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Analysis of potential impacts of climate change on forests of the United States Pacific Northwest

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ABSTRACT

As global climate changes over the next century, forest productivity is expected to change as well. Using PRISM climate and productivity data measured on a grid of 3356 plots, we developed a simultaneous autoregressive (SAR) model to estimate the impacts of climate change on potential productivity of Pacific Northwest (PNW) forests of the United States. Productivity, measured by projected potential mean annual increment (PMAI) at culmination, is explained by the interaction of annual temperature, precipitation, and precipitation in excess of evapotranspiration through the growing season. By utilizing information regarding spatial error in the SAR model, the resulting spatial bias is reduced thereby improving the accuracy of the resulting maps. The model, coupled with climate change output from four generalized circulation models, was used to predict the productivity impacts of four different scenarios derived from the fourth IPCC special report on emissions, representing different future economic and environmental states of the world, viz., scenario A1B, A2, B1 (low growth, high economic development and low energy usage), and COMMIT. In these scenarios, regional average temperature is expected to increase from 0.5 to 4.5 °C, while precipitation shows no clear trend over time. For the west and east side of the Cascade Mountains, respectively, PMAI increases: 7% and 20% under A1B scenario; 8% and 23% under scenario A2; 5% and 15% under scenario B1, and 2% and 5% under the COMMIT scenario. These projections should be viewed as potential changes in productivity, since they do not reflect the mitigating effects of any shifts in management or public policy. For managers and policy makers, the results suggest the relative magnitude of effects and the potential variability of impacts across a range of climate scenarios.

1. Introduction

With accumulating evidence that greenhouse gas concentrations are warming the world's climate, research has increasingly focused on estimating the impacts that are likely to occur under different warming scenarios. Particular attention is focused on changes in forest productivity as a result of climate change (Boisvenue and Running, 2006; Case and Peterson, 2007; IPCC, 2007; IPCC-TGICA, 2007). There are a number of reasons for this attention on productivity of future forests. First, forest productivity is directly influenced by changes in temperature and precipitation regimes. Second, forest productivity drives timber supply analysis and forest planning endeavors. Third, forest productivity impacts many additional forest characteristics such as habitat for wildlife or fuels that increase wildfire risk. Thus, forest land managers need information on how potential forest productivity may be affected by changes in climate. In addition, in 1997 the Kyoto protocol recognized that forests were an important carbon sequestration tool to offset increasing CO_2 emissions. As a result of this function, forests are being considered for inclusion in a variety of proposed legislation focused on carbon markets and sequestration, creating new needs for information on future forest productivity.

There continues to be a debate whether climate change will yield a net gain or loss for forest productivity in more temperate climates like the United States and Canada. Best estimates for 100-year global temperature increases range between 1.8 and 4.05 °C (IPCC, 2007). Predictions are that regional climates will vary substantially, with the Pacific Northwest region of the United States expected to have substantial changes in both temperature and precipitation (IPCC-TGICA, 2007). As a result, potential forest productivity, which is dependent on vegetation composition, soils, climate, and natural and anthropogenic disturbance regimes, can also be expected to change.

To inform the debate as policy makers grapple with potential solutions, better information on the potential interrelations of forests and climate are needed. To address this need for

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information, we use the simultaneous autoregressive model developed in Latta et al. (2009) along with four different IPCC climate change scenarios to project the potential change in forest productivity in the Pacific Northwest at 5-year intervals through the 21st century. The discussion proceeds in the next section with a summary and characterization of previous work. The data and modeling methods are then presented. Following that is a section with model results and spatial evaluation of the percentage change in productivity. Future PMAI maps are then presented along with a brief discussion on impacts of climate change on productivity and concluding remarks.

2. Previous studies

As global focus has shifted to climate change a number of studies have investigated the potential impacts that climate change has had on past forest growth as well as potential forest growth in the future. The work of the IPCC assessment report and associated climate change scenarios provide a synthesis of work completed thus far and more importantly provide a framework for future analyses. There have been a number of studies both regional and across the world that have focused on forests and climate change. Here we will focus on three basic types. One type tracks past climatic and forest growth records for an individual site to determine if changes in climate in the recent past provide insight into forest growth over the same period at that location. A second type looks across a spatial scale at an individual point in time to determine spatial changes in growth as related to spatial changes in climate. These spatial relationships are then expected to suggest future impacts of climate on forest growth. A third study type uses process-based growth models and future climate predictions to estimate how growth will be affected by future climate.

The first group of studies looks at past impacts of changes in climate on forests. For the Pacific Northwest, Mote (2003) reports increases in both temperature (0.7–0.9 °C) and precipitation (13–38%) through the20th century which exceeded global averages. Boisvenue and Running (2006) provide a synthesis of 49 papers examining the impacts on natural forest productivity due to climate change of the last 50 years. Case and Peterson (2007) examined dendrochronological evidence of a century of growth of lodgepole pine (*pinus contorta* var. *latifolia*) in the northern Cascade Mountains and found that high elevation forest growth was positively correlated with temperature, while lower elevation forest growth relied on an interaction of both temperature and precipitation. Nakawatase and Peterson (2006) found similar results in the forests of the Olympic Mountains.

The second group of studies uses relationships between climate and productivity developed from a cross-sectional look at current climate and productivity. Monserud et al. (2006) created a spatial model of site index for lodgepole pine (*Pinus contorta*) in Alberta using Hutchinson's thin-plate smoothing splines with inputs of latitude, longitude, elevation, and site index from 2624 stem-analyzed site tree observations collected from 1000 locations, and mapped the results. Wang et al. (2005) compared site index predictions for a variety of methods (least-squares regression, generalized additive model, tree-based model, and neural network model), also using stem-analysis of lodgepole site trees in Alberta. Studies relating Douglas-fir productivity to geographic and climatic variables have also been completed in British Columbia (Nigh et al., 2004), France (Curt et al., 2001), Portugal (Fontes et al., 2003) and central Italy (Corona et al., 1998). Each of these studies used multiple linear models to relate productivity to the independent variables. Fontes et al. (2003) also generated maps of potential productivity from their models.

While these studies related current climate to current productivity levels and in most cases created maps of their results, they only hinted at the potential effects of changes in those climatic parameters on future productivity in their conclusions. Monserud et al. (2008) estimated a linear model of site index explained by growing degree days and mapped potential future changes in site index for lodgepole pine in Alberta under climate change for the SRESA1B scenario as predicted by a number of GCMs.

The third group of studies utilizes process based growth models to predict future forest outcomes as climate changes. While Milner et al. (1996) and Hall et al. (2006) used process models to map forest productivity in Montana and the Foothills Model Forest in Alberta respectively, McNulty et al. (1994), Aber et al. (1995), and Coops and Waring (2001a,b), Coops et al. (2005) used process models in tandem with different GCM models. Aber et al. (1995) used PnET-II and examined the effects of fixed changes in temperature, precipitation, CO_2 levels, and their combined effects on future forest production in the northeast US. In the Pacific Northwest Coops and Waring (2001b) also estimated the effects of increasing precipitation as well as a GCM generated scenario of future climate in that region.

In summary, past studies have either used non-standardized future climate scenarios, looked at only 1 year in the future, or focused on only one future scenario. We build on previous work by viewing the IPCC scenarios as a range of possibilities, increasing understanding of the range of future forest productivity. In addition, we consider more than one period for prediction. This is critical because while temperature change may be gradual in most GCM projections, precipitation is generally projected to fluctuate, making it important to focus on more than one time period to understand potential impacts. Finally, this study differs from others in addressing spatial model error. Swenson et al. (2005) is the only previous study to present the spatial distribution of their model error. They identify a spatial component to the prediction error, with bias toward over-prediction in the western Klamath range, and under-prediction in the Blue Mountains, Cascades and eastern Siskiyou ranges but took no steps to correct these problems. To reduce this type of spatially correlated error, we use a simultaneous spatial autocorrelation model.

3. Methods

In the present study a model of potential culmination mean annual increment is estimated from forest and climate data for the Pacific Northwest. That model is then used along with projections of future climate change from four general-circulation models for four IPCC climate change scenarios.

4. Forest data

Data for this study were obtained from the Forest Inventory and Analysis (FIA) databases for Oregon and Washington. The FIA databases are part of the national inventory of forests for the United States (Roesch and Reams, 1999; Czaplewski, 1999). A tessellation of hexagons, each approximately 2400 ha in size, is superimposed across the nation, with one field plot randomly located within each hexagon. Approximately the same number of plots is measured each year, each plot has the same probability of selection, and in the western U.S. plots are remeasured every 10 years. Each field plot is composed of four subplots, with each subplot composed of three nested fixed-radius areas used to sample trees of different sizes. Forested areas that are distinguished by structure, management history, or forest type are mapped as unique polygons (also called condition-classes) on the plot and correspond to stands of at least 0.4047 ha in size. Maximum potential mean annual increment (PMAI) is calculated from the stand's site index, which is itself calculated from age and

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height of site trees (Hanson et al., 2002). For our study area there were 4557 forested FIA plots measured between 2001 and 2006 with PMAI values calculated based on 27 different tree species. Of the 4557 plots with PMAI values, 74% were estimated from either Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*) or western hemlock (*Tsuga heterophylla*). PMAI, elevation, and species identifier for the 3356 forested FIA plots of these three primary species in Oregon and Washington plots were obtained from the FIA annual database.

Graphical analysis of plots with site trees of at least two different species from the 3356 FIA plots indicated an upward shift in the PMAI on plots where western hemlock site tree measurements were used, while PMAI showed no discernable trend on plots with both ponderosa pine and Douglas-fir site trees. This upward shift in PMAI on plots for which western hemlock trees were used is most likely due to the shade tolerance of the species. To account for this, an indicator variable for shade tolerance (ST) was used for plots with PMAI calculated from western hemlock trees.

Table 1
Summary statistics for Forest Inventory and Analysis plot data.

Variable	Units	Mean	Maximum	Minimum	Std. dev.
PMAI by elevation (m) class					
0–500	m^3/ha/year	10.9	23.8	0.7	3.6
500–1000	”	7.2	20.7	0.2	3.4
1000–1500	”	4.9	16.0	0.6	2.3
1500–2000	”	3.4	8.9	0.8	1.2
>2000	”	2.5	3.6	1.7	0.8
All	”	7.4	23.8	0.2	4.1
Geographic variables					
Latitude	°	45.4	49.0	42.0	2.0
Longitude	”	−121.6	−116.5	−124.7	2.0
Elevation	m	808.2	2171.4	4.9	504.0
Climatic variables					
Temperature	°C	8.4	13.7	0.8	2.2
Precipitation	cm	143.7	593.9	25.7	90.6
CMI	”	−30.3	83.8	−80.0	19.6

5. Climate data

We used monthly temperature and precipitation normal data for the period 1971–2000 produced by the Parameter-elevation Regressions on Independent Slopes Model (PRISM). The PRISM data is provided on an 800 m grid which produced differences between measured plot elevation and overlaid PRISM grid elevation of as high as 350 m in the mountainous areas of Oregon and Washington. To account for changes in climate due to these elevation differences we utilized a process similar to Wang et al. (2006) where we created a scale-free interpolation process using a 90 m digital elevation model and PRISM temperature and elevation gradients of the larger 800 m grid. The result is a 90 m monthly climate grid. Like Wang et al. (2006) we used this procedure for temperature (T) only and used a simple distance weighting method for precipitation (P).

As a measure of moisture availability we used Climate Moisture Index (CMI) which is a measure of precipitation in excess of evapotranspiration (ET). Hourly short wave incoming solar radiation (SR) was calculated based on Coops et al. (2000) utilizing latitude, longitude, slope, aspect, elevation and the PRISM monthly maximum and minimum temperatures. These hourly values were then used to create monthly averages (SR_m). ET was calculated using the Hargreaves method as presented in Narongrit and Yasuoka (2003) and given by Eq. (1).

$$\mathrm{ET}_m = 0.0135(T_m + 17.78)\mathrm{SR}_m\left(\frac{238.8}{595.5 - 0.55T_m}\right) \qquad (1)$$

where ET_m is evapotranspiration (in mm per day) for the month m and T_m is the average monthly temperature for the month m. CMI is then calculated from precipitation and ET by Eq. (2):

$$\mathrm{CMI} = \sum_{m=1}^{mgs}\left[P_m - \left(\frac{\mathrm{days}_m \times \mathrm{ET}_m}{10}\right)\right] \qquad (2)$$

where CMI is Climate Moisture Index (cm), P is average monthly precipitation (cm) from PRISM data, and *mgs* is an index for the months of the growing season. In this study the growing season months are those that have growing degree days above 10 °C.

Descriptive statistics for the geographic variables along with the climatic variables used in the models are given in Table 1 and maps are provided in Fig. 1.

6. Climate change data

Data regarding the potential future climate regimes of the Pacific Northwest were derived from general-circulation models (GCM) output for a suite of scenarios from the IPCC's fourth assessment report. Annual temperature, precipitation, and solar radiation output were collected for 100 years of projections from the U.S. National Center for Atmospheric Research's Community Climate System Model (CCSM3) version 3.0 (Collins et al., 2006), the French Centre National de Recherches Meteorologiques Coupled Global Climate Model version 3 (Salas-Mélia et al., 2005), the Australian Commonwealth Scientific and Industrial Research Organisation's MK3 (Gordon et al., 2002), and the British Hadley Centre for Climate Prediction and Research's CM3 model (Pope et al., 2000). This was accomplished by linear interpolation of the projected percentage change from the GCM 2000 to 2005 average climate values. The future climate maps were then constructed by applying all the change percentages to the original PRISM derived maps. This prevents problems associated with differences in present climate values between the GCM and PRISM data as well as differences between the coarse GCM spatial scale and the PRISM 800 m grid.

The scenarios are based on the IPCC's fourth assessment report and described in the IPCC General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment (IPCC-TGICA, 2007). Four different scenarios, representing different future economic and environmental states of the world, are explored. The SRESA1B scenario has a future of balanced energy sources, globalization, rapid economic growth, population peaking mid-century then declining, and rapid introduction of technologies. The SRESA2 scenario has a more regionalized future of slower economic growth, population which continuously rises, and slower adoption of technological advances. The SRESB1 scenario has an environmentally sustainable focus with a shift toward an economy centered on service and information with the same population growth assumptions as A1B. The COMMIT scenario has a future in which global CO_2 emissions are held to year 2000 levels.

Fig. 2a shows the projected future temperature for the Pacific Northwest for the four different IPCC scenarios. Projected change in regional temperature ranges from less than half a degree for the Commit scenario to over three and half degrees in scenario A2. After rising the fastest for the first 50 years, the A1B scenario warming tapers off after population peaks in the middle of the century ending less than 3° higher. The environmental focus of the B1 scenario results in a gain of just over one and a half degrees over the century. Fig. 2b shows little or no differentiation between the IPCC scenarios as well as no apparent trends in precipitation. Fig. 2c shows declining future growing season climate moisture index which is a function of the rising temperatures of Fig. 2a, the trendless precipitation of Fig. 2b, and projections of solar radiation that show no apparent trends. A regional map of changes in

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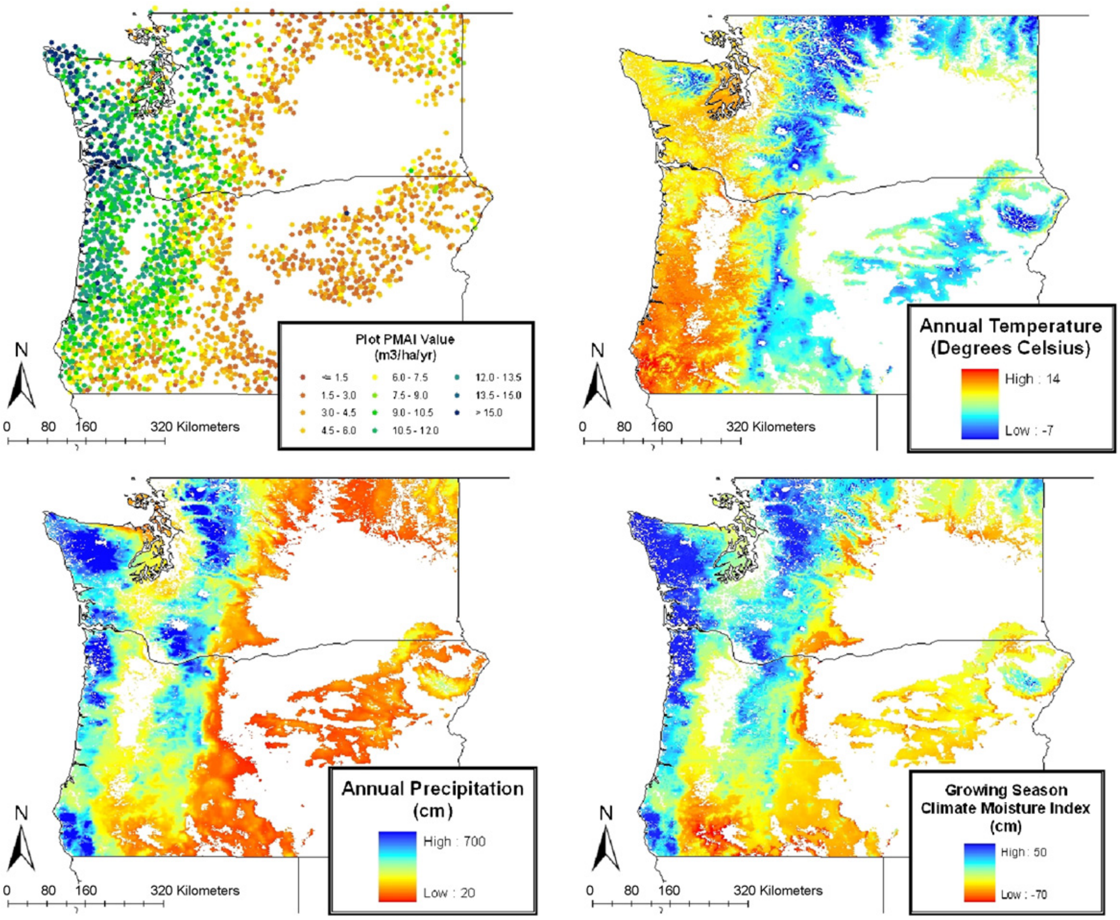

Fig. 1. Maps of approximate plot locations and climatic variables.

temperature through 2097 is given in Fig. 3. This demonstrates not only the disparity of the scale of change between IPCC scenarios, but also the spatial differences in where those changes are projected to take place. A general trend in all cases is the moderating effect of proximity to the Pacific coast. The effects of climate change increase as elevation increases which has the effect of dampening the coastal moderating influence on the Siskiyou Mountains of southwest Oregon and bringing the highest gains in temperature to the higher elevation eastern side of the region.

7. Simultaneous autoregressive model

Latta et al. (2009) compared four different productivity imputation techniques for the Pacific Northwest. Not only did the SAR model outperform the other models, but it reduced the effects of spatial autocorrelation on the resulting productivity maps. Spatial autocorrelation is a frequent occurrence in spatial vegetative modeling as nearby observations are more similar than if they had been selected at random. The result is that the ordinary least squares (OLS) parameter estimates of the original models, while still unbiased, are no longer the most efficient. While testing for and correcting autocorrelation has been prevalent in the econometrics literature for decades, it is just recently gaining acceptance as a method for solving spatial models. In a SAR model the error term is comprised of two components; a stochastic error term and an error term that is a function of the neighboring data error terms. The basic OLS model described in Latta et al. (2009) which consists of Eq. (3), without the ρu_i term, resulted in an adjusted R^2 of 0.64. When tested for spatial autocorrelation however, the Moran's I statistic indicated significant clustering of the error term. The SAR model given by Eq. (3) was generated.

$$\mathrm{PMAI_i} = \beta_1 + \beta_2 T_i + \beta_3 \mathrm{CMI}_i + \beta_4 T \times P_i + \beta_5 T_i^2 + \beta_6 P_i^2 + \beta_7 ST_i + \rho u_i + e_i \tag{3}$$

where $\beta_1 \ldots \beta_7$ are regression parameters, i is the set of reference plots, ρ is the autocorrelation correction parameter, u_i is the spatially autocorrelated error term and e_i is a stochastic error on plot i. The autocorrelated error term is a weighted average of the neighboring plot error terms as given as:

$$u_i = \mathrm{PMAI}_{L_i} - (\beta_1 + \beta_2 T_{L_i} + \beta_3 CMI_{L_i} + \beta_4 T_{L_i} \times P_{L_i} + \beta_5 T_{L_i}^2 + \beta_6 P_{L_i}^2 + \beta_7 \mathrm{ST}_{L_i}) \tag{4}$$

Let $x_{L_i p}$ be the vector of lagged terms for the variables $\{T_{L_i}, \mathrm{CMI}_{L_i}, \mathrm{TP}_{L_i}, T_{L_i}^2, P_{L_i}^2, T_{L_i}\}$ on plot i. The lagged term for the PMAI for plot i, PMAI_{L_i}, is calculated as:

$$\mathrm{PMAI}_{L_i} = \frac{\sum_{k \in \mathrm{NW}_i} w_k \mathrm{PMAI_k}}{\sum_{k \in \mathrm{NW}_i} w_k} \tag{5}$$

$$x_{L_i p} = \frac{\sum_{k \in \mathrm{NW}_i} w_k x_{kp}}{\sum_{k \in \mathrm{NW}_i} w_k} \tag{6}$$

where NW_i is the neighboring window of observation (or plot) i, $\mathrm{PMAI_k}$ is the PMAI-value on observation (or neighbor, plot) k within the neighboring window, x_{kp} the value of climatic variable p on neighboring plot k and w_k the weighting term for observation (or neighbor, plot) k, given as the inverse Euclidian distance between observation i and its neighbor k. This distance is

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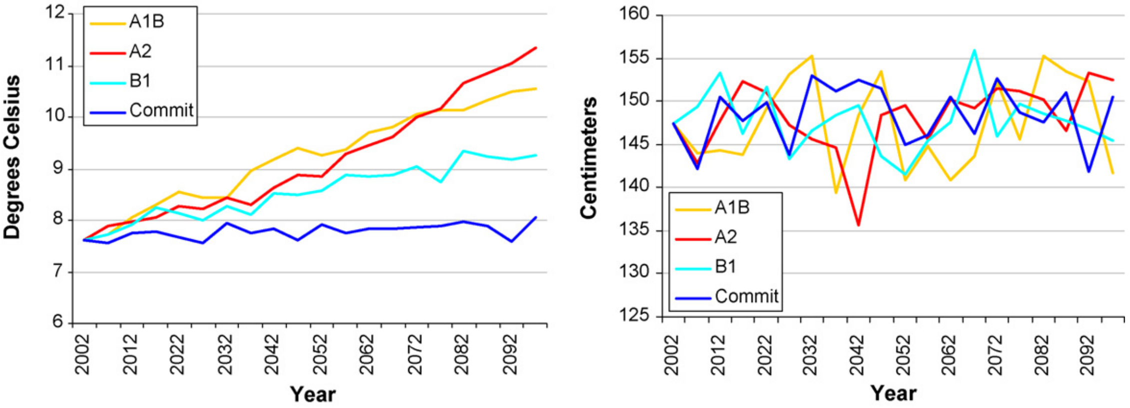
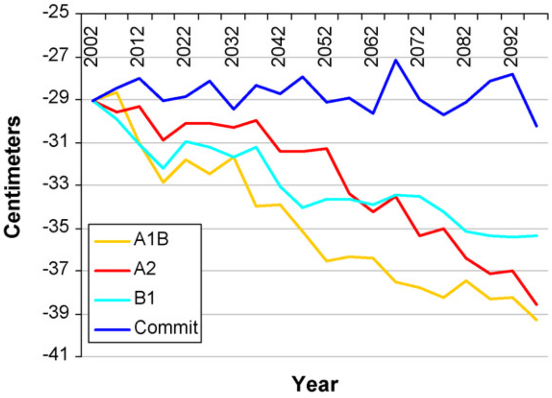


(a) Average annual temperature

(b) Annual precipitation flux



(c) Solar radiation

Fig. 2. GCM predicted change in Pacific Northwest climate variables over the next century by IPCC scenario.

calculated using longitude and latitude decimal degrees and the neighboring window is set to 0.5° (in all directions).

Some potential causes of spatial autocorrelation include measurement error, omitted variables, incorrect equation functional form, and incorrect data transformations. Because we do not know if the factors leading to the autocorrelation will change over time or not, the SAR models error term, u_i, is assumed to be dependent on geographic location and thus remain constant over time. Projecting potential forest productivity for future climate scenarios is accomplished incrementally over 5 year periods by first determining the expected error term (u_i) from Eq. (4). This u_i term is then used along with GCM projected climate data in Eq. (3) to get the future $\mathrm{PMAI_i}$ estimates.

8. Results

The SAR model was estimated using nonlinear least squares. Parameter estimates, asymptotic t ratios and goodness-of-fit statistics for the equations are given in Table 2. The resulting model has an adjusted R-squared of 0.734 with a root mean square error of 2.1 $\mathrm{m^3}$/ha/year. Using the SAR model, future climate change was then estimated for each GCM and IPCC scenario for 25-year periods from 2002 to 2097. Each period represents the average of 5 years of annual data from the GCMs and is presented at the mean year. Averages were then calculated across GCM projections for the results presented below. We first present graphs of aggregate changes broken down by sub-region[1] followed by maps of the productivity differences for each IPCC scenario over the century.

Fig. 4 shows the percentage change in PMAI for each of the four IPCC scenarios over the 100-year time horizon. The first half of the century scenario end with the A1B and A2 scenarios PMAI improving just under 7% while the B1 scenario PMAI goes up approximately 4.5% and the COMMIT scenario PMAI levels show modest gains of just above 1.5%. After the first 50 years the population growth of the A1B scenario tapers off and the A2 scenario emerges with the greatest change in productivity at the end of the century with PMAI values 9% higher than the COMMIT scenario. Sharing the same population growth forecasts as the A1B scenario, the sustainability focus of the B1 scenario leads to more stable average temperatures and forest productivity in the second half of the century. In general, the temperature forecasts given in Fig. 2a are very similar to the PMAI forecasts of Fig. 4 with the

Table 2
Simultaneous autoregressive model parameters and statistics.

Variable	Coefficient	Std. error	*t*-Statistic
β_1	−3.276	2.550	−1.28
β_2	1.029	0.157	6.55
β_3	0.017	0.005	3.58
β_4	0.002	0.000	8.68
β_5	−0.058	0.010	−5.90
β_6	0.000	0.000	−10.82
β_7	3.496	0.157	22.25
ρ	1.041	0.019	56.17
R^2	0.734		
RMSE	2.100 ($\mathrm{m^3}$/ha/yr)		

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[1] The sub regions for this study are split North and South by the Oregon/Washington border, while the Cascade Mountains provide the East and West division.

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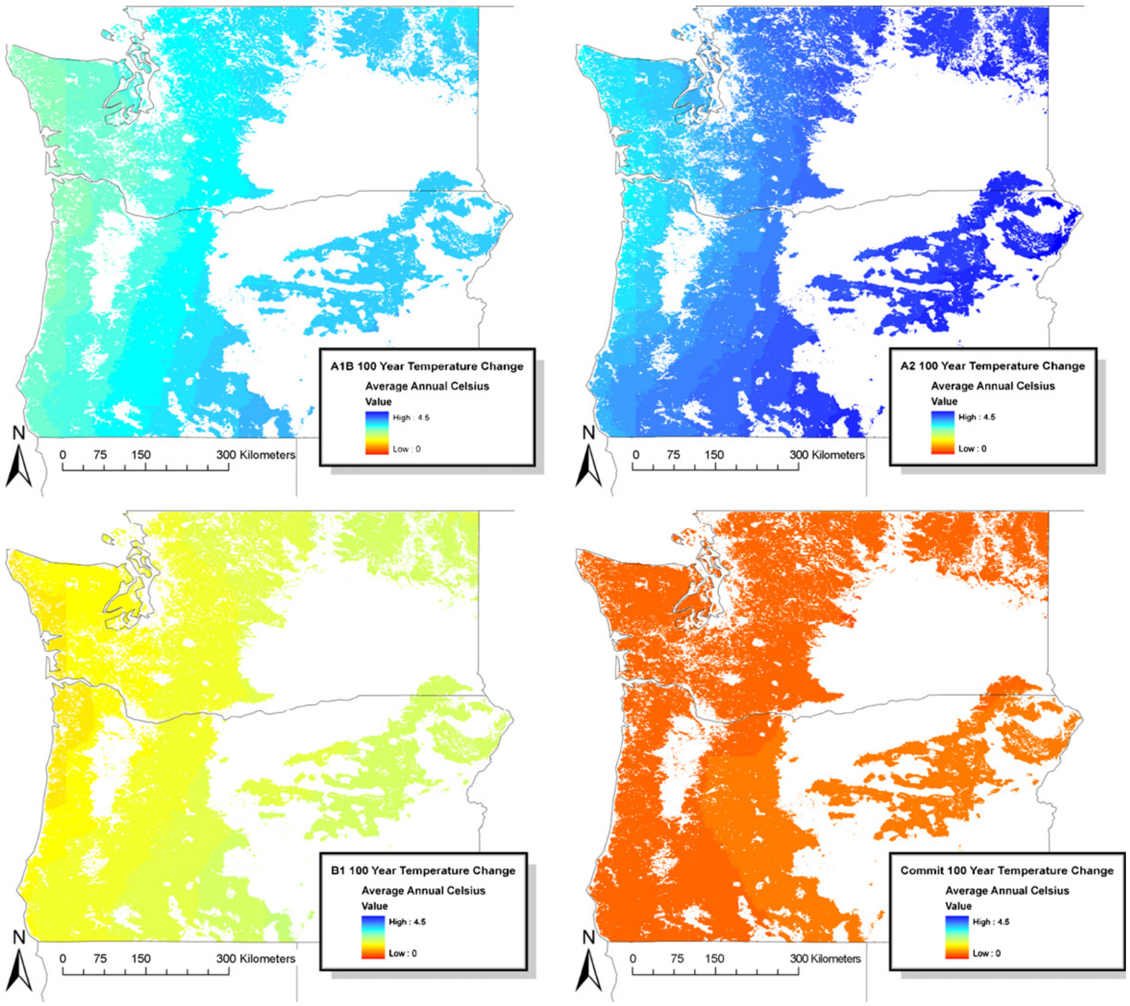

Fig. 3. Change in Pacific Northwest average temperature over the next century by IPCC scenario.

differences due to the short term variation in precipitation and growing season climate moisture index.

While the PMAI change for the entire region shows the extent to which the various climate change scenarios could affect forest productivity in the future, we noted in Fig. 3 that these changes would not be uniform across space. Fig. 5 presents the difference in PMAI by sub region for each IPCC scenario. While Fig. 4 looked at percentage change from current productivity levels, Fig. 5 gives that difference in cubic meters per hectare per year. Some general patterns emerge from looking at the sub-regional effects. The first is that the eastern half of the region will see greater changes in productivity through the next century regardless of the scenario. The resulting changes are even more disproportionate when one considers the lower current productivity on forest land in the eastern part of the region from Table 1. This would lead to a much greater impact if one viewed it in terms of percentages. The second pattern across scenarios in Fig. 5 is that Washington will have greater changes in productivity than Oregon. It may be that because Washington has more forestland with both higher annual precipitation and precipitation in excess of evapotranspiration through the growing season, its productivity responds positively to increases in temperature and length of growing season. These patterns, however, are not as evident in the COMMIT scenario shown in Fig. 5d. With no real change in annual temperature changes, productivity fluctuates mildly with a slight upward trend as precipitation and solar radiation change, but after 100 years show only limited changes from current levels in all sub-regions.

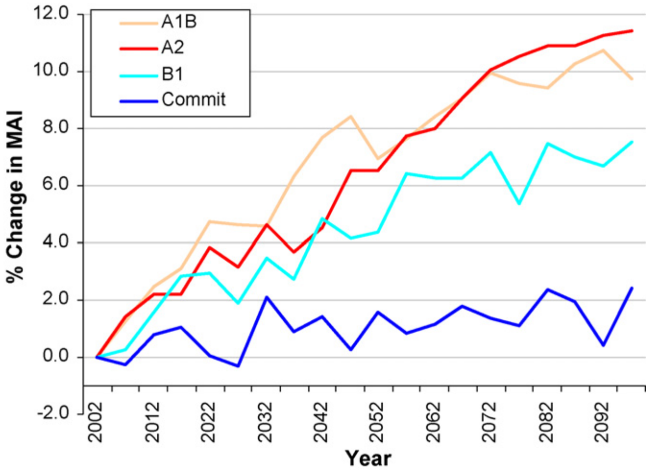

Fig. 4. Pacific Northwest percentage changes from 2002 potential mean annual increment by IPCC scenario.

For each IPCC scenario, maps of forestland productivity, at the end of the century, are presented in Fig. 6. These maps highlight not only the extent to which the scenarios with more of an economic focus, A1B and A2, have much greater productivity gains than the more environmentally focused B1 and Commit scenarios, but also the impact of elevation on future productivity. In all scenarios the

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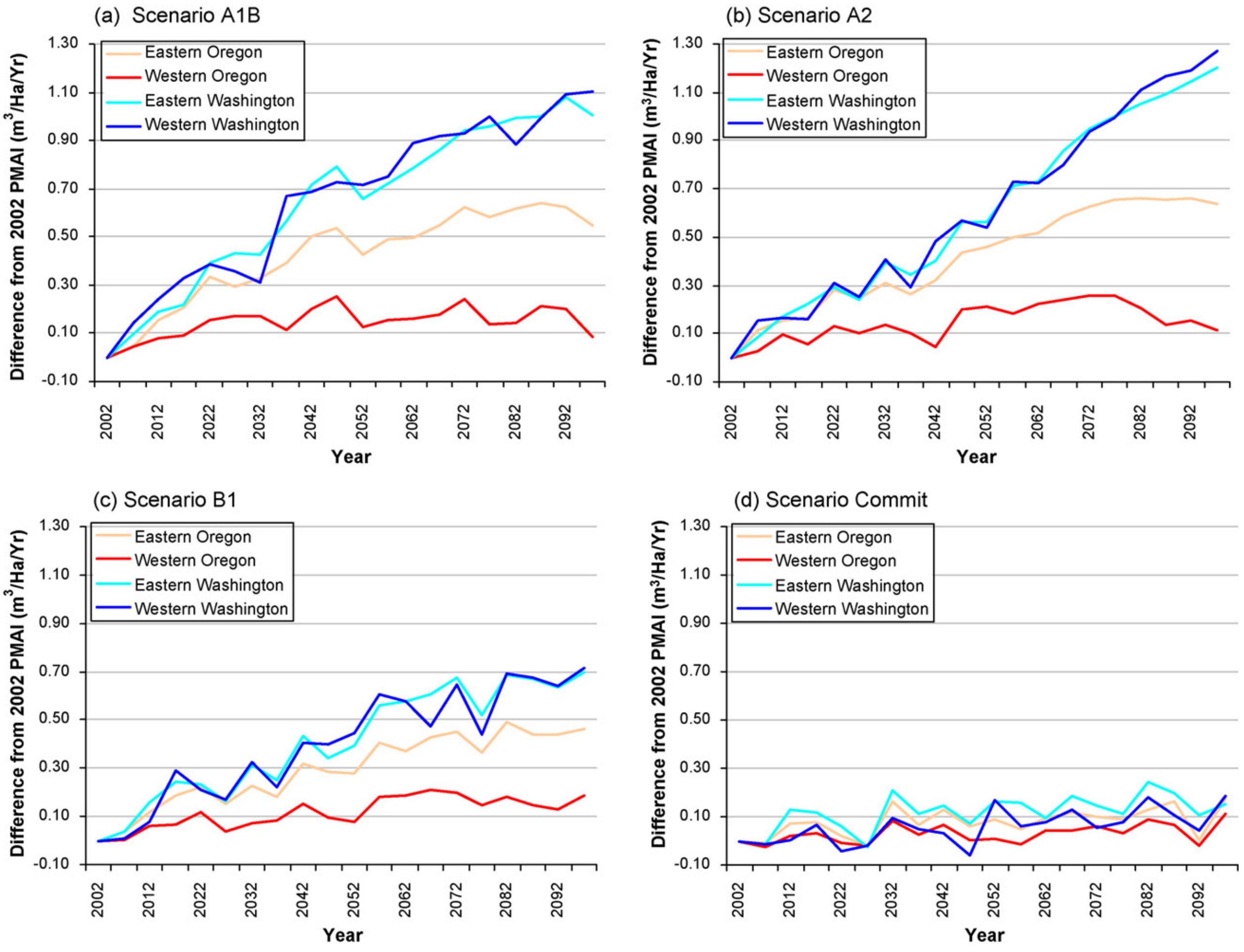

Fig. 5. Pacific Northwest sub regional change in potential mean annual increment from 2002 by IPCC scenario.

Table 3
100-Year changes in potential mean annual increment (m^3/ha/yr) by IPCC scenario.

	Oregon					Washington				
	0–500	500–1000	1000–1500	1500–2000	>2000	0–500	500–1000	1000–1500	1500–2000	>2000
	Elevation (m)					Elevation (m)				
Forestland hectares	2,859,072	2,352,320	3,602,688	2,937,930	324,902	2,828,096	2,666,589	2,688,275	1,010,122	58,710
Current values										
Average PMAI	10.1	7.6	4.9	3.7	2.4	10.4	6.6	4.6	2.5	0.5
Annual temperature	10.9	9.9	7.1	5.6	3.4	9.9	7.5	5.3	2.9	0.5
Annual precipitation	182	170	98	83	107	198	170	154	155	139
Growing season CMI	−25.8	−33.1	−40.2	−41.0	−31.7	−11.1	−27.7	−25.7	−19.8	−6.5
PMAI after 100 Years	(m^3/ha/year)									
A1B	9.8	7.5	5.3	4.6	4.1	10.7	7.5	6.2	4.8	3.0
A2	9.8	7.4	5.3	4.8	4.5	10.9	7.6	6.5	5.3	3.6
B1	10.1	7.7	5.2	4.4	3.4	10.7	7.2	5.7	3.9	1.8
Commit	10.2	7.6	5.0	4.0	2.7	10.6	6.7	4.9	2.8	0.8
100-Year change in PMAI	(m^3/ha/year)									
A1B	−0.3	−0.1	0.4	0.9	1.6	0.3	0.9	1.6	2.3	2.5
A2	−0.3	−0.1	0.5	1.0	2.1	0.4	1.0	1.8	2.8	3.1
B1	0.0	0.1	0.4	0.7	1.0	0.3	0.7	1.0	1.4	1.3
Commit	0.1	0.1	0.2	0.2	0.3	0.1	0.2	0.2	0.3	0.2
100-Year change in PMAI	(%)									
A1B	−2.7	−1.0	8.9	23.4	67.0	2.9	14.4	34.2	92.7	458.3
A2	−2.7	−1.7	9.8	27.7	85.0	4.1	15.2	39.0	111.0	574.2
B1	−0.1	1.3	8.2	17.5	40.0	2.8	10.3	22.4	56.4	240.4
Commit	0.7	1.2	3.3	6.0	10.6	1.1	2.4	5.3	12.8	40.6

Note: Because of rounding, data may not sum to totals.

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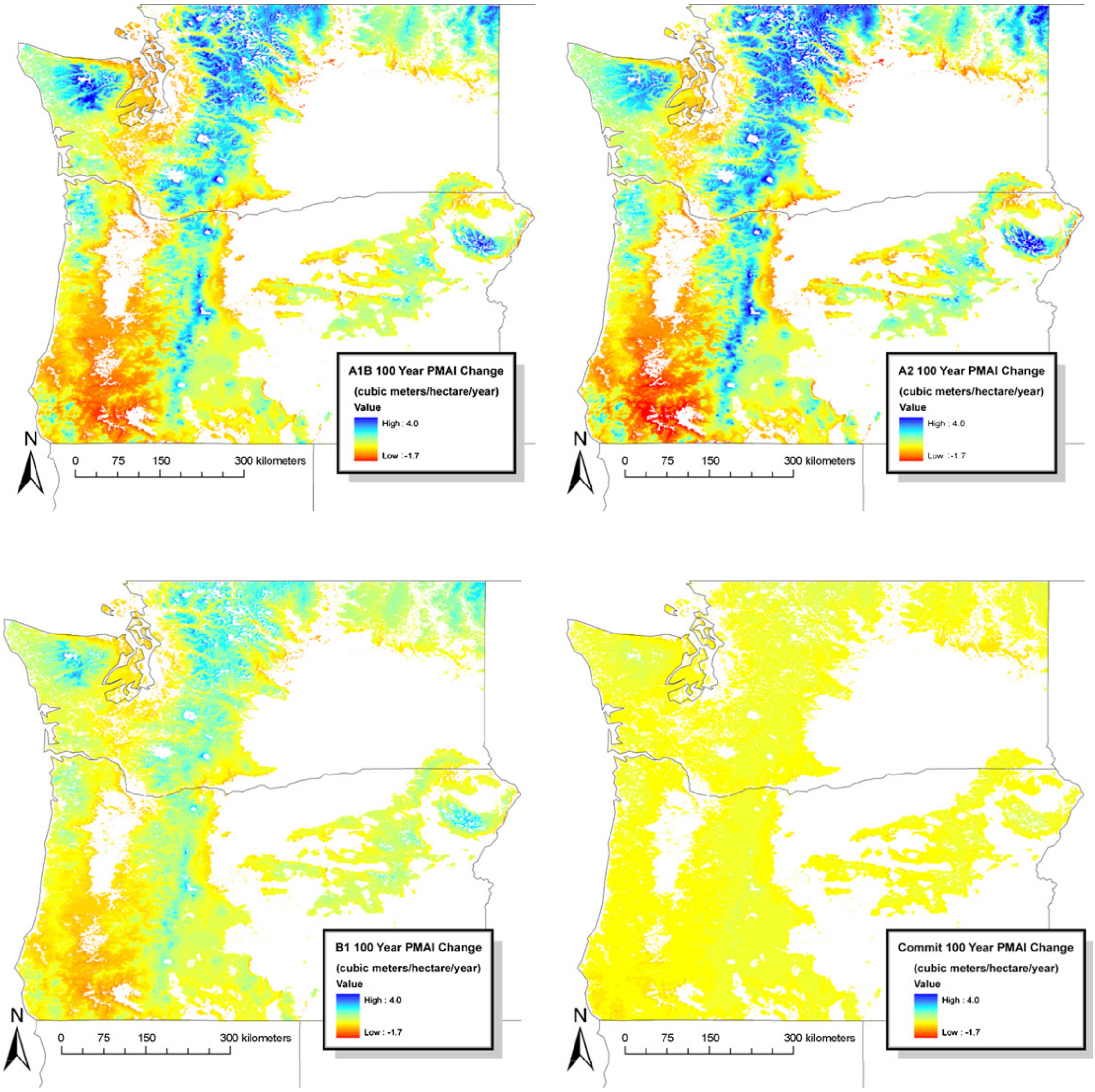

Fig. 6. Change in Pacific Northwest potential mean annual increment over the next century by IPCC scenario.

greatest productivity gains were in the higher elevation forests with forests in the lowlands on the fringe actually declining in productivity. Table 3 shows Oregon and Washington 100-year changes in productivity by 500 m elevation classes. This table confirms that the high productivity low-lying forests are projected to see the lowest levels of increasing productivity and even declining productivity in scenarios A1B and A2 in Oregon.

Water availability decreases with decreasing elevation due to an increase in transpiration caused by the projected increase in temperature. In response to limiting moisture, natural adaption includes lowering biomass production and effective partitioning of photosynthate to different components of trees (Kramer and Kozlowski, 1979). In our study, productivity declined for low elevation areas because of limiting soil moisture through the growing season due to the projected increase in temperature. Our results on low elevation are consistent with Aber et al. (1995)'s findings, which asserted low-elevation areas probably experience water deficits though the growing season in most years. The results of this and other studies inform us that soil moisture management will be central in climate change adaptation in low elevation areas.

Any declines in potential growth are offset by PMAI increases in forestland at elevations greater than 1000 m. These higher elevation forests achieve greater improvements in growth in Washington as opposed to Oregon, most likely due to their lower current productivity level combined with higher precipitation rates and larger gains in temperature. The forests between 500 and 1000 m will also react differently in the two states. In Oregon, the forests of this elevation are substantially warmer with similar annual precipitation and thus they begin 15% more productive than their Washington counterparts, yet the productivity growth is markedly less and even declines in the A1B and A2 scenarios. The forests above 1000 m, likewise, are warmer and more productive in Oregon, yet in all scenarios except the Commit scenario forests in the 1000 to 1500 elevation class are passed by their Washington cohort while the productivity gap between the two states at higher elevations is narrowed.

9. Discussion

Our results indicate that climate scenarios with increase in future temperatures would lead to an overall increase in forest productivity in the Pacific Northwest. This increase will not be consistent across the region, with lower elevations experiencing declines while increase in higher elevation forests partially offset those declines. Information on the potential impacts of climate change on forest productivity is important to forest managers and

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Table 4
Pacific Northwest timberland ownership by elevation class.

	Elevation class (m)					Total
	0–499	500–1000	1000–1500	1500–2000	>2000	
	Thousand hectares					
Oregon						
Federal	638	1135	2166	1,661	90	5,689
Other public	240	115	44	7	–	407
Private	1750	800	1043	263	10	3,866
Total	2629	2049	3253	1,931	100	9,962
Washington						
Federal	152	851	1143	309	11	2,467
Other public	551	293	182	20	–	1,046
Private	1850	1278	692	44	–	3,865
Total	2554	2422	2017	372	11	7,377
Pacific Northwest						
Federal	791	1,986	3309	1,970	101	8,156
Other public	791	407	226	27	–	1,452
Private	3600	2079	1735	306	10	7,730
Total	5183	4472	5270	2,303	111	17,339

Estimates produced from 2001 to 2007 Forest Inventory and Analysis data (http://fiatools.fs.fed.us/fiadb-downloads/datamart.html).

policy makers. Forest productivity will be an important factor for decisions related to timber markets, carbon sequestration, fire risk through fuel accumulation, and a host of other issues.

How decision makers respond to these potential changes may depend in large part on who owns the forest in question. Private forests often have a timber supply objective focused on maximizing financial returns from the forest. In recent years federal forests have focused on ecosystem services such as wildlife habitat, carbon sequestration, and amenity values including recreation and scenic qualities. State lands management tends to fall somewhere between the two as they attempt to balance economic and ecosystem values across the landscape. Forest ownership in the Pacific Northwest is given in Table 4. This ownership pattern presents problems for each of the owner classes. On private lands concentrated at lower elevations, which account for 45% of the timberland base (Table 4) and 83% of the harvest over the last decade (Warren, 2008), future forests will have the challenge of intensifying management to continue to produce forest products at current levels, or allow harvest rates to fall. Federal lands concentrated at higher elevations, which account for 47% of the timberland base and 6% of the harvest over the last decade, will see increases in carbon sequestration rates and be presented with challenges of determining how changes in forest growth affect habitat. The increase in growth will in most cases also lead to increases in fuel accumulation which could lead to changes in fire frequency and severity.

The changes in productivity discussed above should be viewed as potentials. There are very few, if any, land managers who set management priority on maximizing volume from the forest resource. The measure of productivity through PMAI is based on how productive forests could be if managed on a rotation set at the age at which mean annual increment was maximized. Private lands tend to operate on shorter rotations, while public lands often work on longer rotations. The result would be that in both cases actual productivity is less than the culmination potential. If we take the average PMAI for the private owners and national forests in Oregon from the current study we get 8.4 and 6.0 m^3/ha/year, respectively. Using gross growth and acreages reported in Campbell et al. (2004), the annual increment for Oregon in 1999 was 5.6 and 4.8 m^3/ha/year, or 67% and 81% of the values from this study for those same ownerships. Mortality rates were quite different for the ownerships as private timberlands lost 16% of gross growth while national forests of Oregon lost 45% of gross growth to mortality. Removals are different as well with private timberland in Oregon removing 104% of gross growth which when combined with mortality lead to a declining inventory which presents problems for the future when combined with lower productivity for both harvest levels and carbon sequestration. On public lands, removals of 32% of gross growth leads to an increase in growing stock which when coupled with increasing productivity over time could lead to even greater carbon sequestration, increased mortality, and resulting increases in fire risk due to fuel loading.

10. Conclusion

By combining a model that relates climate to forest productivity with scenarios of potential future changes in climate, we found considerable variation in potential future productivity change across both time and space. There are many other issues to consider as we attempt to understand possible changes in the forest resource of the future. Disturbance regimes, including diseases, insect outbreaks, and fire, can also be affected by climate, in turn impacting forest productivity Silvicultural practices can also change over time which could serve to moderate climate change impacts on the forest resources of the Pacific Northwest. Since observed productivity is a function of the species currently present at a site, shifts in species composition or genetic limitations to adaption can impact long-term productivity by changing growth rates as climate changes. Productivity in the short term can be impacted by mortality if climatic conditions move beyond the limits suitable for the species currently present. Regardless of the simplification of these many complex issues, information from studies such as this can inform the debate on policy and management for policy makers and forest managers.

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