3-2016

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Citation Details

Creutzburg, M. K., Scheller, R. M., Lucash, M. S., Evers, L. B., LeDuc, S. D., & Johnson, M. G. (2015). Bioenergy harvest, climate change, and forest carbon in the Oregon Coast Range. GCB Bioenergy.

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GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2016) 8, 357–370, doi: 10.1111/gcbb.12255

Bioenergy harvest, climate change, and forest carbon in the Oregon Coast Range

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Abstract

Forests provide important ecological, economic, and social services, and recent interest has emerged in the potential for using residue from timber harvest as a source of renewable woody bioenergy. The long-term consequences of such intensive harvest are unclear, particularly as forests face novel climatic conditions over the next century. We used a simulation model to project the long-term effects of management and climate change on above- and belowground forest carbon storage in a watershed in northwestern Oregon. The multi-ownership watershed has a diverse range of current management practices, including little-to-no harvesting on federal lands, short-rotation clear-cutting on industrial land, and a mix of practices on private nonindustrial land. We simulated multiple management scenarios, varying the rate and intensity of harvest, combined with projections of climate change. Our simulations project a wide range of total ecosystem carbon storage with varying harvest rate, ranging from a 45% increase to a 16% decrease in carbon compared to current levels. Increasing the intensity of harvest for bioenergy caused a 2–3% decrease in ecosystem carbon relative to conventional harvest practices. Soil carbon was relatively insensitive to harvest rotation and intensity, and accumulated slowly regardless of harvest regime. Climate change reduced carbon accumulation in soil and detrital pools due to increasing heterotrophic respiration, and had small but variable effects on aboveground live carbon and total ecosystem carbon. Overall, we conclude that current levels of ecosystem carbon storage are maintained in part due to substantial portions of the landscape (federal and some private lands) remaining unharvested or lightly managed. Increasing the intensity of harvest for bioenergy on currently harvested land, however, led to a relatively small reduction in the ability of forests to store carbon. Climate change is unlikely to substantially alter carbon storage in these forests, absent shifts in disturbance regimes.

Keywords: bioenergy, biomass energy, carbon, climate change, forest, LANDIS-II, landscape modeling, Oregon Coast Range, simulation modeling

Received 1 October 2014; accepted 29 January 2015

Introduction

Forests provide many important ecosystem services, including wildlife habitat, recreation, soil protection, clean air and water, and timber production. As we face unprecedented global challenges in the twenty-first century, forests are also increasingly recognized for other services, including the ability to store carbon and mitigate the impacts of climate change (Bonan, 2008; D'Amato *et al.*, 2011; Golden *et al.*, 2011; McKinley *et al.*, 2011) and the potential to provide bioenergy from harvest residue (USDOE 2011, Malmsheimer *et al.*, 2011). Bioenergy harvest involves removal of residue such as branches, tops, leaves, small trees, and/or shrubs, along with removing merchantable material as in conventional harvest practices. This harvest residue can be processed to produce electricity or other types of energy (e.g. pellets for wood stoves) from a renewable source of biomass as an alternative to energy from fossil fuels. However, concerns remain over the ability of intensively harvested forests to maintain productivity, sequester carbon, and provide ecosystem services. For example, Harmon & Marks (2002) predicted that removing residue following harvest through prescribed burning substantially lowered the ability of forests to store carbon.

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Soil nutrient concentrations could also decline due to the removal of nutrient-rich material during bioenergy harvest, and could lead to declining productivity over time (Wall, 2012). Studies are mixed, with evidence for positive, neutral, and negative effects of bioenergy harvest on tree productivity, soil and nutrient pools (reviewed in Thiffault *et al.*, 2011).

Novel climatic conditions may interact with timber harvest in as yet unknown ways. Climate change is increasing temperatures and changing precipitation patterns in the Pacific Northwest (Stocker *et al.*, 2013) and has already caused range shifts and mortality in some tree species (Daniels *et al.*, 2011; Hennon *et al.*, 2012). Climate change may produce novel conditions not yet experienced by long-lived forest species, which cannot rapidly migrate or adapt to such changes. The effects of climate change are likely to increase substantially over the next century, with expected increases in mortality due to insects and disease (Kurz *et al.*, 2008), increased frequency and severity of wildfire (Westerling *et al.*, 2006; Littell *et al.*, 2010), and shifting ranges of tree species (Bachelet *et al.*, 2001; Coops & Waring, 2011). Climate change may also reduce carbon sequestration potential and the ability of forests to mitigate climate impacts (Rogers *et al.*, 2011; Loudermilk *et al.*, 2013). If climate change causes increased stress on trees or declines in productivity, it may exacerbate any negative effects of conventional or bioenergy harvest.

US federal agencies have recently been tasked in an executive order to address potential climate change effects and promote climate resilience on federally administered lands (Executive Order 13653). Many federal lands have been managed for multiple uses, including timber production, wildlife habitat, and recreation, and the recent executive order adds carbon sequestration to the list of values. To make informed management decisions and evaluate the best options for maintaining forest productivity, carbon sequestration, and ecosystem health, an assessment of the long-term effects of management actions and climate change on ecosystem properties is required. As it is impossible to study large-scale and long-term processes experimentally, researchers and managers increasingly rely on simulation models to estimate the long-term consequences of current practices and guide management decisions. Simulation modeling provides a framework whereby many scenarios, each containing different assumptions about future conditions or actions, can be explored to reduce some of the uncertainty about the future and help inform management (Thompson *et al.*, 2012). Several simulation models have been used in the Pacific Northwest to understand the effects of timber harvest (Johnson *et al.*, 2007; Harmon *et al.*, 2009) and climate change (Littell *et al.*, 2010; Coops & Waring, 2011; Rogers *et al.*, 2011; Hudiburg *et al.*, 2013a), but few have simulated both (Hudiburg *et al.*, 2013b).

In this study, we simulated the effects of forest management and climate change on above- and belowground carbon storage in a northwest Oregon watershed. We explored 49 combinations of management actions and climate projections to examine a wide range of possible future conditions across a multi-owner landscape. Our study questions were as follows: How might varying rate and intensity of timber harvest affect long-term carbon storage in forest vegetation, detritus, and soils of the Oregon Coast Range? What are the likely impacts of climate change on carbon storage under a range of potential future climatic conditions? Will there be interactive effects between harvesting and climate change?

Materials and methods

Study area

This study focuses on the Panther Creek watershed (PCW), on the eastern slope of the Oregon Coast Range Mountains (Fig. 1). Forests of the Coast Range are highly productive and are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), which provide high-quality timber. The watershed is 7016 hectares in size, but 36% of the area is nonforested, resulting in 4520 hectares of forests simulated for this study. The land ownership and management in the watershed includes private nonindustrial forest (PNIF, 44% of the watershed), private industrial forest (PIF, 39%), and public lands administered by the Bureau of Land Management (BLM, 18%). The climate is characterized by wet winters and dry summers, and soils are productive and high in carbon. In the Coast Range, forests lie within a complex matrix of publically and privately owned lands due to the legacy of historical land development. Historically, these forests were heavily harvested, but passage of the 1994 Northwest Forest Plan dramatically reduced timber harvest and increased carbon storage on federal lands in the region (Krankina *et al.*, 2012). As a result, current stand composition and harvest practices are diverse, ranging from clear-cut harvest on industrial lands to large areas with no or limited harvest on federal lands. The current mix of stand ages range from recent clear-cuts to 300 years, with average stand ages of 46 years on PNIF, 41 years on PIF, and 62 years on BLM lands. Douglas-fir is by far the most common species in the PCW, with other dominant species, including (in order of prevalence) bigleaf maple (*Acer macrophyllum* Pursh), red alder (*Alnus rubra* Bong.), western hemlock, western redcedar (*Thuja plicata* Donn ex D. Don), Oregon white oak (*Quercus garryana* Douglas ex Hook.), and grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.). The major stand-replacing disturbance in the landscape is timber harvest, with large wildfires occurring on a long-rotation interval. Wind throw and fungal diseases such as root rot (*Phellinus weirii*) and Swiss needle cast (*Phaeocryptopus gaeumannii*) can cause mortality and slow growth, but are less prevalent on the eastern slope of the Coast Range, where the PCW is located.

Simulation modeling framework

We used the LANDIS-II forest simulation model (Scheller *et al.*, 2007) to project landscape-scale forest dynamics on a 1-ha grid from 2010 to 2100. LANDIS-II is a process-based simulation model that represents forest communities as tree species-age cohorts within gridded cells across the landscape. LANDIS-II simulates cohort growth, mortality, and regeneration, as dictated by life history and physiological attributes. Species compete for resources within each cell and disperse spatially across cells within a simulated landscape, therefore allowing for shifts in species ranges. LANDIS-II is freely available on the web (www.landis-ii.org) and operates as a core module interacting with extensions, each simulating succession, disturbances, and/or management. We used two extensions for this study: the Century Succession extension and the Leaf Biomass Harvest extension.

The Century Succession extension (Scheller *et al.*, 2011) was derived from the CENTURY Soil Organic Matter model (Parton *et al.*, 1983). In addition to simulating growth, mortality, regeneration, and competition (as described above), it estimates above- and belowground net primary production (NPP), net ecosystem exchange (NEE), multiple pools of live and dead tree biomass (including leaf, wood, fine root, coarse root, coarse woody debris) and active, passive, and slow pools of soil organic matter (Parton *et al.*, 1983). The extension incorporates monthly temperature and precipitation data that, along with other inputs (e.g. soil texture), influence soil water content and nitrogen available for tree growth. The model does not operate at the photosynthetic level but rather simulates growth and competition as dictated by limitations imposed by temperature, water, nitrogen, leaf area, and growing space. As stands age, cohorts approach maximum biomass asymptotically. The extension does not currently include CO_2 fertilization effects.

We used Century extension version 3.1.1, in which we made several model adjustments to simulate forests with large trees, productive soils, and high levels of carbon storage. We increased the range of many inputs (e.g. soil organic matter) and reduced the minimum allowable leaf : wood ratio. We also modified nitrogen retranslocation for conifers so that they could utilize resorbed nitrogen throughout the year, not just during spring leaf flush. These alterations represent an improved version of the Century Succession extension that is more suitable for the Pacific Northwest and other temperate coniferous ecosystems.

We used the Leaf Biomass Harvest extension version 2.0.2 (Syphard *et al.*, 2011) to simulate conventional and bioenergy harvest. This extension is based on the Base Harvest extension (Gustafson *et al.*, 2000), simulating a wide variety of harvest prescriptions and allowing the user to specify the amount of woody and leaf material removed from a site.

Model inputs

Inputs to the LANDIS-II model include initial vegetation data, ecoregion inputs, species and functional group traits, management inputs, and climate data. See Tables S1–S10 for the Century Succession extension parameter values and data sources.

Initial vegetation data. To initialize the simulated landscape with current vegetation information, we used the gradient nearest neighbor (GNN) map for the Oregon Coast Range (map region 223) produced by the Landscape Ecology, Modeling, Mapping and Analysis group for Northwest Forest Plan Effectiveness Monitoring (Ohmann & Gregory, 2002). The GNN method imputes forest inventory plot data to every pixel in the map, characterizing tree species composition, age structure, and many other variables. Inventory plots came from a variety of sources, including the Forest Service Forest Inventory and Analysis (FIA) and Current Vegetation Survey (CVS) programs. From the supplemental TREE_LIVE database, we obtained age information for each individual tree within the imputed forest inventory plots and summarized each plot into species-age cohorts at 10-year age intervals, up to the maximum longevity for each species.

Ecoregion parameters. LANDIS-II divides the study area into ecoregions, each of which are assumed to have homogeneous

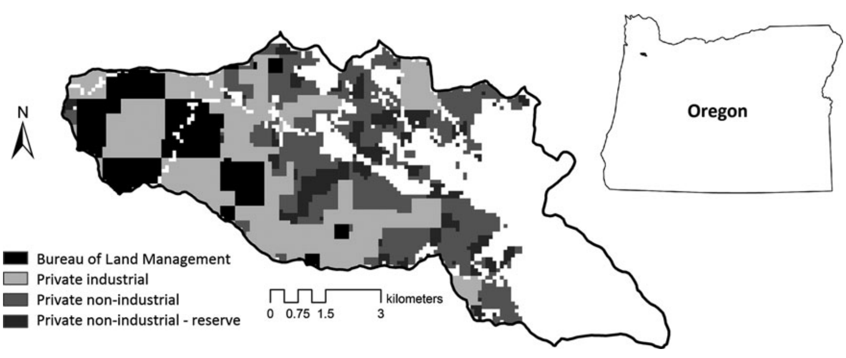

Fig. 1 Management area (ownership type) map of the Panther Creek watershed, located in northwestern Oregon. White areas indicate lands that are nonforested and were not modeled.

soils and climate. We defined nine ecoregions in the PCW, including three climate regions that captured the precipitation gradient from west (170 cm average annual precipitation) to east (111 cm average annual precipitation), and three soil regions, ranging from high soil organic carbon (SOC) (271 Mg C ha^{-1}) to low SOC (135 Mg C ha^{-1}). We defined climate regions based on precipitation grids from the PRISM Group (Daly *et al.*, 1997) and soil regions based on the SSURGO National Soil Survey for Yamhill County (Soil Survey Staff, accessed April 5, 2013). Ecoregion parameters included soil properties such as percent clay and sand, SOC decomposition rates, drainage class, as well as initial pools of carbon and nitrogen. We computed soil parameters as a spatially weighted average to 1 m soil depth. Percent clay, percent sand, field capacity, and drainage class were derived directly from the SSURGO database, and wilting point was calculated as field capacity minus available water content. We determined initial SOC and soil organic nitrogen pools based on data from soil pits collected throughout the PCW (M.G. Johnson *et al.*, manuscript in preparation). Nitrogen inputs were assumed to come from wet and dry deposition, biological fixation in lichens, soil, and decaying logs (Sollins *et al.*, 1980; Johnson *et al.*, 1982; Fenn *et al.*, 2003; Zhang *et al.*, 2012), and fertilization in managed forests. All nitrogen inputs averaged roughly 13 kg N ha^{-1}. All ecoregion parameter values and sources are listed in Tables S1–S10.

Species and functional group parameters. We simulated seven tree species, listed in the Study Area section, and did not simulate any shrub or understory species. The seven simulated species were grouped into four functional groups: conifer-dry (Douglas-fir and grand fir), conifer-mesic (western hemlock and western redcedar), deciduous-dry (Oregon white oak), and deciduous-mesic (red alder and bigleaf maple). All species and functional group parameter values and sources are listed in Tables S1–S10.

Management data. Spatial management inputs included a map of management areas (Fig. 1) and a stand map. The management area map came from the Integrated Landscape Assessment Project (accessed via http://westernlandscapesexplorer.info/AccessILAPDataMapsModelsandAnalyses#GIS). Within the PCW, 44% was mapped as PNIF, 39% as PIF, and 18% was managed by the BLM as an Adaptive Management Area. The PNIF management area was further divided into PNIF-harvested and PNIF-reserve based on surveys by Johnson *et al.* (1999), in which survey 75% of the PNIF respondents indicated that timber harvest was important or very important. We randomly selected 25% of the stands within the PNIF management area, where we excluded harvest to represent PNIF landowners that do not intend to harvest timber on their lands.

Forest stand maps for BLM lands were downloaded from the BLM Oregon/Washington Data Library (accessed via http://www.blm.gov/or/gis/data.php) and converted to raster format. Stand maps were unavailable for private land, and therefore we developed a stand map by classifying the current vegetation map into age groups, and iteratively performing majority filter and boundary clean operations in ARCGIS 10.1 to group stands by age classes, remove very small stands and aggregate observed stand sizes (Johnson *et al.*, 1999; Briggs, 2007). In the final stand map, average stand size was 7 ha in PNIF, 13 ha in PIF, and 7 ha on BLM lands.

Inputs for the individual harvest prescriptions included the following: method for selecting stands for harvest (random for all treatments except BLM thinning, in which the oldest stands within the allowable age range were harvested first); degree of removal [total removal (clear-cut) or percentage of each species-age cohort removed for thinnings]; percent harvested per 10-year time step (rotation); species selected for harvest; and species planted following harvest. For all thinning treatments, we assumed that 60% of the carbon in the specified cohort age range was removed (unpublished BLM data). All species were harvested except Oregon white oak. When a stand was selected for harvest, all cells within the stand were harvested as allowed by the specific prescription parameters. See Management scenarios section and Table 1 for information about the harvest regime in each ownership and management scenario.

Climate data. The Century Succession extension requires monthly temperature and precipitation data for model spin-up (simulating forest succession and carbon accumulation up to 2009) and future projections (years 2010–2100). We obtained climate data from the US Geological Survey GeoData Portal (http://cida.usgs.gov/gdp/) as an area-weighted average for each climate region. For model spin-up, we used climate data from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly *et al.*, 1997) over the period from 1950 to 2009. See Climate scenarios section, below, for information about future climate projections.

Scenarios

We developed a suite of scenarios in a factorial design, including seven management scenarios and seven climate projections, for a total of 49 scenarios.

Management scenarios. The seven management scenarios included no harvest, three harvest rotations (current, accelerated, and industrial), and two harvest intensities (conventional and bioenergy). Each ownership type had an individual harvest regime under each scenario as described in Table 1. See Management data for details about the harvest parameters.

Climate scenarios. The seven climate scenarios included continuing current climate and six models of climate change. Projections under current climate used PRISM data (Daly *et al.*, 1997) from 1950 to 2009. Climate change projections came from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for the Continental US from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Taylor *et al.*, 2012). We obtained 800-m-downscaled climate data from the NEX-DCP30 (Climate Analytics Group and NASA Ames Research Center) data set (Thrasher *et al.*, 2013) for three global circulation models (GCMs) and two greenhouse gas forcing

Table 1 Description of the seven management scenarios modeled in the Panther Creek watershed by ownership category, where applicable. Ownership categories are PIF (private industrial forest), PNIF (private nonindustrial forest), and BLM (Bureau of Land Management)

Scenario name	Harvest rotation	Harvest intensity
No harvest	No harvest on all lands	No harvest on all lands
Current–conventional (business as usual)	PIF: Clear-cut on a 50-year rotation, with planting of Douglas-fir following harvest (Briggs, 2007). PNIF: 25% of stands reserved without any harvest (Johnson *et al.*, 1999); 75% of stands thinned at 20–40 years and clear-cut on a 60-year rotation. BLM: commercial thinning of 40–80 year cohorts on a 100 year harvest schedule; no harvest in stands >80 years	Removed 80% of wood (Zhou & Hemstrom, 2009); remaining 20% of wood and all leaves left on site
Current–bioenergy	Same as Current–conventional	Removed 96% of wood and 80% of leaves
Accelerated–conventional	PIF: Clear-cut on a 40-year rotation, with planting of Douglas-fir following harvest. PNIF: 25% of stands reserved without any harvest; 75% of stands thinned at 20–40 years and clear-cut on a 50-year rotation. BLM: commercial thinning of 40–100 year cohorts on a 60 year harvest schedule; no harvest in stands >160 years	Same as Current–conventional
Accelerated–bioenergy	Same as Accelerated–conventional	Same as Current–bioenergy
Industrial–conventional	All lands (PIF, PNIF, BLM) harvested with clear-cut on a 50-year rotation, with planting of Douglas-fir following harvest	Same as Current–conventional
Industrial–bioenergy	Same as Industrial–conventional	Same as Current–bioenergy

scenarios, called representative concentration pathways (RCPs). We selected GCMs of future climate change using two criteria: (1) GCMs that were ranked in the top 11 in an assessment of the performance of GCM historical projections compared to observed climate data for the Pacific Northwest (Rupp *et al.*, 2013) and (2) GCMs that spanned a wide range of projected future annual temperature and precipitation for the Pacific Northwest (Table 2). The GCMs chosen were as follows: CanESM2 (Canadian Centre for Climate Modeling and Analysis), projecting hotter and wetter future conditions; CCSM4 (National Center of Atmospheric Research), projecting warmer future conditions with similar precipitation; and HadGEM2 (Met Office Hadley Center), projecting hotter and drier future conditions. For each GCM, we used two RCPs representing varying levels of greenhouse gas forcing, including a low forcing scenario (RCP 4.5) and a high forcing scenario (RCP 8.5).

Data assimilation and model calibration

Literature and data were used to calibrate the Century extension for the PCW. We completed a literature review of Pacific Northwest forests to determine expected patterns of growth, carbon accumulation, and NEE with species composition, site

Table 2 Temperature and precipitation projections under current climate (years 1950–2009, top row) and six climate change scenarios for the Panther Creek watershed projected at the end of the century (2091–2100). Future climate projections are comprised of a global circulation model (CCSM4, HadGEM, and CanESM) and a representative concentration pathway [4.5 (low forcing) and 8.5 (high forcing)]. Values are shown annually and separately for winter months (December, January, and February) and summer months (June, July, and August). T_{max} values report maximum monthly temperature (°C) averaged across years, T_{min} values are minimum monthly temperature (°C) averaged across years, and Ppt is annual precipitation (cm) averaged across years

	Annual			Winter months			Summer months		
Climate scenario	T_{max}	T_{min}	Ppt	T_{max}	T_{min}	Ppt	T_{max}	T_{min}	Ppt
Current	16.6	5.1	135.7	8.2	1.0	63.7	25.3	9.7	6.3
CCSM4-4.5	19.6	8.0	170.9	10.8	3.3	77.1	28.7	13.0	7.2
CCSM4-8.5	21.0	9.4	169.9	11.5	4.2	77.5	30.4	14.7	8.6
HadGEM-4.5	20.7	9.4	169.2	12.1	4.9	79.8	29.8	14.3	6.7
HadGEM-8.5	23.0	11.7	176.8	14.4	7.1	84.0	32.3	16.9	6.1
CanESM-4.5	20.2	9.0	191.6	11.0	4.2	94.1	30.5	14.5	5.9
CanESM-8.5	23.5	12.4	197.8	13.4	6.8	105.6	35.0	19.0	7.0

type, and stand age (Harcombe *et al.*, 1990; Vogt, 1991; Runyon *et al.*, 1994; Acker *et al.*, 2002; Janisch & Harmon, 2002; Smithwick *et al.*, 2002; Campbell *et al.*, 2004; Harmon *et al.*, 2004; Sun *et al.*, 2004; Humphreys *et al.*, 2006; Hudiburg *et al.*, 2009; Krishnan *et al.*, 2009; Raymond & Mckenzie, 2013). To calibrate the Century Succession extension, we began with single-cell simulations, iteratively adjusting parameters (e.g. shape parameters for temperature response and moisture sensitivity) to match patterns of growth and NEE in literature and flux towers (Falk *et al.*, 2008; Thomas *et al.*, 2013). Then we calibrated other parameters (e.g. SOC decay rates for each soil pool) across the whole PCW to ensure that starting conditions matched input data and landscape-scale processes were adequately simulated. We used biomass estimates from the GNN maps (derived using the component ratio method) to calibrate our initial aboveground carbon from model spin-up (Fig. 2). The following criteria were used to ensure that the final calibration was adequate: (1) Initial aboveground carbon was within 10% of GNN estimates across all ecoregions (Fig. 2); (2) projected aboveground carbon and aboveground NPP was within the range of values and followed trends found in the literature with stand age; and (3) initial SOC was within 10% of measured values and SOC accumulated 5–15% in all SOC pools over 90 years without harvest.

Simulation model runs

We simulated 10-year time steps for years 2010–2100. Each scenario was replicated five times to account for stochastic variability in climate and seedling establishment. Raw values were output by ecoregion and reported values were weighted by area. Due to the large number of scenarios, we combined the climate change projections into three categories for graphical purposes: current climate, low forcing climate change (all three GCMs under RCP 4.5), and high forcing climate change (all three GCMs under RCP 8.5).

Results

Management

At the initiation of the simulations, total ecosystem carbon was 500 Mg C ha^{-1}, with 27% in aboveground live biomass, 47% in mineral soil, and 7% in aboveground detritus (woody debris and litter). Belowground live and dead biomass encompassed 14% and 5% of total ecosystem carbon, respectively (not reported separately below). Without any harvest, projected ecosystem carbon storage in forests of the PCW increased by 224 Mg C ha^{-1} (45%), storing up to 724 Mg C ha^{-1} in the PCW by the end of the century (Fig. 3a). Current harvest rates slightly increased ecosystem carbon storage [10 Mg C ha^{-1} (2%)], and accelerated harvest slightly decreased ecosystem carbon storage [18 Mg C ha^{-1} (4%)]. In the industrial scenario, where clear-cutting was prescribed across the entire watershed, landscape carbon declined by 80 Mg C ha^{-1} (16%). Under current harvest rates, a total of 186 Mg C ha^{-1} was removed as harvested material over the 90-year simulation; under the accelerated harvest scenario, a total of 209 Mg C ha^{-1} was removed; and under the industrial scenario, 265 Mg C ha^{-1} total was removed.

Most of the variation among management scenarios was due to projected differences in aboveground live carbon, which ranged from an increase of 111 Mg C ha^{-1} (82%) under no harvest to a decrease of 68 Mg C ha^{-1} (50%) under industrial harvest (Fig. 3b). Soil carbon accumulated slowly [total increase of 15–26 Mg C ha^{-1} (6–11%) over 90 years] in all management scenarios, showing little response to harvest rate

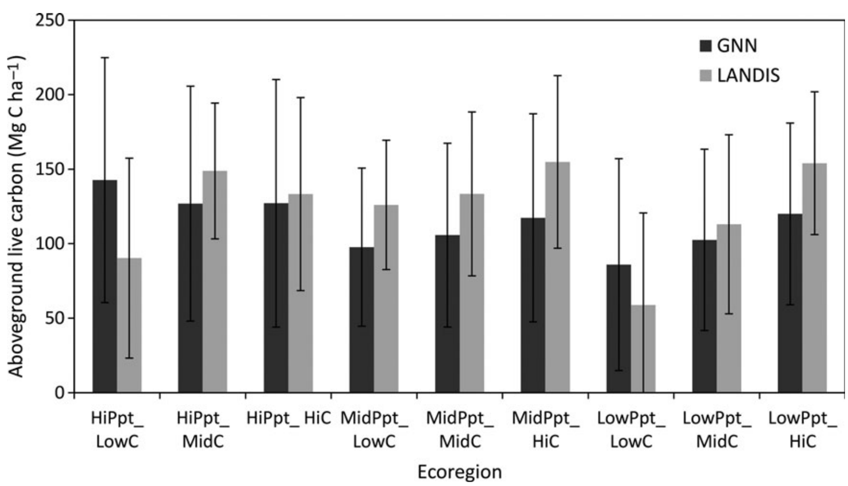

Fig. 2 Aboveground live carbon estimates for each ecoregion in the Panther Creek watershed from gradient nearest neighbor (GNN) imputation (year 2006) and LANDIS-II at the initiation of simulations (year 2010). Error bars show ± 1 SD across all cells within each ecoregion. Ecoregions are defined based on annual precipitation level (high [HiPpt], medium [MidPpt], and low [LowPpt]) and soil carbon (high [HiC], medium [MidC], and low [LowC]). See Ecoregions section for more detail.

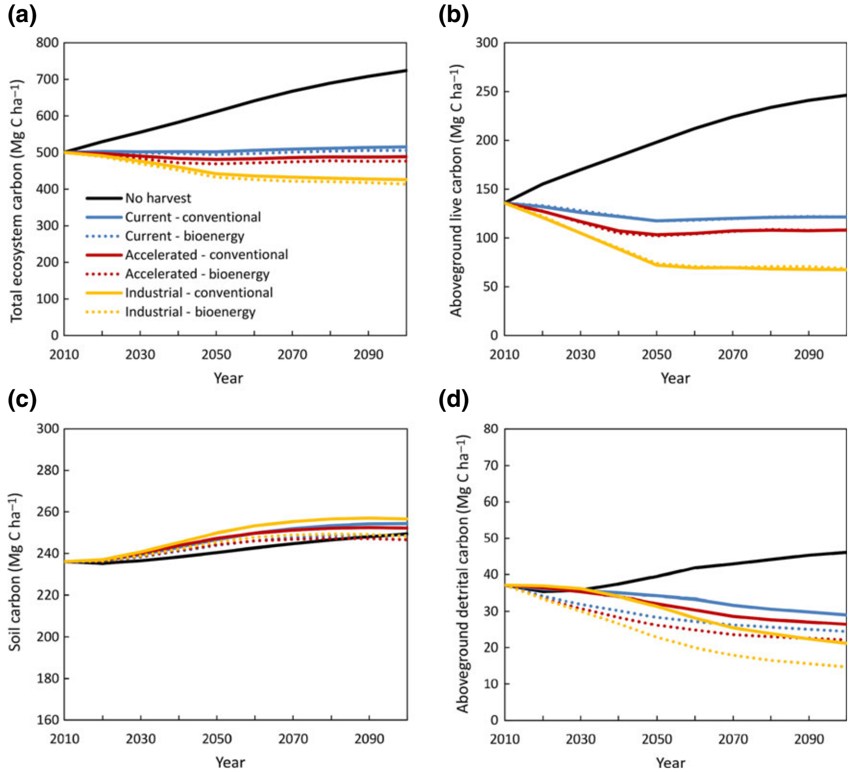

Fig. 3 Change over 90 years in ecosystem carbon pools across seven management scenarios under current climate (no climate change). Scenarios are described in Table 1. Panels depict total ecosystem carbon (a), aboveground live carbon (b), soil carbon (c), and aboveground detrital carbon (d). Note that the *y*-axis range varies among panels and that the soil carbon *y*-axis does not start at zero.

except for a slightly faster accumulation in the early years of the simulation followed by a leveling off late century, under the harvested scenarios (Fig. 3c). Aboveground detrital carbon increased by 9 Mg C ha^{-1} (25%) without harvest but declined under all harvest scenarios, with greater declines as harvest rate and intensity increased [up to declines of 22 Mg C ha^{-1} (60%) under the industrial bioenergy scenario] (Fig. 3d).

Compared to conventional harvest, bioenergy harvest reduced total ecosystem carbon by 10–12 Mg C ha^{-1} (2–3%) at the end of the century (Fig. 3a). Aboveground live carbon was unaffected by harvest intensity, but bioenergy harvest caused slower soil carbon accumulation [6–8 Mg C ha^{-1} (2–3%) lower levels than conventional harvest] and declines in aboveground detritus [4–6 Mg C ha^{-1} (11–17%) decrease relative to conventional harvest] (Fig. 3b–d). For both of these pools, the impact of bioenergy increased with harvest rate (i.e. the difference between conventional and bioenergy harvest increased from current to accelerated to industrial harvest rates).

Climate change

Carbon continued to accumulate under all climate projections until the end of the century without harvest, although climate change slowed ecosystem carbon accumulation by 38 Mg C ha^{-1} (8%) at the end of the century, compared to current climate (Fig. 4a). Projected climate change lowered aboveground live carbon by 6–10 Mg C ha^{-1} (4–7%), lowered soil carbon by 12 Mg C ha^{-1} (5%), and reduced detrital carbon by 7–9 Mg C ha^{-1} (13–16%), relative to current climate with no harvest (Fig. 4b–d). High climate forcing led to slightly greater reductions in carbon storage than low forcing, but there was high overlap and more variation among GCMs than among forcing scenarios.

In addition to annual trends, we examined the seasonal patterns of growth in response to climate change to better understand the physiological limitations experienced by trees under projected climate change. We examined monthly growth limitations from water and temperature (note that there are other growth limitations in the model not discussed here). By the end of the century, rising temperatures in both summer and winter under all climate change scenarios resulted in a lower temperature limitation and higher growth in winter, spring, and fall months (Fig. 5). Conversely, in summer months, increasing limitation from high temperatures combined with water stress reduced summer growth. GCMs varied substantially (Table 2) in the

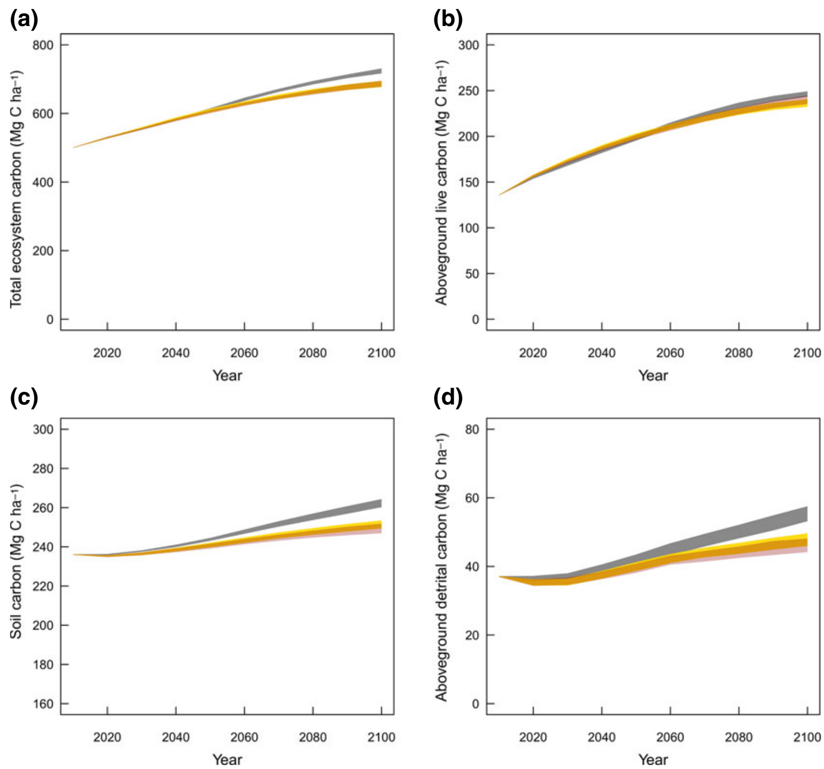

Fig. 4 Change over 90 years in ecosystem carbon storage across seven climate scenarios (grouped into three categories), without harvest. The envelopes depict the mean ± 1 SD under current climate (gray), three low forcing climate change scenarios (yellow), and three high forcing climate change scenarios (pink). Where envelopes overlap, colors are blended (e.g. overlap between yellow and pink produces orange). Panels depict total ecosystem carbon (a), aboveground live carbon (b), soil carbon (c), and aboveground detrital carbon (d). Note that the *y*-axis range varies among panels and that the soil carbon *y*-axis does not start at zero.

degree of temperature and water limitation, ranging from relatively small changes (CCSM4) to high summer water limitation (HadGEM) and high temperature and water limitation (CanESM).

Management – climate change interactions

Interactions between management and climate change indicated a lower impact of climate change under harvested scenarios (Fig. S1). Although aboveground carbon decreased slightly (6–10 Mg C ha^{-1}) under climate change without harvest, it actually increased by a similar amount [6–12 Mg C ha^{-1} (6–18%)] under the six harvested scenarios, relative to current climate. The impacts of climate change on soil and detrital carbon did not change direction, but climate change appeared to have a lower impact without harvest. For instance, under the no harvest scenario, soil carbon

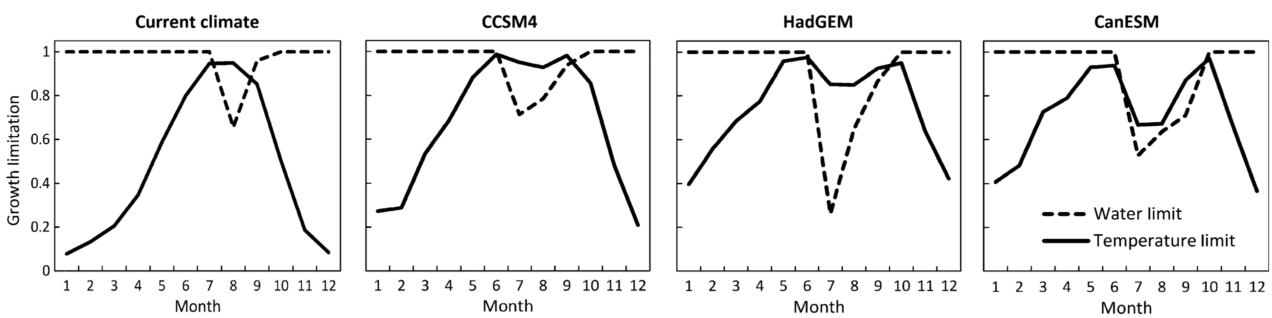

Fig. 5 Monthly temperature and water limitations to tree growth under current climate (left) and three global climate models under the RCP 8.5 forcing scenario (middle and right). Growth limit values closer to one indicate that a particular resource is unlimiting, and values close to zero indicate a strong limitation. Graphs depict growth limitations at year 2100 for a mixed species single-cell simulation, averaged across five replicates.

was reduced by 12 Mg C ha^{-1} under climate change relative to current climate, whereas soil carbon declined by only 2–3 Mg C ha^{-1} (1%) with climate change under the industrial harvest scenario. Similarly for detrital carbon, climate change caused a decline of 7–9 Mg C ha^{-1} relative to no climate change without harvest, but was nearly the same under the industrial harvest scenario. Taken together, the overall decline in ecosystem carbon accumulation with climate change projected under no harvest (Fig. 4a) disappeared in the harvested scenarios, and even slightly reversed [increase of 10 Mg C ha^{-1} (2%)] in the industrial harvest scenarios.

Discussion

Many questions related to sustainability in forested landscapes require information about complex, interacting processes over long time frames. Evaluating the comparative effects of multiple harvest practices has important implications for long-term forest management, particularly when anticipating climate change (Thompson *et al.*, 2012). In this study, we used a simulation model to explore a large range of potential future conditions and assess their implications for forest carbon storage. We simulated varying management practices in a heterogeneous watershed, encompassing an intermixture of ownership types with very different management strategies. These variations in management practices had important implications for carbon storage, as the balance of harvested timberlands and lightly or unharvested areas determined whether carbon would accumulate, decline, or maintain current levels across the landscape.

Management

The management scenarios considered in this study varied widely, ranging from managing for maximum carbon storage (no harvest) to industrial harvest across all lands (industrial scenario), with multiple scenarios in between. Ownership patterns in the Coast Range are a mosaic of federal and private land, currently managed very differently due to restrictions placed on federal lands resulting from the Northwest Forest Plan. The current and accelerated harvest scenarios reflect this heterogeneity in management across the PCW, and projections of ecosystem carbon storage in the PCW under current and accelerated harvest rates suggest that these scenarios are likely to maintain levels of carbon storage similar to those currently found in these forests. However, under the industrial scenario, carbon storage declined relative to current levels. In the industrial scenario, the entire watershed was harvested similar to PIF lands, with an additional 29% of the landscape available for timber harvest that was unharvested or lightly harvested in the other scenarios. Our findings suggest that federal lands and other nonindustrial private lands provide an important counterbalance to intensive industrial forestry in Coast Range forests. If enough lightly harvested or unharvested land remains on the landscape, carbon storage can be maintained even with intensive private industrial management practiced on some lands. However, if there were major changes to federal forest policy or if more private nonindustrial landowners were to start harvesting for timber, forest ecosystem carbon storage may decline.

Harvest rate (current, accelerated, and industrial) had the expected impact on aboveground carbon; as more trees were removed, aboveground carbon declined. In contrast, harvest rate had little effect on soils, representing the largest carbon pool in the PCW and many other heavily managed forests in the Pacific Northwest. Projected soil carbon increased slowly over time under all scenarios, as organic material from plant biomass accumulated (Kelly *et al.*, 1997). Soil carbon initially increased at a slightly higher rate under harvested scenarios, as roots from harvested trees began to decompose and contribute to SOC, but leveled off later in the century. Although an increase in soil carbon with harvest may be counterintuitive, it is not unexpected, and reviews have shown that harvest impacts on soil carbon can be positive, neutral, or negative (Johnson & Curtis, 2001; Nave *et al.*, 2010). This pattern is also consistent with some studies that found increases in SOC with harvest of coniferous species (Johnson & Curtis, 2001). Increasing harvest rate and intensity also reduced aboveground detrital carbon, consistent with much of the literature (Johnson & Curtis, 2001; Nave *et al.*, 2010). Because soil carbon represents such a large carbon pool and is relatively resilient to management impacts, soil carbon buffers the overall impact of harvest on the ecosystem.

Our simulations suggest harvesting residue for bioenergy along with conventional timber harvest would likely have little additional effect on total ecosystem carbon storage, although it does reduce soil and detrital carbon storage compared to conventional harvest. The impacts of bioenergy harvest were small, but they appeared to increase with faster harvest rotation, indicating that there might be more concern about the sustainability of bioenergy harvest in the most frequently harvested plantations. Some studies in the Pacific Northwest have found that bioenergy harvest does not reduce forest productivity or SOC (Holub *et al.*, 2013; Knight, 2013), but others document negative impacts (Proe & Dutch, 1994; Walmsley *et al.*, 2009; Wall, 2012). Our results were not sensitive to the amount of residue harvested, as simulations varying levels of wood and leaf removal up to 100% of all plant material (data not shown) showed similar impacts. However, we did not simulate other nutrients besides nitrogen, and repeated bioenergy harvest could make other soil nutrients such as calcium, phosphorus, or potassium limiting in the long term (Thiffault *et al.*, 2011). In reality, bioenergy harvest can vary widely in intensity, from removal of tops only with branch and leaves left on site, to whole-tree harvest, to complete removal including stumps. These various bioenergy practices can have very different ecosystem impacts. Our simulations under conventional harvest assume that most of the detrital material is left on site, even though site preparation can remove much of the detrital material prior to replanting. Therefore, in some cases, conventional harvesting may actually have site impacts more similar to bioenergy harvest.

In this study, we only report the ecosystem impacts of harvest and did not attempt to quantify the overall climate change feedbacks associated with conventional or bioenergy harvest. For instance, we do not quantify emissions from transportation of wood products, conversion of harvest residue to usable energy sources, ability to substitute for fossil fuels as an energy source, and many other considerations needed to determine the full implications of bioenergy harvest. It is also important to note that some of the carbon conventionally harvested in the landscape is used in long-lived structures (e.g. buildings) and can provide long-term carbon storage off-site. Many researchers have evaluated the full carbon cycle implications of bioenergy harvest in mitigating climate change, and its impacts on forested landscapes throughout the world (e.g. de Jong *et al.*, 2007; Kaul *et al.*, 2010; Winford & Gaither, 2012; Zanchi *et al.*, 2012; Mika & Keeton, 2013). Recent studies in the Pacific Northwest indicate that bioenergy harvest is unlikely to offset greenhouse gas emissions as a climate change mitigation strategy (Hudiburg *et al.*, 2011, 2013b; Mitchell *et al.*, 2012; Schulze *et al.*, 2012), but impacts likely vary regionally (Winford & Gaither, 2012). Interest remains in using forest bioenergy production as part of a climate change mitigation strategy across the United States and other parts of the world (U.S. Department of Energy, 2011, IPCC, 2014).

Climate change

Climate change is expected to have major consequences for forested ecosystems over the next century (Bonan, 2008; Intergovernmental Panel on Climate Change, 2014, Vose *et al.*, 2012). In the Pacific Northwest, expected changes include increased summer drought stress, shifting species ranges, and increasing disturbance frequency (Mote *et al.*, 2014). Our simulations indicate that climate change may slightly lower carbon storage potential in the PCW, mostly driven by losses of soil and detrital material to heterotrophic respiration. However, the balance of production and respiration varied among management scenarios, and scenarios with timber harvest tended to sustain lower respiration-related carbon losses. Studies have shown that surficial soil respiration increases with soil warming (Rustad *et al.*, 2001), but the responsiveness of resistant soil organic matter to temperature is still unclear (Davidson & Janssens, 2006).

All climate models projected higher annual temperatures by the end of the century, with winter minimum temperatures rising 2.3–6.1 °C and summer maximum temperatures increasing by 3.4–9.7 °C. All climate models also projected greater winter precipitation in the PCW, although projections of summer precipitation varied from drier to wetter depending on the climate model. Warming temperatures resulted in a longer growing season for coniferous species that retain leaves throughout the year and are currently limited primarily by temperature in the winter, early spring, and late fall. However, increasing cool-season productivity was counterbalanced by declining production in the summer due to heat and drought stress, as predicted in other studies of Pacific Northwest conifers (Littell *et al.*, 2008; Chmura *et al.*, 2011; Beedlow *et al.*, 2013). The climate scenarios with the greatest increases in winter production also showed the greatest productivity declines in summer months, with the result of largely canceling out variation among climate scenarios. Therefore, annual levels of aboveground live carbon and productivity were affected very little by climate change.

Climate change may affect Coast Range forests in additional ways not considered in this study. The greatest impacts of climate change in Pacific Northwest forests may be from increasing disturbance frequency and intensity (Chmura *et al.*, 2011; Raymond & McKenzie, 2012), which we did not simulate in this study. Wildfire frequency is expected to increase with climate change (Littell *et al.*, 2010; Rogers *et al.*, 2011; Raymond & McKenzie, 2012) and may interact with other disturbances (e.g. insects and disease) to shape future forests in the region. Additionally, many Pacific Northwest conifers, including Douglas-fir and western hemlock, require winter chilling for normal bud burst and growth. Increasing winter temperatures under climate change may not provide enough cold days for continued normal growth, flowering, and seed germination (Cumming & Burton, 1996; Chmura *et al.*, 2011), but we were not able to model this effect. We also did not simulate CO_2 fertilization, which will likely increase production under climate change due to increased photosynthetic rates and water use efficiency (Coops & Waring, 2001; Norby *et al.*, 2005; Hudiburg *et al.*, 2013b; Keenan *et al.*, 2013). Therefore, we may be underestimating production under elevated atmospheric [CO_2] with climate change, although at least one experimental study found no significant effect of rising atmospheric [CO_2] on Douglas-fir growth (Olszyk *et al.*, 1998).

Uncertainty and model limitations

There are many sources of uncertainty in simulation modeling, beginning with uncertainty in model parameters and assumptions. The Century Succession extension simulates a wide range of processes and therefore requires a large number of input parameters. Due to the rich history of ecological studies in Pacific Northwest forests, we were able to obtain field-based data for many parameters (Tables S1–S10). However, some values were not available in the literature and others had a wide range of variability in their estimates. Additionally, projections of climate change are inherently uncertain in many ways, including uncertainty about greenhouse gas emissions levels, the climate forcing resulting from those emissions, localized climatic effects resulting from global patterns, and the impacts of changing climatic conditions on individual species and interspecific interactions (Knutti & Sedlacek, 2013). We intentionally chose several climate models to encompass much of the likely range of future climate conditions in the Coast Range, but the range of actual uncertainty is much higher than is captured in our projections.

Calibration is another major challenge with the use of simulation models, as few data sources are generally available for calibration, and variability and uncertainty in available data sets are often high. We used a set of criteria to ensure that model calibration was adequate (see Data assimilation and model calibration), but our simulations highlighted areas for potential improvement in the LANDIS-II Century Succession extension. The model tended to underestimate summer productivity and heterotrophic respiration, appearing to be overly sensitive to the dry summers experienced in the Pacific Northwest and underestimating soil water holding capacity. This appears to be a common limitation among multiple simulation models used in the Pacific Northwest (Schaefer *et al.*, 2012; Hudiburg *et al.*, 2013a). However, our aim was to adequately simulate processes over long time frames and compare outcomes of multiple scenarios, rather than precisely predict seasonal patterns. The LANDIS-II model also simplifies the modeling of management activities to harvest practices that affect entire species-age cohorts. Although we can model a wide range of silvicultural practices and species-specific management activities, we cannot simulate more subtle changes in silviculture, such as retention of individual trees or snags, which can be important for wildlife habitat.

Conclusions

In this study, we used a simulation modeling framework to explore a wide range of future management actions and climatic conditions across a multi-ownership watershed. Our results indicate that maintenance of current carbon storage levels are possible under current practices partially due to unharvested federal and nonindustrial private lands that counterbalance intensive forestry operations practiced on private industrial lands. We also find that the ecosystem impacts of bioenergy harvest are likely to be minor, suggesting that bioenergy could potentially provide a low impact, renewable energy source in the region if markets and processing facilities become available. Soils contained the largest reservoir of carbon in the PCW and were relatively resilient to the impacts of harvest, although soil carbon accumulation slowed under climate change due to increasing heterotrophic respiration. Overall, management impacts were more influential on landscape condition than climate change, which caused relatively small declines in carbon accumulation in some pools. However, indirect effects of climate change, such as changes to disturbance regimes (e.g. increases in wildfire) warrant further study across larger landscapes.

Acknowledgements

Funding was provided by the U.S. Bureau of Land Management and Environmental Protection Agency Interagency Agreement DW-14-95829801-0. Thanks to George McFadden of the Bureau of Land Management, and Greg Johnson, David Marshall, and Scott Holub of Weyerhaeuser for project input. Thanks to the Landscape Ecology, Modeling, Mapping and Analysis team for providing vegetation maps and the Ameriflux network for providing flux tower data. Special thanks to the members of the Dynamic Ecosystem and Landscapes Lab at Portland State University for help and feedback throughout this study, with particular thanks to Alec Kretchun and Matthew Duveneck for their willingness to share their expertise in LANDIS-II modeling. Two anonymous reviewers provided comments that improved an earlier version of this manuscript. The views expressed here are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency or Bureau of Land Management.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Interactive effects of management and climate scenarios on major ecosystem carbon pools. Projections are shown for current climate (left), and three global circulation models (GCMs) under a low forcing scenario (RCP 4.5, middle) and high forcing scenario (RCP 8.5, right).
Table S1. LANDIS-II general species parameters.
Table S2. Ecoregion table.
Table S3. Available light biomass table.
Table S4. Light establishment table.
Table S5. Century succession species parameters.
Table S6. Century succession functional group parameters.
Table S7. Initial ecoregion parameters.
Table S8. Ecoregion parameter table.
Table S9. Monthly maximum above-ground net primary productivity (ANPP) table (g m^{-2}).
Table S10. Maximum biomass table.