

Projected climate change impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA

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Abstract Upland forests in the Pacific Northwest currently provide a host of ecosystem services. However, the regional climate is expected to warm significantly over the course of the 21st century and this factor must be accounted for in planning efforts to maintain those services. Here we couple a dynamic global vegetation model (MC2) with a landscape simulation model (Envision) to evaluate potential impacts of climate change on the vegetation cover and the disturbance regime in the Willamette River Basin, Oregon. Three CMIP5 climate model scenarios, downscaled to a 4 km spatial resolution, were employed. In our simulations, the dominant potential vegetation cover type remained forest throughout the basin, but forest type transitioned from primarily evergreen needleleaf to a mixture of broadleaf and needleleaf growth forms adapted to a warmer climate. By 2100, there was a difference (i.e., climate/vegetation disequilibrium) between potential and actual forest type for 20–50 % of the forested area. In the moderate to high climate change scenarios, the average area burned per year increased three to nine fold from the present day. Forest harvest on private land is projected to be affected late in the century because of fire altering the availability of rotation-age stands. A generally more disturbed and open forest landscape is expected, which may significantly alter the hydrologic cycle.

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1 Introduction

Forest resource managers increasingly rely on spatially-explicit scenarios of vegetation dynamics in landscape to regional scale planning exercises (He et al. 2008). Relevant management objectives include maintaining a sustained yield of wood products, conservation of biodiversity (Shifley et al. 2008), and assessment of vegetation change impacts on hydrology. These simulations can be particularly advantageous when multiple ecosystem services must be considered (Nelson et al. 2009).

As the potential magnitude of anthropogenically driven climate change becomes clearer (IPCC 2014), it is becoming more important to incorporate impacts of projected climate change into forest planning efforts (Spies et al. 2010). Notable impacts of climate change on forests will include alteration of the disturbance regime (Allen et al. 2010; Keane et al. 2008; Marlon et al. 2009), disruption of the carbon cycle (Law and Waring 2015), shifts in the geographic distribution of vegetation types (Bu et al. 2008), increases and decreases in forest productivity (Latta et al. 2010), and changes in tree species composition (Coops and Waring 2011). In the Pacific Northwest, these potential impacts have been studied using climate change scenarios and a variety of empirical or process-based modeling approaches (Rogers et al. 2011; Shafer et al. 2001) but projections of climate change impacts have tended not to include the role of land use.

In this study, we integrated an agent-based landscape simulation model (Envision) with results from a dynamic global vegetation model (MC2). Both Envision and MC2 were driven by CMIP5 climate scenarios developed in support of the 5th IPCC report (IPCC 2014). Agent-based models allow for rule-based decisions on events such as harvesting, and for expression of externally prescribed probabilities of fire (Rounsevell et al. 2012). Our goal was to evaluate the sensitivity of forest area, biogeography, rates of fire, rates of harvest, and forest age class distribution to three climate change scenarios. Our domain was the Willamette River Basin (WRB) in western Oregon, which is about two-thirds forested uplands and one-third the Willamette Valley itself (largely agricultural and developed areas). The forested area is characterized by a strong elevationally-driven climatic gradient and a complex mixture of public and private ownership.

2 Methods

2.1 Overview

We employed a landscape simulator (Envision) to project changes in the disturbance regime, in the vegetation cover type, and in forest stand age over the Willamette River Basin (WRB) for the 2010–2100 interval. The simulator ran at an annual time step and at a spatial resolution associated with Landsat-based polygons of land cover/land use. State-and-transition models (STMs) for the complete suite of forest land cover/land use states were specified. The STMs capture successional stages as well as climate change induced alteration of the potential vegetation cover types. The initial distribution of forest stand age and the probabilities for disturbance by harvest and fire were from satellite (Landsat) observations. Future harvest levels were dependent on target rates and the availability of rotation age stands; the future incidence of fire depended on output from the fire model in an off-line run of a dynamic global vegetation model (MC2). A potential vegetation cover type template covering each year and

each polygon was also produced by MC2. Three alternate climate scenarios were evaluated based on different general circulation climate models (GCMs). Mapped annual outputs included potential vegetation cover type, actual (i.e., realized) vegetation cover type, forest stand age, incidence of harvest, and incidence of fire.

2.2 The climate scenarios

Our choice of general circulation models (GCMs) was informed by a study (Rupp et al. 2013) in which the 5th Coupled Model Intercomparison (CMIP5) project GCMs were ranked with respect to how well they simulated historical weather patterns in the Pacific Northwest, notably the observed ~ 0.5 °C increase in MAT over the 20th century. The selected scenarios represent essentially low, medium, and high levels of climate warming (Table S1, hereafter S refers to Supplementary Material). The majority of GCMs do not project much change in annual precipitation for the Pacific Northwest region (Rupp et al. 2013). We selected MIROC5 RCP 8.5 (hereafter ModClim) for an intermediate scenario, GFDL-ESM2M RCP 4.5 (hereafter LowClim) for the low warming scenario, and HadGEM2-ES RCP 8.5 (hereafter HighClim) for the high warming scenario. The GCMs were run from 1950 to 2100, with historical climate observations used to remove bias in the historical period. The GCM outputs were downscaled to the 4 km resolution using the Multivariate Adaptive Constructed Analogs (MACA) approach (Abatzoglou and Brown 2011). Data is available in netCDF format (MACA 2014).

2.3 The dynamic global vegetation model

We used the MC2 dynamic global vegetation model (DGVM). MC2 (Figure S1) is version 2 of the MC1 DGVM (Halofsky et al. 2013; Rogers et al. 2011). We ran MC2 over our spatial domain at a spatial resolution of 2.5 arc-minutes (~ 4 km). Documentation and source code for MC2 are available on-line at <https://envision.bee.oregonstate.edu/svn/mc2> and <https://sites.google.com/site/mc1dgvmmusers>. Potential vegetation cover simulated by MC2 with the contemporary climate shows good agreement with Kuchler's potential vegetation cover (Kuchler 1975) (Figure S1).

MC2 uses its carbon cycle submodel (CENTURY, Parton et al. 1993) to estimate the productivity of a site and the relative productivity of woody and herbaceous vegetation based on climate, soil, elevation, and latitude. MC2's biogeography submodel uses the CENTURY output and climate to categorize the best-suited natural vegetation type as one of 5 biomes (e.g., forest vs. grassland) and one of 12 physiognomic classes (e.g., deciduous broadleaf vs. evergreen needleleaf). These classes are defined based on climate (i.e., decision tree thresholds). Additional class descriptors related to climate (e.g., temperate vs. subtropical) were used to refine the vegetation type classification for the Pacific Northwest. During an MC2 run, the potential vegetation cover type (VCp) is regularly updated based on the climate and the biogeography thresholds. This output provided a template of VCp for use in our landscape simulator. MC2 was initialized with climate data representing 1895–1950 (PRISM, Daly et al. 2008) and run forward from 1950 to 2100 with the downscaled GCM climate data.

The MC2 wildfire model (Lenihan et al. 2008a; Lenihan et al. 2008b) initiates fires based on fuel moisture conditions (driven by temperature and relative humidity), with critical parameters in the form of Canadian Forest Fire Weather System BUI (Build-up Index) and FFMC (Fine Fuel Moisture Code) indices (Stocks et al. 1989). Here, the BUI and FFMC thresholds were adjusted to produce a fire regime that approximated the historical rate of stand-

replacing fire in our domain during the 1985–2010 interval (see below). Preliminary analyses indicated that the appropriate thresholds varied slightly between GCMs, so the fire model parameter adjustment was done separately for each GCM scenario. The annual forest area burned from the MC2 model runs was then used to prescribe year-by-year proportion of forest area burned for input to the Envision simulation.

2.4 The landscape simulator

We used the Envision modeling framework (Bolte et al. 2007; Envision 2014) to annually update vegetation status (cover type and stand age if forest) and to impose disturbances (harvest, fire, and land use change). The range of actual MC2 vegetation cover types (VCa) included all currently existing forest and nonforest cover types in the WRB, as well as several MC2 VCp cover types that might exist under an altered climate (Table S2).

The initial condition of the landscape was mapped in the form of polygons, i.e., Integrated Decision Units (IDUs). The spatial configuration of these management-scale polygons (mean size = 19.2 ha) was based on Landsat remote sensing data and forest inventory data (Halofsky et al. 2014; ILAP 2013). The Integrated Landscape Assessment Project (ILAP) also provided a species-level vegetation classification. We assigned a stand age to each forested IDU based on overlay of the IDU coverage and a reference stand age coverage. For stand age ≤ 25 , that coverage used Landsat-based LandTrender results (Kennedy et al. 2010; Kennedy et al. 2012), which evaluate the pixel-level trajectories of a vegetation-relevant spectral vegetation index. Stand age in 2010 was determined from the year of disturbance. For stand age > 25 , we used a stand age coverage derived from Landsat-based Gradient Nearest Neighbor Analysis (Ohmann et al. 2012). Boundaries for land ownership and protection status (Figure S3, Table S3) were from the U.S. Geological Survey (GAP 2014).

A cross-walk between the ILAP-based vegetation classes and the MC2 VC classes (Table S2) was developed by overlaying the two coverages (both approximately 2010 vegetation) as in Halofsky et al. (2013) and in consultation with participants in ILAP project (Miles Hemstrom, Oregon Institute of Natural Resources, personal communication). Because of differences in the classification schemes and because the IDU coverage was at a finer spatial resolution than the 4 km climate data driving the MC2 model runs, there was some residual disagreement between the initial VCp in MC2 and the initial VCa coverage in Envision (< 20 % of the forested area).

The Path Landscape Model (PATH 2014) was used to specify the complete range of possible state transitions associated with each of 7 MC2 VC types (Table S2). In the simplest case, these transitions followed an age-based succession from a recently disturbed stand to an old-growth forest state. Alternate pathways were associated with disturbances such as thinning, harvesting, and fire. The initial set of STMs for the study area was developed by the ILAP and are available (ILAP_STMs 2014). Our single large Path “megamodel” provided for transitions from a VCa to a different VCa when a disturbance occurred and the climate had changed enough to support a different cover type (as determined by the VCp template from MC2). In the course of the simulations, only areas that were initially forest were allowed to change VC type. Envision also accounts for transitions between native vegetation and urban or agricultural land, but these changes were relatively small in these simulations (0.65 % of the land surface) and are not discussed further here.

Because of large differences in the Pacific Northwest among land ownership classes in forest management history (Garman et al. 1999), we stratified the harvest probability in

Envision by land ownership class. The initial probability of harvest for stands of harvestable age on private lands — ≥ 60 years old, the approximate rotation age in this ecoregion (Emmingham 2002) — was set based on the observed harvest rate from 1986 to 2010 in the WRB (Kennedy et al. 2010; Kennedy et al. 2012). These Landsat-based observations suggested a harvest rate of 1.3 % per year across all private forestland, equivalent to $\sim 11,740$ ha per year. The area harvested per year in the future was maintained at the same level unless the availability of forest area with age class ≥ 60 fell below the prescribed area. The same procedure was followed for unreserved public lands. The observed historical rate of harvest was 0.5 % per year on all public forestland not reserved from harvest, equivalent to ~ 3240 ha per year. Permissible stand age was set for 40–80 years since older forests are largely conserved for wildlife on public lands.

The initial probability of fire was likewise based on observations of the Landsat record (Kennedy et al. 2012), but we did not stratify by ownership class. Over the 1986–2010 period, we observed 0.2 % per year of forestland area was burned in the WRB. The future extent of fire was based on the MC2 results, thus capturing the increasing incidence of fire associated with warming climate. Annual area burned was input to Envision and fires were placed randomly on the landscape by the SpatialAllocator process (Envision 2014). Fire size was 22,500 ha except when only a fraction of that was needed to reach the prescribed total area burned.

3 Results

The contemporary vegetation of the WRB is dominated by grassland/cropland in the valley floor and coniferous forest in the uplands (Fig. 1a). The west-to-east environmental gradient of decreasing temperature and increasing precipitation from the valley bottom east to the crest of the Cascades mountain range (Fig. 1b) drives a change from maritime conifer to cool needleleaf forest and ultimately to subalpine conifer forest. The contemporary forest age class distribution differs substantially between public and privately owned forestland (Figure S3), with a substantially larger proportion of the forestland in older age classes on public land (which tends to be at higher elevations) (Fig. 1a, S3).

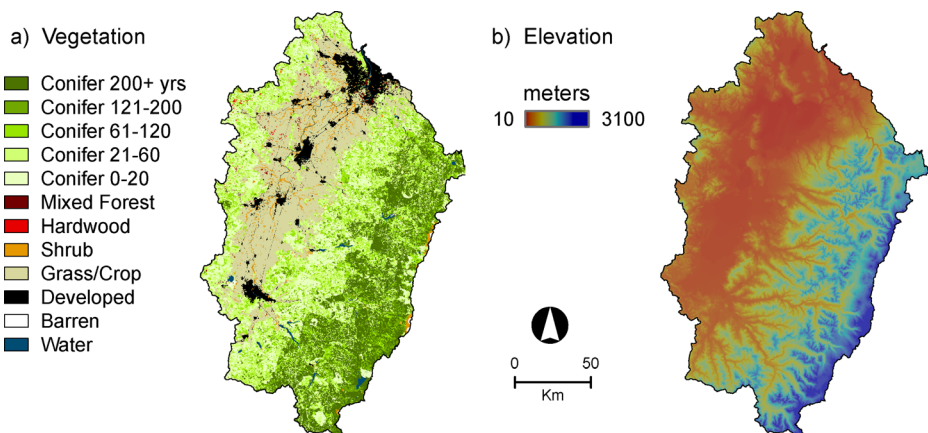


Fig. 1 The Willamette River Basin study domain: (a) Vegetation cover and conifer age class, (b) Elevation

For the ModClim scenario, the simulated forest area burned per decade in the 2010–2100 period was 0.6 \% year^{-1} . Fire tended to be concentrated in particular years, with as much as 25 % of the forested area burning in a high fire year late in the 21st century (Fig. 2). The HighClim scenario (warmest temperatures) induced larger areas of fire per year, with average area burned per year increasing by a factor of nine relative to the historic period. In the LowClim scenario, the area burned per year was slightly below the historic rate.

In the LowClim scenario, the harvest rate on private land was initially stable (Fig. 3) at about 1.5 % of the area per year, consistent with a 60 year rotation and limited fire. Towards the end of the scenario, the harvest rate decreased about 30 % in response to a declining availability of harvest age stands. On public lands that were available for harvesting, there was a stable harvest rate of 0.5 % per year. Under the more severe fire regimes in the ModClim and HighClim, the area of private forests old enough to be harvested decreased such that the harvest rate began falling off sooner and ended up at a lower level by the end of the century. This effect was not observed on available public lands where the initial harvest rate was much lower.

The climate-induced shifts in potential vegetation cover type were proportional to the magnitude of the climate change (Fig. 4). With the least warming, there was little change in potential vegetation type, whereas with the highest warming scenario the potential vegetation cover type changed over the entire river basin by the end of the 21st century. For the most part,

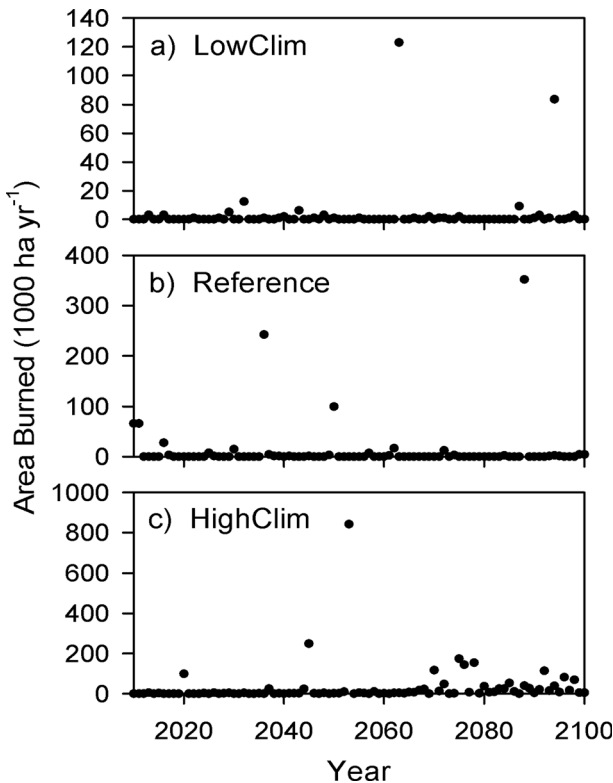


Fig. 2 Area burned per year: (a) LowClim, (b) ModClim, (c) HighClim

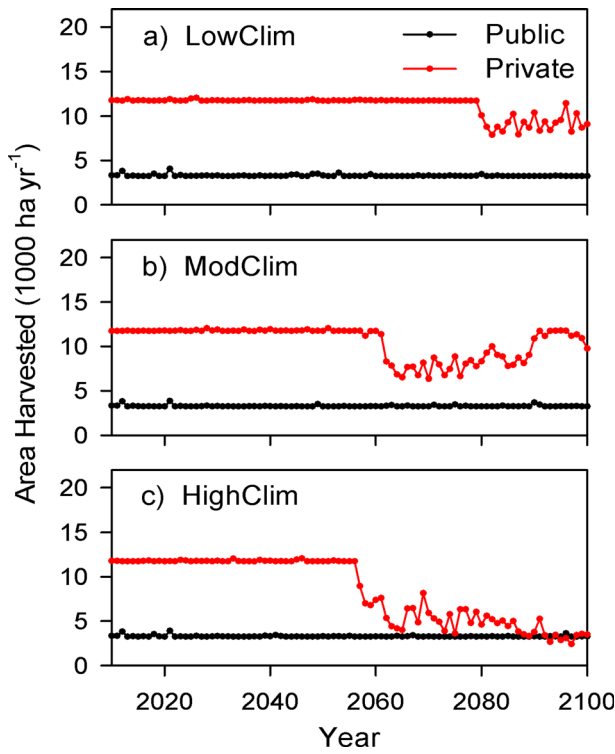


Fig. 3 Area harvested per year (public and private): (a) LowClim, (b) ModClim, (c) HighClim

forest vegetation types were replaced by other types of forest. At lower elevations, maritime and dry conifer forest types were replaced by subtropical mixed forest. Subalpine forest was lost as a potential forest type by 2100 in all the climate scenarios.

The change in the actual vegetation type lagged the change in potential vegetation type in all scenarios. By 2100 in the LowClim scenario, the area of upland vegetation in disequilibrium was 22 % of the total forest area. However, that proportion rose in the other two scenarios

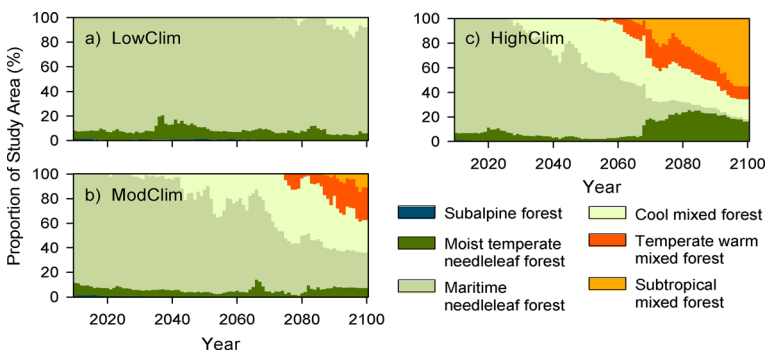


Fig. 4 Time series for potential vegetation cover type proportions on the Willamette River Basin uplands: (a) LowClim, (b) ModClim, (c) HighClim

(53 % in ModClim, 56 % in HighClim) by the end of the century. Much of the speckling in the actual vegetation cover in 2100 (Fig. 5b) is where stand replacing disturbances, either harvests or fire, induced a change in vegetation cover type to the underlying potential vegetation cover type (Fig. 5a).

4 Discussion

4.1 The climate scenarios

Among the GCMs evaluated by Rupp et al. (2013) there was a central tendency in the array of outcomes in terms of change in MAT. Our ModClim scenario approximated that central tendency. However, there is currently no basis for privileging one GCM over another (Knutti et al. 2010), thus each of our three climate scenarios is in principle equally probable. Given the current level of uncertainty about future climate, the land cover/land use scenarios developed here are best viewed as efforts to capture the key processes and to explore the range of potential outcomes.

4.2 Changes in the disturbance regime

4.2.1 Fire

Our area burned rate of 0.2 % per year for recent decades from satellite data is consistent with the estimate for a similar period in the West Cascades using the fire scar approach (Weisberg and Swanson 2003). However, even within the satellite record there has been an increase in area burned per year in the West Cascades ecoregion (Turner et al. 2015) and more generally in the western U.S. (Dennison et al. 2014; Westerling et al. 2006), both associated with climate warming.

For the two warmer climate scenarios, the MC2 fire model projected 3 to 9 fold increases in annual area burned over the course of the 21st century. Although the statistical relationships

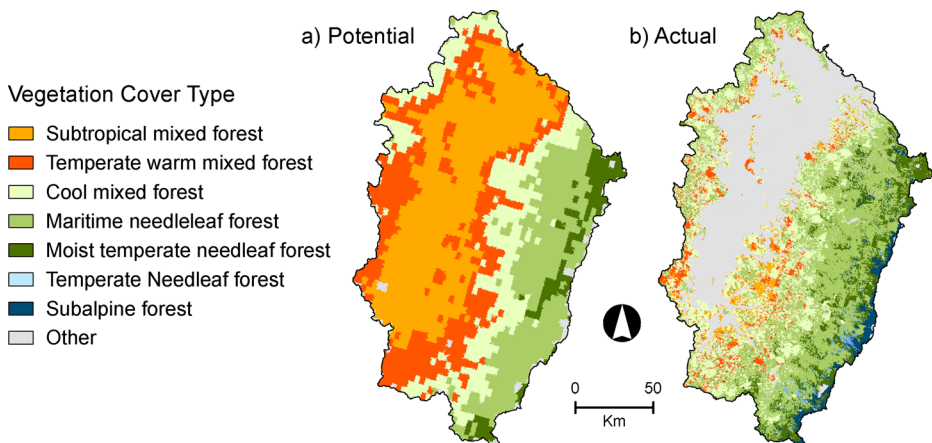


Fig. 5 Vegetation distribution in 2100 for the ModClim scenario: (a) Potential Vegetation Cover type (from MC2), (b) Actual Vegetation Cover type (from Envision)

between weather and fire were weak in the reference historical record because of the relatively few fires, the empirical analysis of Littell et al. (2009) for the western Cascade Mountain ecoregion likewise suggested that an increase of about that magnitude could be expected under future climate conditions. An earlier application of the MC2 fire model using CMIP3 climate scenarios indicated a similar trend in the Pacific Northwest region (Rogers et al. 2011). Projections of area burned in the forests of British Columbia to the north of our study area suggest that much of the forests could see a fire return interval of about 50 years, i.e., 2 % of the area burned per year (Nitschke and Innes 2013). In California to the south, forest wildfire is projected to increase as much as 100 % (Westerling et al. 2011).

The temporal pattern of fire in the MC2 simulations was characterized by occasional high fire years driven by relatively warm weather. This pattern is consistent with historical observations in the Pacific Northwest (Abatzoglou and Kolden 2013; Whitlock et al. 2003). Fire suppression has generally been successful in this region (Gedalof et al. 2005) but may not be in the future because of more frequent extreme weather conditions – particularly warm temperatures and a preceding dry period, in combination with easterly flow from the warmer, drier areas east of the Cascade Mountains (Hostetler et al. 2005). Thinning and prescribed fire are potential management options, but the degree to which they would reduce fire risk remains controversial (Stephens et al. 2009).

Previous to the 1910–2010 era of low fires associated with fire suppression, there was a period of a high incidence of fires around 1850 to 1910 in the Pacific Northwest (Weisberg and Swanson 2003) and specifically in the West Cascades ecoregion (Weisberg 2009). That pattern is believed to be associated with the settlement era. However, prior to 1500 there was also a region-wide period of extensive fire, probably driven by drier and possibly warmer conditions (Steinman et al. 2012; Weisberg and Swanson 2003). Our projected rate of 0.6 to 1.8 % per year over the 2010 to 2100 period from the two warmer scenarios is comparable to the observed relatively high rate prior to 1500.

4.2.2 Harvest

The initial stand age class distribution of private forest land showed a significant area (62 %) at ≥ 60 years of age. This reservoir of harvestable land decreased in the initial decades of our scenarios because in each year, the amount of area harvested (and reset to a stand age of zero) was greater than the area which reached a stand age of 60. Eventually, the reservoir of harvestable area was consumed. In all three climate scenarios, there was ultimately a decline in the area harvested per year, with an earlier threshold associated with more fire. The harvest rate recovered in large measure in the LowClim and ModClim scenarios because stands cut or burned earlier in the scenario reached rotation age. The harvest rate continued falling to near zero in 2100 in the HighClim scenario because of the large area burned.

We also ran simulations assuming a rotation age of 40, which is being achieved on some high productivity sites in the WRB (Doug Maguire, Oregon State University, personal communication), and the impact of fire on harvest rates was lower (having no impact in the LowClim scenario). Our simulations did not assume a lower incidence of fire on private compared to public land, as has been observed in recent decades in western Oregon and Washington (Healey et al. 2008), which would boost the availability of harvest age stands on private land. Salvage logging of burned stands could help maintain the rate of wood removals.

On public lands the relatively low harvest rate of 0.5 % per year was maintained in all scenarios. Average stand age gradually increased in the LowClim scenario but fell in the

ModClim and HighClim scenarios because of the greater incidence of fire. In practice, managers on federal lands in the WRB are moving towards thinning as opposed to clearcuts. Thus achieving the same volume of harvest removals would require larger areas and could potentially face constraints if burned area rates are high.

4.3 Changes in vegetation cover type

In all of the MC2 simulations, the VCp for the WRB uplands remained a type of forest throughout the 21st century. However, in the ModClim and HighClim scenarios, widespread shifts in potential forest type were evident. Note that results here are sensitive to the prescription of soil water holding capacity (Peterman et al. 2014). Previous simulations of climate change impacts in the WRB area using a climate envelope approach (Shafer et al. 2001) and a gap-phase biogeography model (Busing et al. 2007) have similarly suggested retention of forests but changes in forest type. The maritime influence of the nearby Pacific Ocean, and the continued high levels of annual precipitation in the climate projections, tend to buffer the forests of the West Cascades from climate warming (Law and Waring 2015).

At high elevations in the WRB, subalpine forests were replaced by cool conifer forests in the simulations (e.g., Subalpine fir replaced by Pacific silver fir). At mid elevations, the shift from maritime conifer – generally associated with Douglas-fir and western hemlock – to more mixed forest types was driven in the MC2 biogeography submodel by a threshold in minimum winter temperature. Hardwood species such as Big Leaf Maple and conifer species such as Grand fir increased in dominance.

Potential vegetation cover type in the relatively low elevation Willamette Valley periphery changed from maritime conifer to subtropical mixed forest in the ModClim and HighClim scenarios, here driven by the coldest month temperature. The most likely broadleaf species would be Pacific madrone and tanoak, as is currently the case at mid elevations in the Sierra Nevada Mountains 800 km to the south (Fowells 1965). These evergreen broadleaf species would benefit from the projected warmer winters and can tolerate the projected drier summers.

The degree of disequilibrium between potential and actual vegetation cover type was influenced both by the magnitude of the climate change and by location. The increase in disequilibrium by the end of the century in the ModClim and HighClim scenarios compared with the LowClim scenario was driven primarily by the larger area in which VCp changed. As in a previous study in this region (Yospin et al. 2015), there was significant disequilibrium in low elevation areas that were potentially mixed semitropical forest by the end of the simulation. The degree of disequilibrium was not much different between ModClim and HighClim because the incidence of fire, which allows a reset of vegetation cover type, increased with the magnitude of climate change, i.e., more fire compensated for more changes in VCp.

The recent climate in the western U.S. is already appreciably warmer than in previous decades (Waring et al. 2014) and increases in tree mortality have been linked to climate change (van Mantgem et al. 2009). Spatially-explicit landscape simulation of potential and actual vegetation could be particularly effective in adaptation efforts (Mori and Johnson 2013; Stephens et al. 2013). Using climate observations, stands in different locations could be regularly assessed for the degree to which the vegetation type is out of equilibrium with the local climate, and hence at risk for attack by pests and pathogens. The most vulnerable stands could be prioritized for thinning or harvest.

The Oregon Forest Practices Act requires that harvested land be replanted (OFPA 2014). Typically the same tree species as was harvested – often with further differentiation by genetic

provenance – is replanted. Our results support the conclusion that there will be an increasing need for additional management decisions post disturbance throughout the 21st century (Rehfeldt et al. 2014a). DGVMs driven by the latest downscaled GCM climate data could potentially provide guidance on what type of vegetation to replant after disturbance. Even in the case when a species change is not needed, a provenance change may be advisable (Rehfeldt et al. 2014b; Wang et al. 2006). Douglas-fir is the most common species in managed plantations in the WRB and both tree ring studies of interannual variation in growth (Chen et al. 2010) and common garden studies suggest significant interpopulation level differences. Thus assisted migration and attempts to match genotype and projected climate may be needed (Rehfeldt et al. 2014a).

4.4 Modeling limitations

Several potentially important factors were not accounted for in our current modeling approach. Within population genetic variation, which would support in situ adaptive evolution (Aitken et al. 2008), was not considered. Secondly, the rotation age was fixed whereas in practice it could be lowered to reduce the degree of disequilibrium between climate and vegetation composition. Also, our simulations did not allow for change in vegetation composition without stand replacing disturbances. Gap-phase models, which track replacement of individual trees, offer the opportunity to evaluate the role of tree-level mortality to vegetation change (Busing et al. 2007). These models are also relevant to addressing the constraints on vegetation change imposed by background rates of seed dispersal (Davis 1989).

4.5 Related consequences of a climate-induced vegetation change

Over the course of the 20th century, private forests in the Pacific Northwest were largely converted from relatively old native forests to intensively managed plantations (Garman et al. 1999). Hence the age class distribution is now circumscribed at the high end. Our simulations suggest that harvests and fire will continue to maintain that pattern into the future. Public forestland was subject to a similar management scheme beginning around 1950, but public policy changed in the early 1990s with the implementation of the Northwest Forest Plan (USDA 1994). Consequently, there remains a wider range of stand ages and more relatively old forests on public lands than on private lands. Increased incidence of fire is likely to reduce mean stand age and the proportion of the landscape in the old-growth condition (Healey et al. 2008). Our simulations assumed all fires were stand replacing, but historically mixed severity fire has been common in the West Cascades Mountains (Tepley et al. 2014), hence the proportion of unevenaged stands will likely increase as the incidence of fire increases.

In the ModClim and HighClim scenarios, the proportion of the landscape that is recently burned and relatively open (i.e., low leaf area) increases. Our simulations did not include pest and pathogen disturbances, which are also likely to increase with climate warming (Preisler et al. 2012). More relatively open areas (from disturbance) would result in lower mean leaf area. The dry conifer and semitropical mixed forests which replace the maritime conifer forests would also have relatively lower equilibrium leaf area. These decreases in leaf area could lead to reduced growing season evapotranspiration (despite higher evaporative demand). New spatially explicit hydrologic modeling efforts that account for changes in leaf area associated both with the disturbance regime and with the forest type are needed to evaluate these complex interactions.

5 Summary

Mid-range climate projections for the WRB over the course of the 21st century suggest a warming on the order of 3 °C in MAT and little change in annual precipitation. Our landscape scale simulations indicate there will be widespread disequilibrium between the climate and the vegetation cover type over the course of the 21st century. Forests of various types are likely to be maintained on the uplands. The area burned per year is expected to increase by up to a factor of nine over the historical rate. This increase means that the area of forest available for harvest may decrease towards the end of the century. The changing disturbance regime will generally cause a shift to a younger and more open forest landscape with corresponding influences on the hydrologic regime.

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