameters evaluated**	**Value**	**Impact on result (%)**
Optimum	CHP substitution efficiency	0.78	These are the optimum or best case scenario conditions and were used for the results. The other sets of parameter values are compared to the FCO_2 value obtained for this parameter set. Negative values indicate emissions savings.
	Ethanol substitution efficiency	0.36	
	Percentage wood products still in use or in landfill	0.64	
	Fire emissions reductions	75%	
Moderate	CHP substitution efficiency	0.68	FP +3% EC +5% BP +13%
	Ethanol substitution efficiency	0.26	
	Percentage wood products still in use or in landfill	0.54	
	Fire emissions reductions	75%	
Low	CHP substitution efficiency	0.58	FP +9% EC +12% BP +28%
	Ethanol substitution efficiency	0.16	
	Percentage wood products still in use or in landfill	0.44	
	Fire emissions reductions	50%	
Combustion	Woody biomass combustion coefficients	30% combustion of all aboveground woody biomass	FP -9% EC -6% BP +1%
Wood Substitution	Included wood substitution in LCA	36% substitution benefit of structural wood products pool	FP -2% EC -3% BF -10%

Table A7. Forest Inventory Analysis plot information for the study region.

Ecoregion[1]	Number of Plots	With Increment Data	With Phase 3 measurements	Percentage excluded
BM	885	857	672	22
CB	129	126	101	20
CO	672	633	509	20
CP	75	66	48	27
CR	1057	1036	819	21
CV	13	11	10	9
EC	1097	1069	855	20
KM	1154	1137	878	23
MB	57	53	42	21
NB	115	106	76	28
NC	482	477	359	25
NR	338	334	258	23
PL	174	169	122	28
SM	204	192	167	15
SN	1275	1258	1035	18
WC	1019	998	801	20
WV	115	109	91	17

[1] BM, Blue Mountains; CB, Central Basin; CO, California Chaparral and Oak Woodlands; CP, Columbia Plateau; CR, Coast Range; CV, Central California Valley; EC, East Cascades; KM, Klamath Mountains; MB, Mohave Basin; NB, North Basin and Range; NC, North Cascades; NR, Northern Rockies; PL, Puget Lowlands; SB, Sonoran Basin; SM, Southern California Mountains; SN, Sierra Nevada; SR, Snake River; WC, West Cascades; WV, Willamette Valley.

Table A8. Equations and factors used to calculate carbon stocks, fluxes, and life-cycle assessment.

Component	**Code**	**Equation**	**Notes**
Bole Biomass [1]	Biomass_b	Bole Volume Equation*Wood Density	Bole volume derived from allometric equation using DBH (diameter at breast height) and height; (Jenkins et al. 2003, Hudiburg et al. 2009)
Branch biomass	Biomass_{br}	Allometric Equation	Derived from DBH and/or height;(Jenkins et al. 2003, Hudiburg et al. 2009)
Bark biomass	Biomass_{ba}	Allometric Equation	Derived from DBH and/or height; (Jenkins et al. 2003, Hudiburg et al. 2009)
Foliage biomass	Biomass_f	Allometric Equation	Derived (allometry) from DBH and/or height; (Jenkins et al. 2003, Hudiburg et al. 2009)
Coarse root biomass	Biomass_{cr}	Allometric Equation	Derived from a volume equation developed for Douglas-fir and species-specific wood densities; (Jenkins et al. 2003, Hudiburg et al. 2009)
Leaf Area Index [2]	LAI	Biomass_f/ LMA	Calculated from Biomass_f and leaf mass per unit leaf area (LMA)
Fine root biomass	Biomass_{fr}	$(\exp(4.4179+(.3256*\text{LAI})-(.0237*\text{LAI}^2))$	(Van Tuyl et al. 2005), Supplemental plot data ($p<0.001$, $R^2 = 0.41$, $n=36$)
Understory shrub biomass [3]	Biomass_s	a*(1-(exp(-b*Shrub Volume)))	Shrub volume calculated as the product of the recorded fraction plot cover, plot area, and height
Coarse woody debris Volume	Volume_{cwd}	$(9.869/(8*L))*(D^2)^5$	Where, L is the transect length in meters and D is the diameter of the piece in centimeters (Van Wagner 1968, Harmon and Sexton 1996, Waddell 2002)
Coarse woody debris biomass	Biomass_{cwd}	Volume_{cwd} * Adjusted Density	Derived by multiplying Volume_{cwd} by a decay class adjusted species-specific density

Component	**Code**	**Equation**	**Notes**
Wood NPP (Bole, Branch, Bark, and Coarse Roots)	NPP_w	$Biomass_{w2}$ – $Biomass_{w1}$	Difference between biomass of woody components at current and previous time steps
Foliage NPP[4]	NPP_f	$Biomass_f$/ Foliage Retention time	Biomass of foliage divided by the average number of years of foliage a stand carries[5]
Fine root NPP	NPP_{fr}	$Biomass_{fr}$ * 1.2 $year^{-1}$	Average fine root turnover (1.2 year-1) obtained from the literature and supplemental plot data (Keyes and Grier 1981, Campbell et al. 2004a)
NEP	NEP	ANPP – Rh_{wood} – litterfall + Δ root + Δ soil C	Where Δ fine root and Δ soil C are assumed to be zero over the time period(Giardina and Ryan 2002)
Litterfall		NPP_f x 0.79	Average mass retention of 21%; (van Heerwaarden et al. 2003)
Dead Wood Rh	Rh_{wood}	$Biomass_{cwd}$ - $Biomass_{cwd}$ *exp(-kt)	Where k value is calculated as a function of piece size, genus, precipitation, and mean annual temperature (http://www.bgc-jena.mpg.de/bgc-organisms/pmwiki.php/Research/FET)

[1] Species-specific wood densities were obtained from US Forest Service wood density survey for western Oregon (Maeglin and Wahlgren 1972), the Forest Products Laboratory wood handbook (1974) (Laboratory 1974), and from wood cores obtained on our supplemental plots. Wood densities were reduced according to decay class for standing dead trees (Waddell 2002).

[2] Leaf specific mass (LMA) was obtained from a look-up Table of species-specific values obtained from measurements on the supplemental plots in each of the ecoregions. In some cases, a species-specific value was not available and therefore a closely related species was used.

[3] The parameters ‘a’ and ‘b’ are regression coefficients that vary by species. Equations were developed from harvested shrubs at the supplemental field plots.

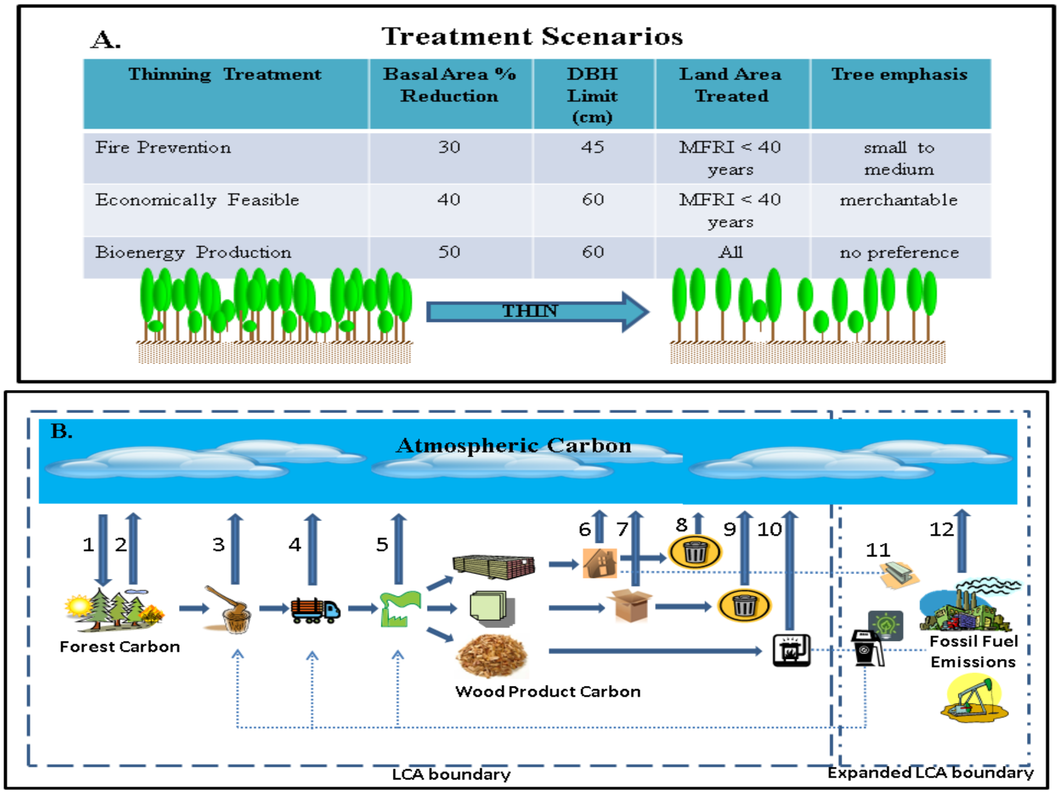
[4] Foliage (branch) samples from evergreen species were collected at all supplemental plots and the average number of years of growth retained on each branch was recorded to calculate retention time. Samples were also dried and weighed. New shoot growth was recorded for foliage NPP. This information was used to construct species and ecoregion specific lookup Tables for the FIA plots.

Table A9. Comparison of combustion factors by source and fuel category.

Source	**Forest Types**	**Fuel Category**	**Combustion Factor (Fraction Combusted) by severity**			
			High	**Moderate**	**Low**	**Unburned/Very Low**
Campbell et al., 2007	Mixed Conifer, Douglas-fir, Western Hemlock, Tanoak, Jeffrey Pine	Trees	0.08	0.07	0.03	0.00
		Snags	0.18	0.14	0.11	0.01
		Shrubs	0.86	0.66	0.42	0.00
		Foliage	1.00	0.76	0.75	0.70
		FWD	1.00	0.76	0.75	0.70
		CWD	0.78	0.58	0.61	0.62
		Litter	1.00	0.76	0.75	0.70
		Duff	0.99	0.51	0.54	0.44
Meigs et al., 2009[1]	Ponderosa Pine	Live Trees	0.03	0.014	.003	n.a.
Wiedinmyer and Hurteau (2010)[2], Wiedinmyer et al., 2006	n.a.	Aboveground woody mass	0.30	0.30	0.30	0.30
		Litter/Duff	0.90	0.90	0.90	0.90

[1] From Consume 3.0 simulations (Ottmar et al. 2006) and field measurements of consumption

[2] Combustion factors were not indicated to vary by severity in the reported citations



A. **Treatment Scenarios**

Thinning Treatment	Basal Area % Reduction	DBH Limit (cm)	Land Area Treated	Tree emphasis
Fire Prevention	30	45	MFRI < 40 years	small to medium
Economically Feasible	40	60	MFRI < 40 years	merchantable
Bioenergy Production	50	60	All	no preference

Figure A1. **A**. Thinning treatment scenarios. Included are the percent basal area reductions, the maximum tree diameter (DBH) that can be harvested, and the land area where the proposed treatment would be implemented. The treatments remove enough live biomass in order to lower risk of wildfire and provide biomass for bioenergy. MFRI is the mean fire return interval. **B**. Boundary of the processes accounted for in the life-cycle assessment (LCA). The boundary was expanded to account for substitution of fossil fuels by bio-energy. Full lines show C flow and dotted lines show energy flow. Arrows show fluxes and lines show substitution. Carbon is exchanged between the forest and the atmosphere through photosynthesis (1) and respiration (2) and lost to the atmosphere via fire (2) or removed by harvest (3). The carbon removed is used for bioenergy or wood products. Transport of the biomass to either end use utilizes fossil fuels and contributes to the total fossil fuel emissions (FFE) (4). FFE are associated with both manufacturing of wood products and both forms of bioenergy production (energy is required to convert the biomass to a useable form of energy; (5)). Biomass utilized for wood products can end up in a long term storage product (structural wood), a short term product (paper), imported, or exported. Some wood product carbon reenters the atmosphere through slow (6; wood) or rapid (7; paper) decomposition or combustion while some of it is eventually disposed in landfills (8 and 9) where it is very slowly decomposed. Biomass utilized for bioenergy can be burned or converted to cellulosic ethanol, releasing carbon to the atmosphere (10). Wood products can be substituted for fossil fuel products (11) and bioenergy emissions can be substituted for fossil fuel emissions associated with use, extraction, and production (12).

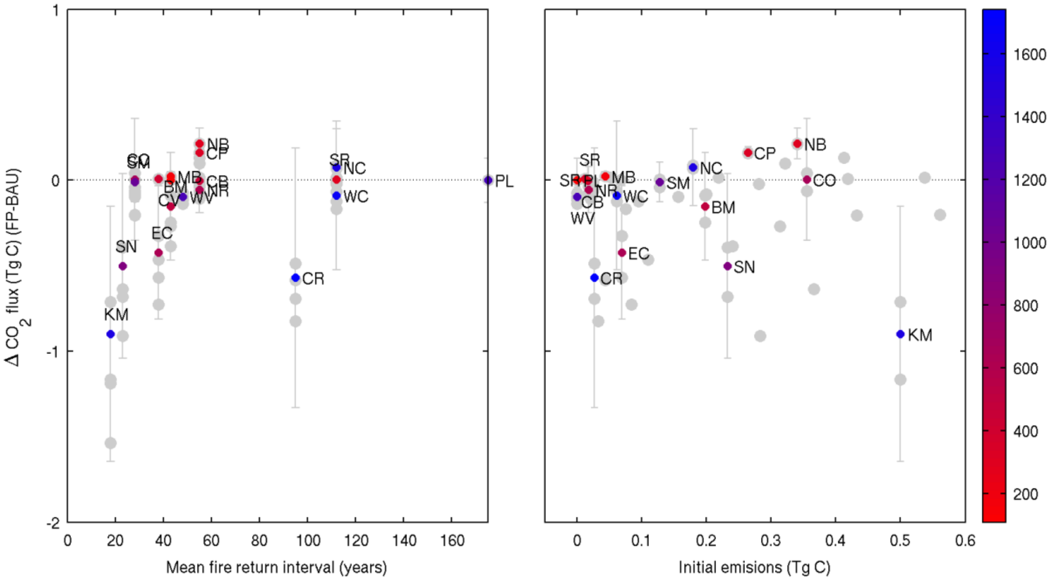


Figure A2. (A) MFRI (Mean Fire Return Interval) verses delta CO_2 (Fire Prevention; FP – Business as Usual; BAU) and (B) initial emissions versus delta CO_2.

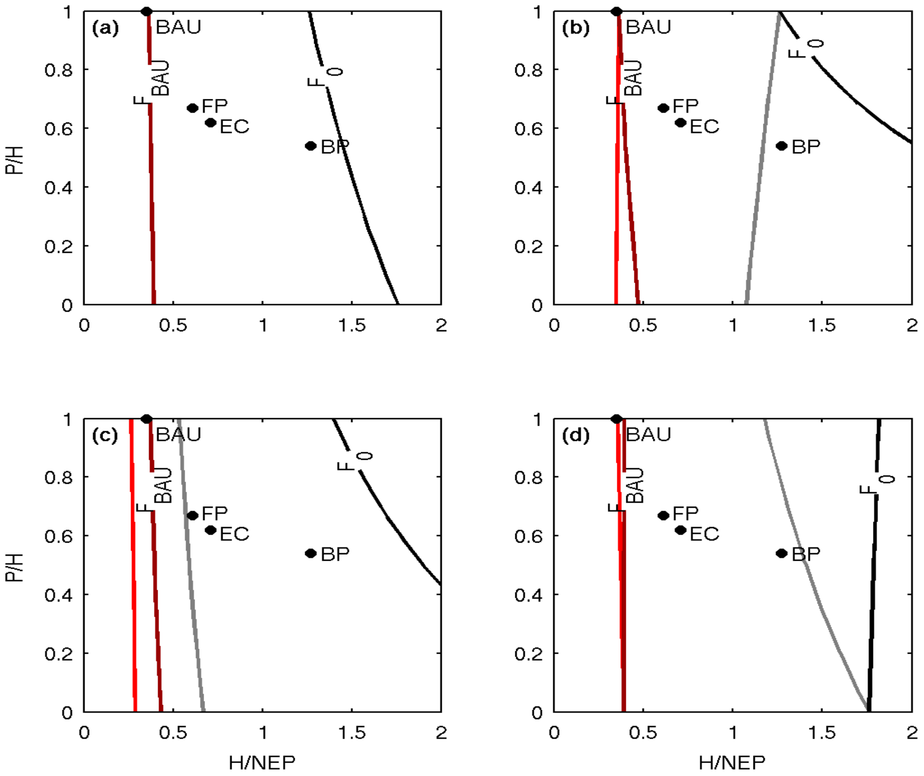


Figure A3. Conceptual analysis of harvest to NEP ratio, product mix, and varying efficiencies of bioenergy production. The x-axis is the harvest to NEP ratio, the y-axis is the product to harvest ratio (a value of 1 indicates all harvest is in wood products, a 0 indicates all harvest is used for bioenergy). F_0 lines (black and grey) are the combinations for carbon-neutral flux and F_{BAU} (dark red and red) are the lines where the flux is equal to BAU. A) Energy mix is 50:50. B) Energy mix is varied. Dark red line = BAU and red line = where the energy mix ratio flux is equal to BAU. Black line = 100% biomass combustion and the grey line = 100% cellulosic ethanol conversion. Nearly all of the harvest must be used for bioenergy to realize a lower emission than BAU. C) Fossil fuel inputs are varied. Black line = fossil fuel inputs are equivalent to product biomass (least efficient) and grey line = No fossil fuel inputs required (most efficient). Even if no fossil fuel inputs are required, only a small increase in harvest decreases emissions compared to BAU. D) Amount of wood in short term pool is varied and used for bioenergy instead of going to landfill. Black line = 100% of wood product enters short term pool and then used for bioenergy and the grey line = 100% of wood product enters long term pool. With complete recycling of wood waste (no short term pool) for use as bioenergy, there is still very little emissions savings.

Appendix B: Supporting information for Chapters 3 and 4

Methods for formatting regional downscaled climate forcing dataset for use by CLM4

The regional downscaled dataset includes daily precipitation, minimum and maximum temperature, and wind speed. To format the datasets for use by CLM4, the required shortwave radiation and relative humidity were calculated incorporating algorithms from DAYMET (Thornton et al. 1997), and methods for sub-daily calculations as described by (Göeckede et al. 2010). We created hourly atmospheric forcing data files to be used in offline CLM4 simulations. Source data files are from the climate impacts group (Salathe 2008) and are downscaled historical and future ECHAM5 AR2 files specifically designed for the Pacific Northwest http://www.cses.washington.edu/data/ipccar4/.

The specific variable calculations are as follows:

1. Air temperature: The regional input files provide daily minimum and maximum temperature. Daylength was used to apply a diurnal pattern to the minimum and maximum temperatures.
2. Wind speed: The regional input files provide daily estimates of wind in m/s. Wind speed was assumed to be constant for sub-daily time steps.
3. Relative humidity: Percent relative humidity was calculated using the hourly mean temperatures calculated above and vapor pressure.
    a. DAYMET and MTClim algorithms were used to calculate vapor pressure from temperature, precipitation, and solar radiation. Vapor pressure was then used to calculate relative humidity (RH):
        i. RH = 100 * (VP/SVP); where VP = the average daily vapor pressure in Pascals and SVP = the saturation vapor pressure. SVP varies with temperature.
        ii. SVP = 610.78 * exp(T/(T+238.3)*17.2694); where T is the current temperature in degrees C.
4. Precipitation: The input files provide daily sums of precipitation. This needed to be distributed over the day, but not evenly. CLM will evaporate off the water too quickly and none of it will reach the plant roots. The precipitation was split into 3 equal

amounts of precipitation and dropped at 8 hour intervals similar to the NCEP dataset where it is dropped at 6 hour intervals. We recognize more sophisticated diurnal precipitation algorithms using site observations could be developed, but more locations with sub-daily patterns of rainfall would be necessary for the region.

6. FSDS: Incoming shortwave radiation or incident solar is not provided in the input files. Again, DAYMET algorithms were used. The inputs required are daily Tmin, Tmax, precipitation, latitude, longitude, and elevation all of which are available from the downscaled regional dataset.

Methods for making PFT modifications in CLM4

There are 17 PFTs in CLM4, eight of which are forested. Because we did not need the tropical or boreal PFTs, we reorganized the PFT physiological file to represent the variation between and within the temperate evergreen needleleaf PFT among the ecoregions. The old and new PFT assignments are shown in Table B1 and Table B2 below. We also show the parameters that varied for each new PFT. The surface datasets and the dynamic PFT file were altered to match the new PFT assignments. Inventory and remote sensing data were used to identify within region PFT percentage cover for ‘fir’ versus ‘pine’ where necessary.

Methods for stem allocation modification in CLM4

The PFT physiology file includes an option to have the fraction of annual NPP allocated to stem wood versus foliage change with the increasing annual sum of NPP throughout the year. The equation is for all forested PFTs:

$$\text{Allocation ratio} = (2.7 / (1.0+\exp(-0.004*(\text{annsum\_npp}(t) - 300.0)))) - 0.4 \qquad \text{Eq. 1}$$

Where ‘annsum_npp’ is the total PFT NPP summed over the year at the current timestep(t). The ratio is constrained to be 0.20 when NPP = 0 and does not exceed 2.2 for NPP values greater than 1000 g C m^{-2} yr^{-1}. Using inventory data, we found annual stem wood to foliage allocation ratios as high as 3.0 for the mesic ecoregions and no higher than 2.0 for the semi-arid ecoregions. We were unable to investigate seasonal allocation ratios with the inventory data. We modified the equation to increase allocation to stem wood for lower values of NPP in the Coast Range, West Cascades and Klamath Mountains (mesic) and decrease allocation to stem wood for all values of NPP in the Blue Mountains and East Cascades (semi-arid; Figure B1 and Table B3).

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Table B1. CLM PFT original configuration and the new subgroup that replaced the original PFT for regional variation in CLM_eco and CLM_stem.

CLM PFT	Description	New PFT
1	Evergreen needleleaf (temperate)	CR all, KM fir*
2	Evergreen needleleaf (boreal)	WC fir
3	Deciduous needleleaf (boreal)	BM all
4	Evergreen broadleaf (tropical)	WC, KM pines
5	Evergreen broadleaf (temperate)	No change
6	Deciduous broadleaf (tropical)	EC fir
7	Deciduous broadleaf (temperate)	No change
8	Deciduous broadleaf (boreal)	EC pines
9	Evergreen broadleaf shrub	No change
10	Deciduous broadleaf shrub (temperate)	No change

* Fir includes Douglas-fir and true firs

Table B2. Model physiological parameters that vary for subgroups of PFTs in each ecoregion

New PFT (PFT number)	Specific Leaf Area (SLA; m^{-2} / g C)	Foliar C:N	Foliar % Leaf N in Rubisco	Leaf Longevity	Mortality rate (%)
CR all, KM fir (1)	.013	35	5.0	5	0.8
WC fir (2)	.013	48	5.0	5	1.0
BM all (3)	.007	55	3.5	3	1.3
WC, KM pine (4)	.009	50	3.7	3	1.0
EC fir (6)	.010	43	3.7	5	0.8
EC pine (8)	.007	56	3.7	3	1.0

Table B3. Stem wood allocation equations for each ecoregion PFT. The equation was only varied for ecoregions where stem wood was significantly over- or underestimated. Maximum allocation is the upper limit of annual NPP that will be allocated to stem wood production versus foliage production.

New PFT (PFT number)	Allocation Equation	Maximum allocation
CR all, KM fir (1)	2.6/ (1.0+exp(-0.010*(annsum_npp(t) - 100.0))) - 0.25	2.4
WC fir (2)	2.6 / (1.0+exp(-0.010*(annsum_npp(t) - 100.0))) - 0.25	2.4
BM all (3)	2.0 / (1.0+exp(-0.0035*(annsum_npp(t) - 300.0))) - 0.27	1.7
WC, KM pine (4)	2.7 / (1.0+exp(-0.004*(annsum_npp(t) - 300.0))) - 0.4	2.2
EC fir (6)	2.6 / (1.0+exp(-0.010*(annsum_npp(t) - 100.0))) - 0.25	2.4
EC pine (8)	2.7 / (1.0+exp(-0.004*(annsum_npp(t) - 300.0))) - 0.4	2.2

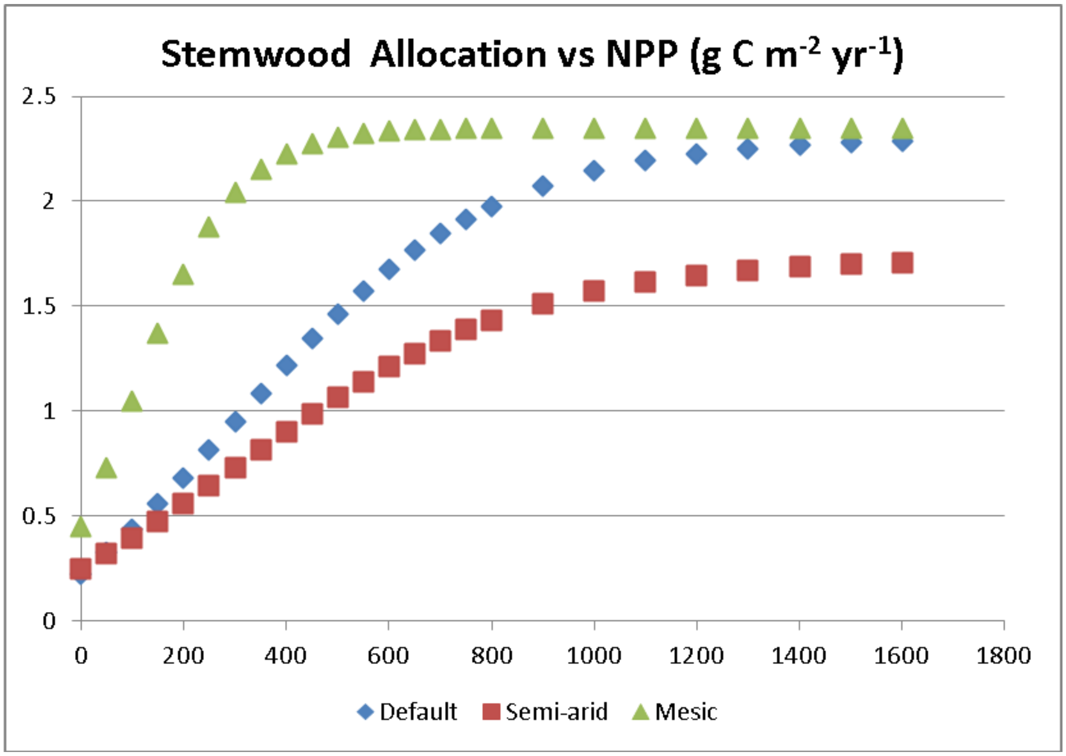

Figure B1. Stemwood allocation (ratio of stem wood allocation to foliage allocation) versus NPP. The default CLM4 equation is blue and the modified equations are for mesic (Green) and semi-arid (Red).

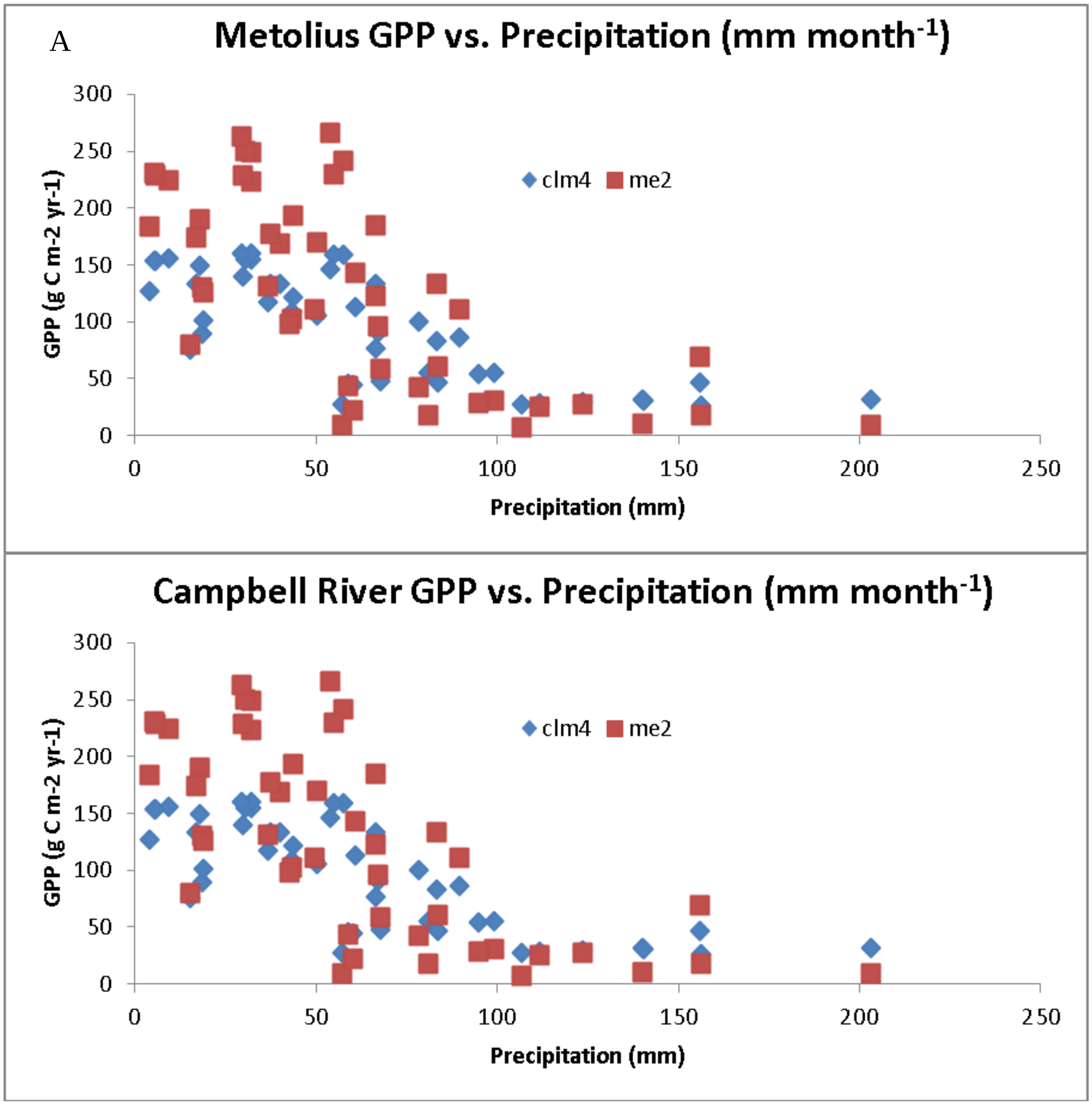

Figure B2. GPP versus monthly precipitation at the flux towers sites. Red squares are tower observations of GPP and blue diamonds are the CLM simulated monthly GPP values. CLM4 is underestimating GPP for the low values of precipitation (summer months).

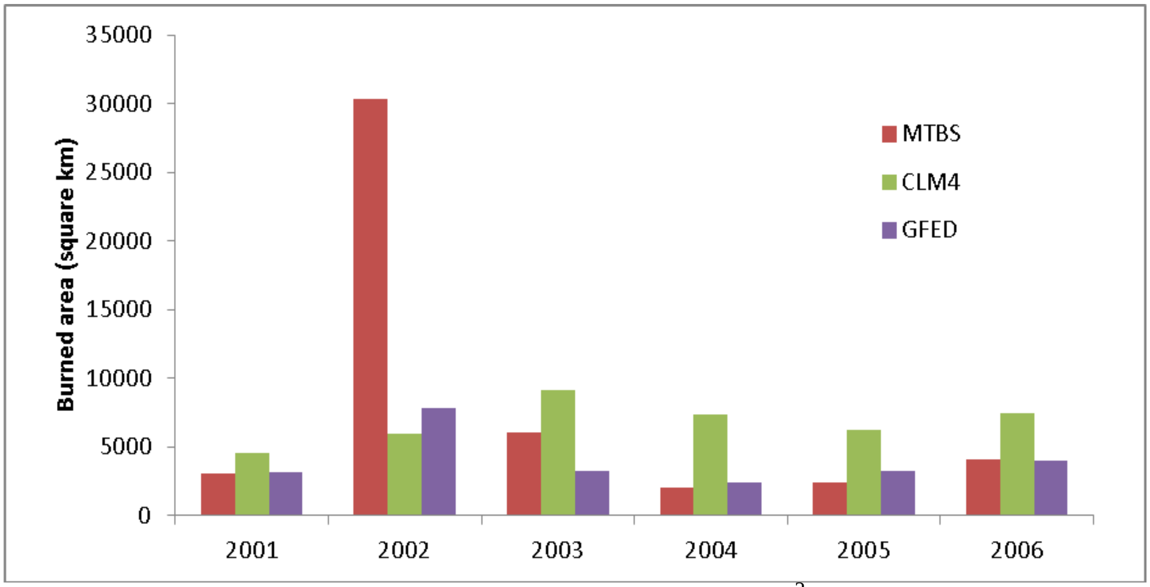

Figure B3. Historical annual area burned in Oregon (km^{-2}). Estimates are from the Monitoring Trends in Burn Severity database (MTBS; Eidenshink, J. et al. 2007), the Global Fire Emissions Database (GFED; van der Werf, G. et al. 2010), and CLM4. CLM4 overestimates burn area in Oregon for all years except for 2002 compared to the remote sensing based estimates. CLM4 does not include a fire suppression algorithm that could be contributing to the high bias. However, burn area estimates do not exceed more than 2% of the land area for any year. GFED estimates are known to be the lowest for burn area compared to other models (French et al. 2011)

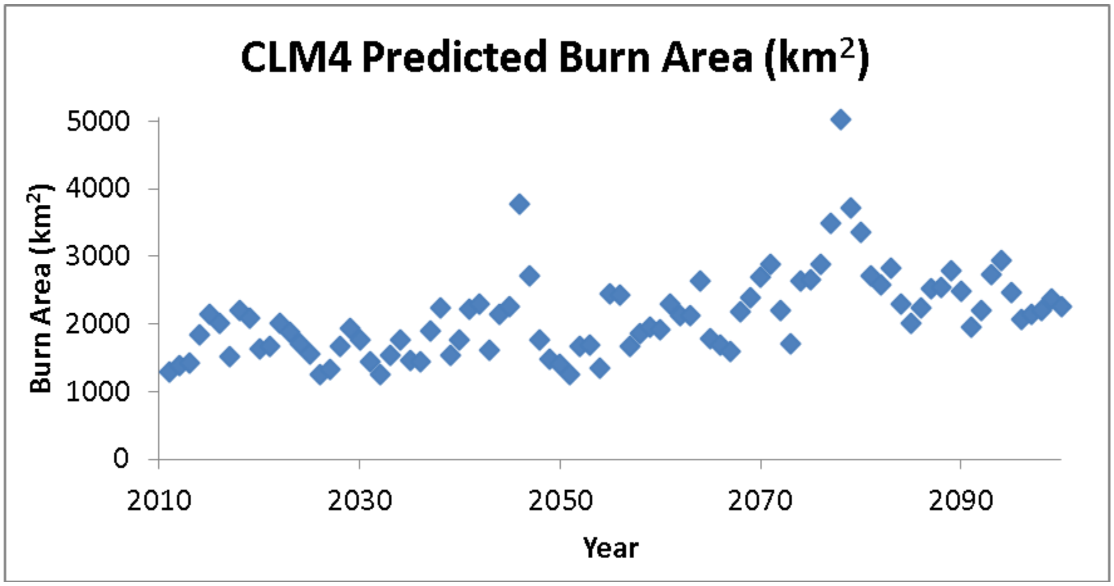

Figure B4. Burn area is predicted to double over the next century.

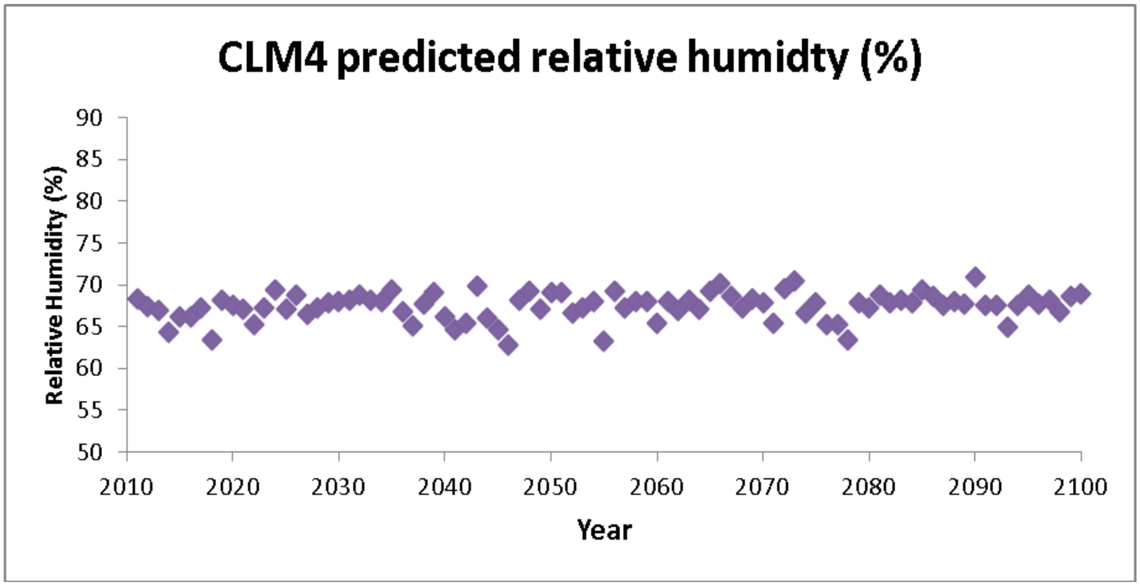

Figure B5. Predicted annual relative humidity (%) using the downscaled regional climate data and DAYMET algorithms. Relative humidity remains constant.

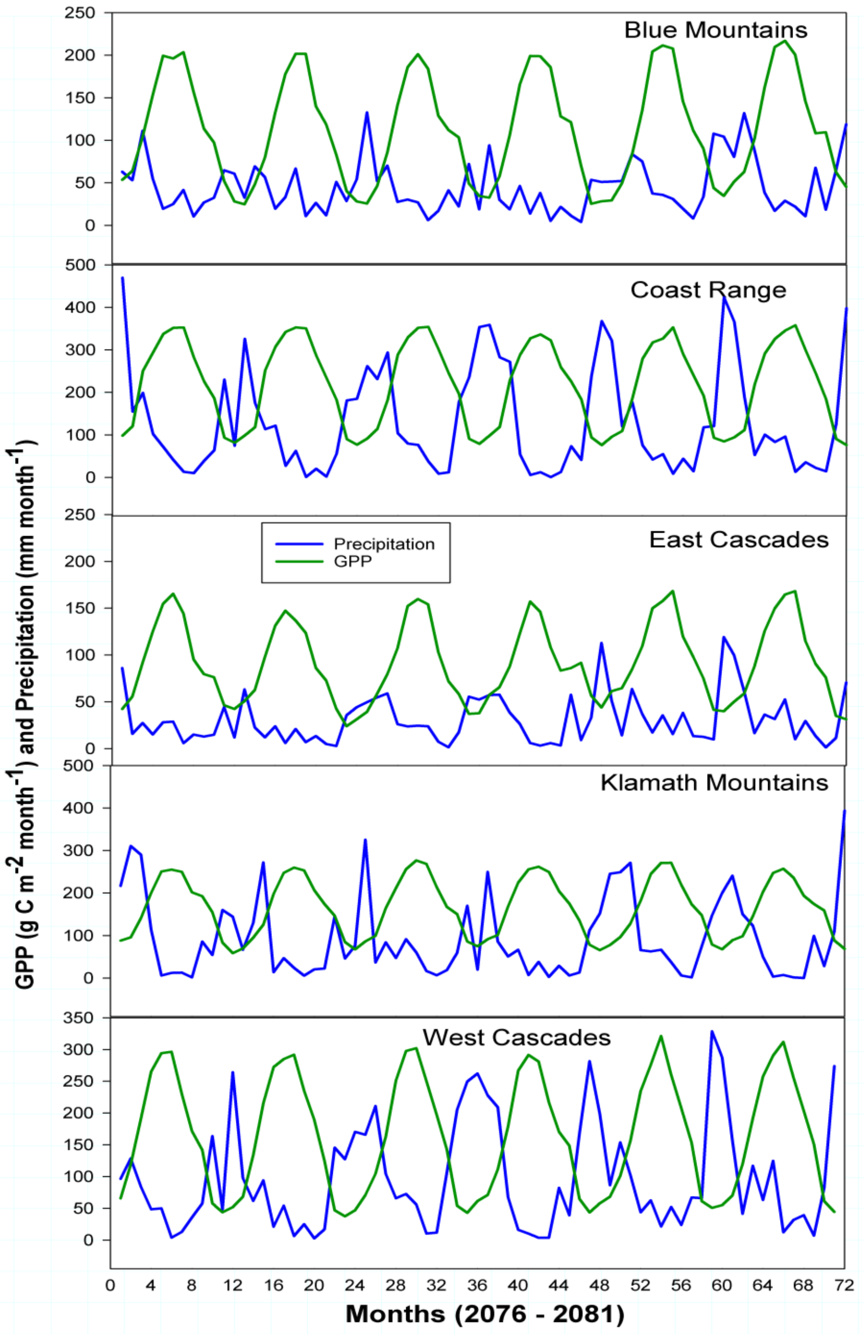

Figure B6. Monthly GPP and monthly precipitation for a period of drier years (2076-2078) followed by a period of wetter years (2079-2081). For the East Cascades and Blue Mountains there is a slight increase in summer GPP in the last two years.

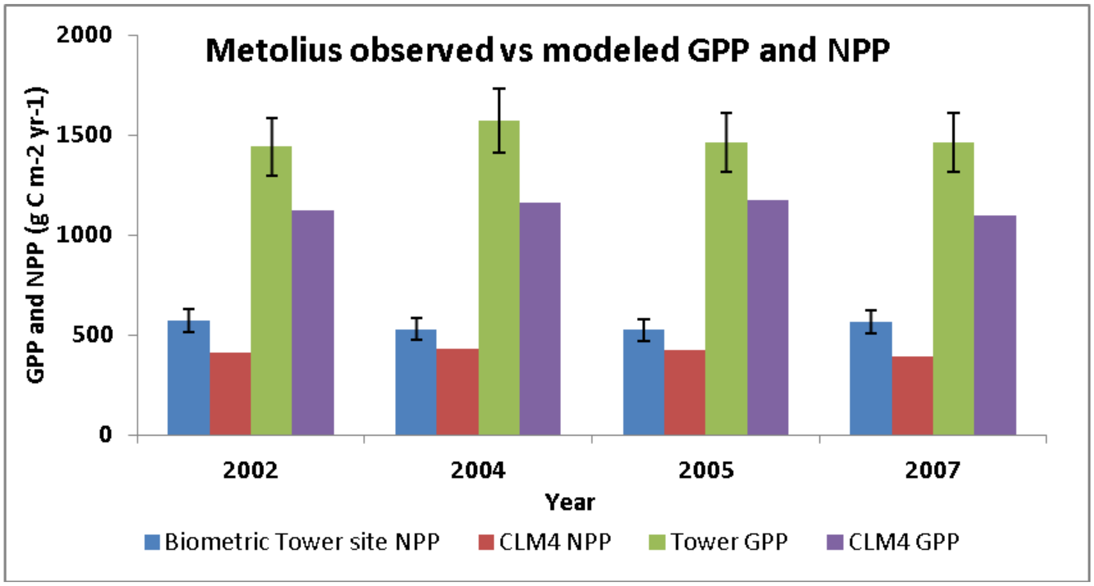

Figure B7. Metolius tower site observation of annual NPP (from biometric methods) and annual GPP (from eddy-covariance data) versus CLM4 modeled annual NPP and GPP. Uncertainty in observations is indicated by the black error bars. NPP is underestimated by an average of 24% while GPP is underestimated by and average of 30%.