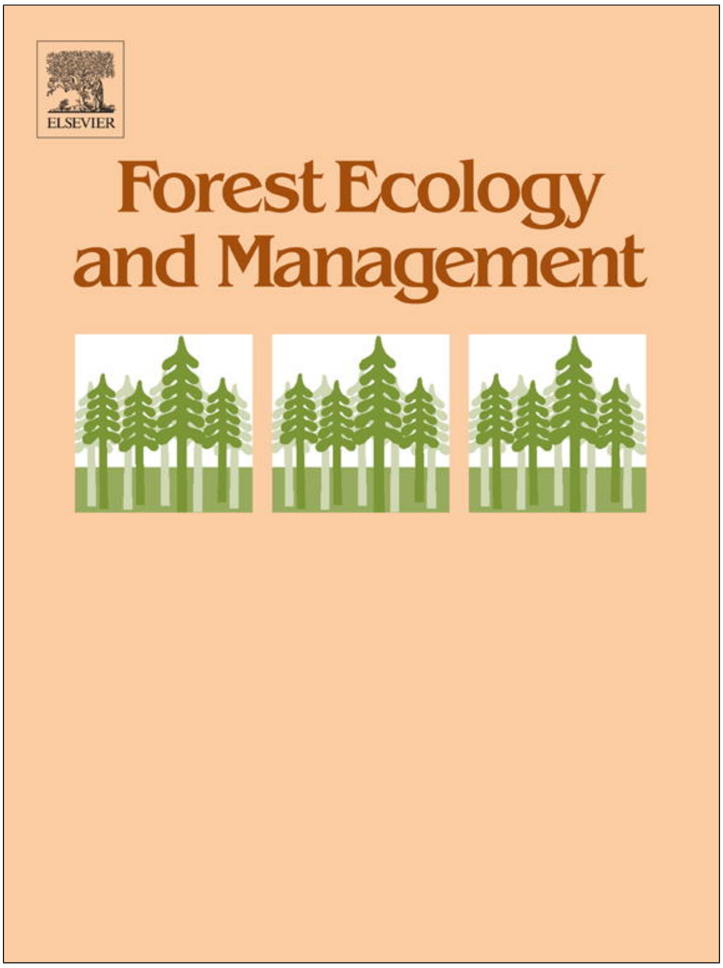
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Climate effects on red alder growth in the Pacific Northwest of North America

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ABSTRACT

We investigated the effects of climate on the growth of red alder across a broad latitudinal gradient and over a wide range of growing conditions in the Pacific Northwest of North America (PNW). Data for this study came from a study established in 1988 that includes 31 research installations located between the Pacific Coast and the Cascade Mountains in Oregon, Washington, and British Columbia. The growth-climate model developed includes: summer heat moisture index (SHM), mean warmest month temperature (MWMT), spring precipitation (PPTsp), and initial height; and captures 78% of the variation in red alder volume increment. Based on this model, estimates of potential future growth were generated for three climate scenarios (i.e., cccma_cgcm3_A2-run4 'warm and wet' of the Canadian Centre for Climate Modeling and Analysis; and ukmo_hadcm3_B1-run1 'cool and moist' and ukmo_HadGEM1_A1B-run1 'hot and dry' of the Hadley Centre for Climate Prediction and Research). These projections indicate a potential increase in volume increment of up-to 12% by the 2080s. Range-wide maps were generated for the volume increment potential (VIP) for the reference normal period 1961–1990, for the 'warm and wet' climate scenario, and the 2050s time period, suggesting that climate change may cause a substantial shift in the range and productivity of red alder in the PNW. In addition, maps of the predicted VIP of red alder for the Campbell River District in BC were generated and indicate an overall increase in projected growth of red alder. This study provides evidence that climate change will likely lead to expansion of the range and potential increases in growth for red alder in conjunction with assisted migration of provenance in the PNW. While these results indicate potential increased opportunities for extension of the range of red alder and opportunities for its management, care must be taken to avoid planting alder on sites with high risk of damaging agents such as cold outflow winds, frost, or drought.

1. Introduction

With predicted future climates resulting from climatic changes (IPCC, 2007), the growth and survival of red alder (*Alnusrubra* [Bong.]) in the Pacific Northwest of North America (PNW) will likely be affected. However, the long term consequences to the range and growth of red alder and other tree species are still largely unknown (e.g., Spittlehouse, 2008). In the PNW, climate change has already been related to changes in the hydrological balance that can lead to increasing summer drought, tree mortality, increased forest wildfire activity (Mote et al., 2005; Westerling et al., 2006; van Mantgem et al., 2009; Stewart et al., 2004) and to shifts in the bioclimatic envelopes of ecosystems and species (Hamann and Wang, 2006). Tree growth is directly affected by climate and, as average temperature rises, future climates may favour species better suited to warmer climates (e.g., Spittlehouse, 2008). Studies have also shown that the rate of climate change is outpacing the rate of natural selection and seed migration with potentially negative consequences to forest productivity (e.g., O'Neill et al., 2008). However, the mountainous topography of the PNW has created a great genetic diversity within tree species which can help the current tree species to adapt to the warmer climate (Johnston, 2009).

The range of red alder extends from California to southeast Alaska. Red alder grows in humid climates preferring moist, well-drained alluvial soils (Harrington, 1990) with low winter temperatures, short growing season and lack of precipitation being the main limits to the range of red alder. It is mostly a lowland species commonly found within 200 km of the seacoast at elevations below 750 m (500 m near Campbell River BC). Since it is a shade-intolerant early successional species it is found mostly on sites that have experienced disturbances such as clearcutting, fire, flooding or landslides. Although it often competes with regenerating conifers due to its more rapid early growth, red alder can potentially enhance long-term site productivity and conifer growth by increasing soil nitrogen availability through its ability to fix atmospheric nitrogen (Miller and Murray, 1978; Bormann et al.,

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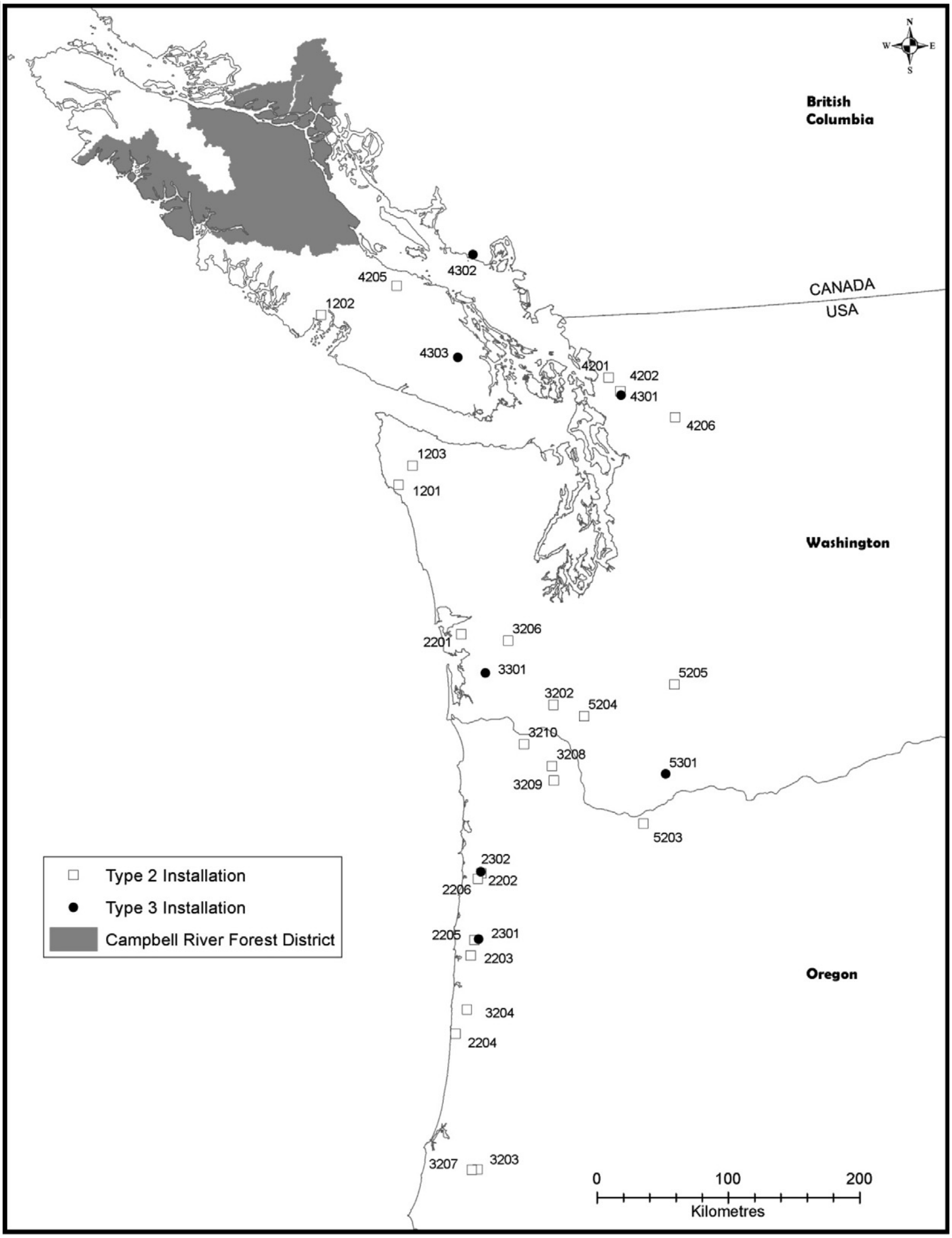

Fig. 1. Location of the Type 2 and Type 3 installations used in this study and the boundaries of the Campbell River Forest District.

1994). Red alder also produces valuable lumber that is used for furniture, pallets and pulp.

The objective of this study is to investigate the effects of climatic variables on the growth of red alder throughout a broad latitudinal gradient in the PNW. Then, in order to evaluate the potential effects of climate change on tree growth, the growth–climate models developed were then used to project the growth of red alder using three future climate scenarios. The Campbell River Forest District was used as case study to explore potential shifts in the range of red alder.

Table 1
Monthly, seasonal and annual climate variables generated by Climate WNA used for examining climate effects on growth of red alder.

Annual variables	
MAT	Mean annual temperature (°C)
MSP	Mean annual summer (May to September) precipitation (mm)
DD>5	Degree-days above 5 °C, growing degree-days
eFFP	The day of year on which frost-free period ends
PAS	Precipitation as snow
AHM[a]	Annual Heat Moisture Index
SHM[b]	Summer Heat Moisture Index
MWMT	Mean Warmest Month Temperature
MCMT	Mean Coldest Month Temperature
Seasonal variables	
TAVat	Autumn mean temperature (°C)
TAVwt	Winter mean temperature (°C)
TAVsp	Spring mean temperature (°C)
TAVsm	Summer mean temperature (°C)
PPTat	Autumn mean precipitation (mm)
PPTwt	Winter mean precipitation (mm)
PPTsp	Spring mean precipitation (mm)
PPTsm	Summer mean precipitation (mm)

[a] AHM = MAT + 10/(MAP/1000).
[b] SHM = MWMT/(MSP/1000).

2. Methods

Data for this study came from the Hardwood Silviculture Cooperative (HSC) red alder stand management study established in 1988, which aims at creating an information base for the management of red alder (http://www.cof.orst.edu/coops/hsc/). Data was compiled for red alder from 31 research installations (Fig. 1). All installations are located between the Pacific Coast and the Cascade Mountains in Oregon, Washington, and British Columbia and cover a wide range of growing conditions. The overall climate for the region is humid oceanic, with a distinct dry summer and a cool, wet winter. Soils varied from shallow sandy loams to very deep silty clay loams. The plantations were all established between 1988 and 1997 with 1-year old seedling sand variable, operational levels of vegetation control.

The Type 2 installations are part of a red alder variable density study established on recently harvested sites, stratified by region and site class, and planted to densities ranging between 247 and 2965 trees per hectare (tph). For this study, we selected control plots with a target planting density of 568 tph. The Type 3 installations are part of a mixed red alder and Douglas-fir replacement series study with a constant target stand density of 742 tph and five proportions of red alder and Douglas-fir (i.e., 1.0/0; 0.50/0.50; 0.25/0.75; 0.11/0.89; 0/1.0). For this study we selected the pure red alder plots planted at 742 tph. Permanent measurement plots (with 20 m buffers) ranged from 0.134 to 0.202-ha. In each plot, individual trees were tagged.

Diameter at breast height (DBH) and total height of each tree were first measured at plantation age 3 (total age 4) and measured again every 3 years since. In order to avoid the confounding effect of competing vegetation during the early stages of stand development (e.g., herbs and shrubs), we did not include the measurements at plantation age 3. Since height was sub-sampled within each plot, linear relationship between DBH and height were used to calculate the missing height values. Stem volume (cm^3) was then calculated at each measurement date assuming a conical bole using DBH and total height. Stem volume increment was calculated as the difference between two consecutive measurements for each tree for each three-year interval.

Climate WNA software (Wang et al., 2006, 2012), was used to calculate historical monthly, seasonal and annual climate variables

Table 2
Information for red alder plantations used for this analysis: location, planting year, basic climate information (averaged over the study period), number of observation (Obs.) and number of increments (Inc.) with year period (Year) for each installation (Inst.) by species (Spp.) and installation type. The climate variables presented are the Summer Heat Moisture index (SHM), the Mean Warmest Month Temperature (°C) (MWMT), and spring precipitation (mm) (PPTsp).

HSC type	Inst.	Latitude	Longitude	Elev.	Planting year	SHM	MWMT	PPTsp	Obs	Inc. (Year)
2	1201	47.889	−124.505	133	1990	40.4	16.3	610	384	3 (1996–2002)
2	1202	49.066	−125.277	172	1993	20.5	17.3	1271	275	3 (1999–2005)
2	1203	48.021	−124.358	168	1995	40.6	17.4	743	206	2 (2001–2004)
2	2201	46.850	−123.915	123	1989	58.2	17.5	503	227	3 (1995–2001)
2	2202	45.196	−123.787	355	1990	38.1	17.4	736	244	3 (1996–2002)
2	2203	44.629	−123.914	102	1991	55.3	15.7	499	311	3 (1997–2003)
2	2204	44.091	−124.077	288	1993	58.0	16.7	548	222	3 (1999–2005)
2	2205	44.737	−123.872	95	1993	59.9	16.7	504	268	3 (1995–2005)
2	2206	45.159	−123.821	439	1994	43.5	17.2	759	257	3 (2000–2006)
2	3202	46.342	−123.026	223	1989	65.5	17.7	447	174	3 (1995–2001)
2	3203	43.145	−123.908	323	1991	79.8	19.3	527	308	3 (1997–2003)
2	3204	44.255	−123.963	233	1991	61.7	18.7	643	336	3 (1997–2003)
2	3206	46.797	−123.449	164	1992	72.9	17.3	493	286	3 (1998–2004)
2	3207	43.142	−123.962	226	1993	95.8	18.8	433	230	3 (1999–2005)
2	3208	45.919	−123.064	459	1996	96.3	17.2	378	105	2 (2002–2005)
2	3209	45.819	−123.052	482	1994	104.9	16.8	356	338	3 (2000–2006)
2	3210	46.078	−123.332	363	1996	80.5	17.8	412	169	2 (2002–2005)
2	4201	48.574	−122.316	119	1988	62.6	17.8	282	239	3 (1994–2000)
2	4202	48.477	−122.201	188	1989	54.1	17.8	332	322	3 (1995–2001)
2	4205	49.259	−124.483	332	1993	68.8	17.5	349	160	3 (1999–2005)
2	4206	48.275	−121.655	145	1994	59.5	19.4	455	360	3 (2000–2006)
2	5203	45.492	−122.205	390	1991	61.7	19.4	525	247	3 (1997–2003)
2	5204	46.254	−122.731	232	1992	62.8	18.3	473	419	3 (1998–2004)
2	5205	46.439	−121.826	633	1996	65.1	18.5	490	146	2 (2002–2005)
3	2301	44.744	−123.833	137	1994	63.3	17.0	517	199	3 (1996–2005)
3	2302	45.209	−123.791	449	1995	41.3	16.8	756	150	2 (1998–2004
3	3301	46.581	−123.686	333	1995	54.6	16.7	620	347	3 (1997–2006)
3	4301	48.451	−122.195	259	1994	51.3	18.2	391	291	3 (1996–2005)
3	4302	49.46	−123.672	276	1991	41.0	17.2	491	193	3 (1994–2005)
3	4303	48.756	−123.864	173	1993	87.2	17.8	318	209	3 (1996–2005)
3	5301	45.827	−121.962	398	1997	70.0	18.2	607	141	2 (1999–2005)

(e.g., mean annual temperature, mean summer precipitation, growing degree days) for individual locations based on the latitude, longitude and elevation up to year 2009.

The relationships between volume increment divided by initial size (i.e., height) and the climate variables, presented in Table 1, were modeled using multiple linear regression analysis. The variables were screened with the 'stepwise' selection method using the REG procedure in SAS version 9.2 (SAS Institute Inc., Cary, NC). Stepwise selection identified 13 of the 17 climate variables tested as being significantly ($\alpha = 0.05$) related to volume increment divided by initial height. We then tested for co-linearity of these climate variables using the CORR procedure in SAS software (SAS Institute Inc., Cary, NC) and if Pearson's correlation coefficient was higher than 0.7 ($\alpha = 0.05$) only one (randomly selected) of the two climate variables was retained for further calculations. Of the seventeen climate variables tested: the summer heat moisture index (SHM), the mean temperature of the warmest month (MWMT), spring precipitation (PPTsp), and mean annual temperature (MAT) proved to be the strongest predictors of red alder volume increment divided by initial height.

We then examined the effects of these climate variables on growth of red alder using non-linear mixed effects models. Tree size (height and diameter) at the beginning of each three year growth period was tested as independent variables together with the climatic variables selected. The initial size advantage hypothesis states that trees with a larger initial size are more competitive than their smaller cohorts and therefore growth analyses improve when taking into account the initial size of the trees (e.g., Larocque, 1998). Initial height (HTi) provided the strongest correlation with volume increment (VI) and it was used as an additional explanatory variable, similar to the results found in Comeau et al. (2003).

To account for auto-correlation related to repeated measurements of each tree, several combinations of predictors were tested as random factors, with tree ID as the subject (Hall and Bailey, 2001).The models tested are:

$$\mathrm{VI}_{ij} = \beta_0 \times \exp(\beta_1 \cdot \mathrm{SHM}_{ij} + \beta_2 \cdot \mathrm{MWMT}_{ij} + \beta_3 \cdot \mathrm{PPTsp}_{ij} + \beta_4 \cdot \mathrm{MAT}_{ij}) + \varepsilon_{ij} \tag{1}$$

$$\mathrm{VI}_{ij} = \beta_0 \times \exp(\beta_1 \cdot \mathrm{SHM}_{ij} + \beta_2 \cdot \mathrm{MWMT}_{ij} + \beta_3 \cdot \mathrm{PPTsp}_{ij} + \beta_4 \cdot \mathrm{MAT}_{ij}) \times \mathrm{HTi}_{ij}^{(\beta_5)} + \varepsilon_{ij} \tag{2}$$

$$\mathrm{VI}_{ij} = (\beta_0 + b_{0ij}) \times \exp(\beta_1 \cdot \mathrm{SHM}_{ij} + \beta_2 \cdot \mathrm{MWMT}_{ij} + \beta_3 \cdot \mathrm{PPTsp}_{ij} + \beta_4 \cdot \mathrm{MAT}_{ij}) \times \mathrm{HTi}_{ij}^{(\beta_5)} + \varepsilon_{ij} \tag{3}$$

$$\mathrm{VI}_{ij} = (\beta_0 + b_{0ij}) \times \exp(\beta_1 \cdot \mathrm{SHM}_{ij} + \beta_2 \cdot \mathrm{MWMT}_{ij} + \beta_3 \cdot \mathrm{PPTsp}_{ij}) \times \mathrm{HTi}_{ij}^{(\beta_5)} + \varepsilon_{ij} \tag{4}$$

$$\mathrm{VI}_{ij} = (\beta_0 + b_{0ij}) \times \exp(\beta_1 \cdot \mathrm{SHM}_{ij} + \beta_2 \cdot \mathrm{MWMT}_{ij} + \beta_3 \cdot \mathrm{PPTsp}_{ij}) \times \mathrm{HTi}_{ij}^{(\beta_5 + b_{1ij})} + \varepsilon_{ij} \tag{5}$$

where VI_{ij} is annual volume increment over the measurement interval (cm^3) β_0, β_1, β_2, β_3, β_4 and β_5 are fixed parameters, and two random effects, b_{0ij} added to the multiplicative intercept (β_0), and b_{1ij} added to the power associated with the initial height (HTi_{ij}) of the tree (β_3) (normally distributed with mean zero and an unknown variance component) associated with the ith tree. The index j represents the multiple measurements recorded per tree. And ε_{ij} represents the remaining unexplained error, also assumed to be normally distributed with mean zero and an unknown variance component. Since MAT in Eq. (3) is not significantly different from zero, it was removed in Eqs. (4) and (5). Parameter estimation for both fixed-effects and mixed-effects models was completed using the NLMIXED procedure in SAS statistical package version 9.2 (SAS Institute Inc., Cary, NC).

The models were compared using several criteria including: (1) the Akaike information criterion (AIC; Burnham and Anderson, 1998), (2) the coefficient of determination (Pseudo R^2), (3) the root mean square error (RMSE), and (4) residual's plots. AIC is the log-likelihood penalized by the number of parameters.

The best model was then used to predict the volume increment of red alder under future climate conditions for the Campbell River District. Since the predicted volume increment is for combinations of climate conditions rather than an individual tree or a stand, it is termed volume increment potential (VIP). Since the focus of this study is on general relationships between climate and VIP, we substituted initial height with an average standard value of 5.17 m across the data set. Climate WNA was used to generate the climate variables required by the model for both the full geographic range of red alder as well as for the Strathcona Timber Supply Area (TSA) for three future time periods: 2020s, 2050s and 2080s (Wang et al., 2012). We used three future climate change scenarios recommended by Murdock and Spittlehouse (2011), which included cccma_cgcm3_A2-run4'warm and wet' (Canadian Centre for Climate Modeling and Analysis), ukmo_hadcm3_B1-run1 'cool and moist' (Hadley Centre for Climate Prediction and Research), and ukmo_HadGEM1_A1B-run1 'hot and dry' (Hadley Centre for Climate Prediction and Research). The coordinate input files for Climate WNA were prepared based on the digital elevation models (DEM) obtained from Shuttle Radar Topography Mission (SRTM) at a resolution of 1 km for western North America and 90 m for the Strathcona TSA.

Using these procedures, we estimated and mapped the volume increment potential (VIP) of red alder, range wide and in Campbell River District using ArcGIS (version 10). VIP was estimated for each grid cell at the corresponding resolution for each time period and filtered by the bioclimatic envelopes of this species (Wang et al.,

Table 3
Parameter estimates (reported with standard errors)for predicting volume increment for red alder as calculated from equation [1], [2], [3], [4], and [5] described in section 2. The number of observations is 7763.

Eq.		SHM	MWMT	PPTsp	MAT	HT Initial	Random parameters	
	β_0	β_1	β_2	β_3	β_4	β_5	σ^2_{b0}	σ^2_{b1}
(1)	90.3638 (11.059)	−0.0029 (0.000379)	0.09871 (0.007862)	−0.00121 (0.000061)	0.01755 (0.007797)	–	–	–
(2)	16.1013 (1.6872)	−0.0022 (0.000319)	0.02401 (0.005738)	−0.00009 (0.000041)	0.01922 (0.008677)	1.258 (0.01771)	–	–
(3)	22.8302 (3.2381)	−0.0025 (0.00038)	0.03169 (0.008487)	−0.00017 (0.000051)	N.S.*	1.0447 (0.01822)	52.401	–
(4)	24.0745 (3.2902)	−0.0024 (0.00037)	0.03821 (0.007504)	−0.00014 (0.000049)	–	1.045 (0.01825)	58.503	–
(5)	25.1081 (3.4769)	−0.0029 (0.000394)	0.04103 (0.007688)	−0.00016 (0.00005)	–	1.0122 (0.019)	22.356	0.01

*N.S. = Not Significant ($\alpha = 0.05$).

Table 4
Statistical information for the models predicting volume increment for red alder as calculated from Eqs. (1)–(5) described in Section 2.

Eq.	(Pseudo) R^2	RMSE cm^3 10^{-2}	Akaike's information criterion (smaller is better)
(1)	0.05	236.7	109649
(2)	0.55	163.7	101195
(3)	0.79	111.8	100082
(4)	0.79	111.7	100083
(5)	0.78	112.8	99962

$$(pseudo)R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2};\ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-k}};\ AIC = -2\ln(\mathrm{L}) + 2k;$$

where y_i – observed values; $\hat{y}_i$ – predicted values; $\bar{y}$ average; n – sample size; k – number of mode parameters; ln (L) – logarithm of the likelihood function.

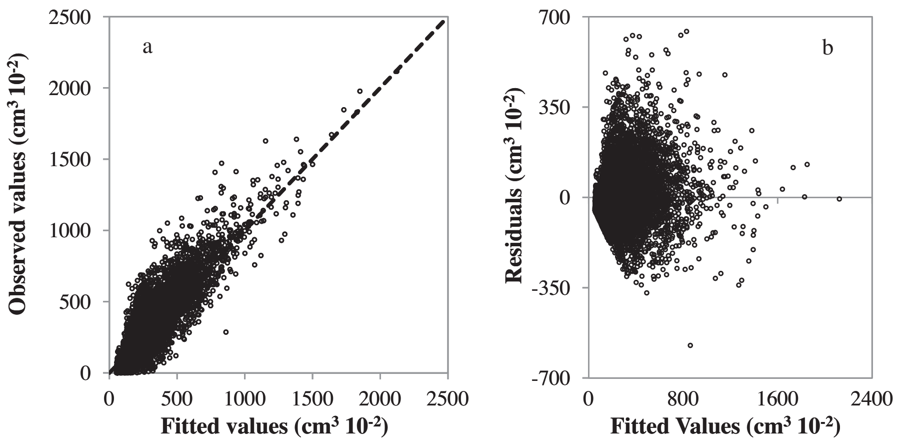

Fig. 2. Performance of the model for red alder stem volume increment (based on Eq. (5); Table 3): scatter plot of fitted against observed values (a), and scatter plot of residuals against the predicted values (b). VIP is expressed in units of $cm^3 \times 10^{-2}$; consequently VIP values shown on the graph axes and elsewhere in this paper should be multiplied by 100 to provide values in cm^3.

Table 6
Climate information (for three climate variables) and VIP values for three future climate scenarios and normal climate values (1961–1990) for two CWH biogeoclimatic subzones representative of dry and wet climatic regimes: xm (Campbell River) and vm (Esperanza). The climate variables presented are: Summer Heat Moisture index (SHM), Mean Warmest Month Temperature (°C) (MWMT), and spring precipitation (mm) (PPTsp).

	SHM				MWMT				PPTsp				VIP		
	1961–90	2020s	2050s	2080s	1961–90	2020s	2050s	2080s	1961–90	2020s	2050s	2080s	2020	2050	2080
Warm and wet															
xm	58.8	59.9	65	77.7	16.9	18.7	19.9	21.6	290	321	341	365	226	233	240
vm	23.3	23.6	24.9	30.1	16.6	17.9	19	20.7	779	860	919	977	223	230	241
Hot and dry															
xm	58.8	77.8	103.5	110.5	16.9	18.8	21.2	22.7	290	296	299	308	216	221	230
vm	23.3	30.3	40.2	41.6	16.9	18.2	20.5	22.4	779	796	800	831	224	239	256
Cool and moist															
xm	58.8	73.6	79.4	84.6	16.9	18.4	19.8	20.8	290	295	307	303	215	224	230
vm	23.3	29.3	30.6	32.6	16.9	18	19	20.1	779	795	818	800	222	230	240

2012). The Campbell River District was selected for a more detailed investigation. This District covers approximately 700,000 ha of north central Vancouver Island BC and parts of the adjacent mainland coast and associated islands.

3. Results

For each installation, the information related to the location, elevation, year of planting, climate variables, number of observations, number of increments and the years of the studied period included in the final model (average SHM, MWMT, PPTsp over the study period) are presented in Table 2.

The model that provided the best overall fit is Eq. (5) and included: summer heat moisture index (SHM), mean warmest month temperature (MWMT), spring precipitation (PPTsp), initial height (HTi) and two random effects, b_0 added to the multiplicative intercept (β_0), and b_1 added to the power associated with the initial height of the tree (β_3) (Tables 3 and 4). This final model explained approximately 78% (RMSE = 112.8 $cm^3 \times 10^{-2}$) of the variation in

Table 5
Potential percent increase in red alder volume increment in comparison to past volume growth (1994–2006) for three future climate scenarios based on three time periods.

Warm and WET			Hot and dry			Cool and moist		
2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
3.8	7.6	10.8	2.7	5.1	12.1	3.9	3.8	9.7

volume increment for red alder. The model and independent variables were all significant at $\alpha = 0.01$ and a scatter plot, showing how well the model predicts observed values, is presented in Fig. 2. The skewed distribution for low growth values shown in Fig. 2 is a consequence of assuming that growth is zero for height initial equal to zero, which leads the model to slightly over predicting growth for small trees, but avoids negative growth values estimates for trees below 1.3 m (which are outside the data range).

Based on the projections of three future climate scenarios for the entire study area (Table 6), Eq. (5) indicated a potential increase in volume increment of up-to 12% by the 2080s (i.e., hot and dry scenario) (Table 5). Range-wide maps were generated for predicted volume increment potential (VIP) for the reference normal period 1961–1990, for the warm and wet climate scenario, and the 2050s time period (Fig. 3). In addition, maps of the predicted VIP of red alder for the Campbell River District were generated for the reference period (1961–1990), the three climate scenarios, and the three time periods (Table 6). The map of the District for the 'warm and wet' scenario (Fig. 4) shows increases in red alder volume increments for a large percentage of the area through the 2080s. Similar trends are also shown for the 'hot and dry' scenario (Fig. 5). However for the 'cool and moist' scenario (Fig. 6) results suggest a smaller increase in volume increment through the 2080s than is indicated by the other two scenarios.

4. Discussion

Results from our analysis indicate that climate change may cause a shift in the range and productivity of red alder in the PNW. Other recent studies have also indicated that the range of several species may expand northward (Thomson et al., 2009), and to higher elevations (Miyamoto et al., 2010), as a consequence of climate change, as is also indicated for red alder in this study. These results are consistent with the findings of Hamann and

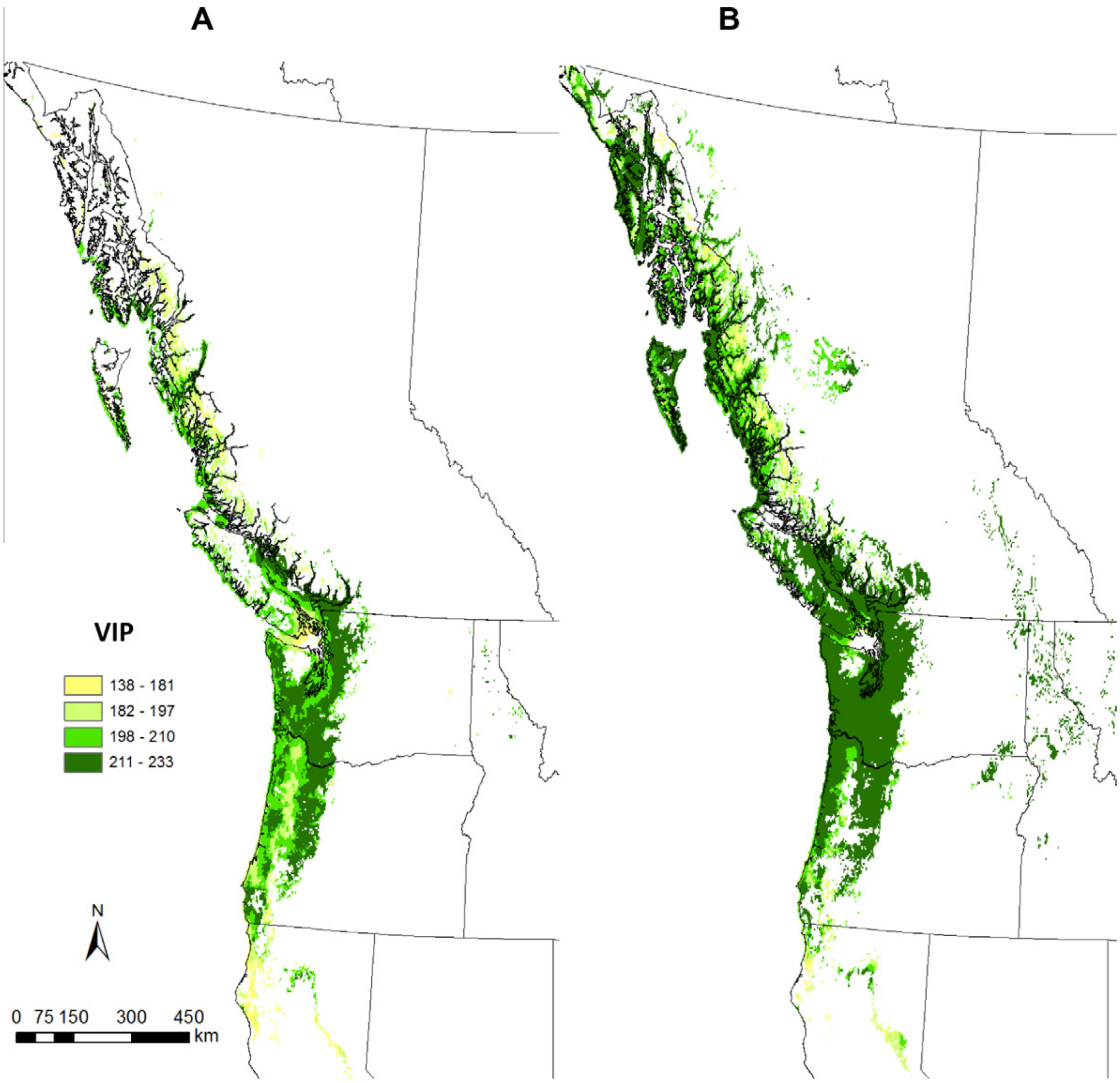

Fig. 3. Red alder range-wide distribution maps by predicted volume increment potential(VIP; $cm^3 \times 10^{-2}$) for the reference normal period 1961–1990 (A) and 2050s (B) based on the warm and wet climate scenario.

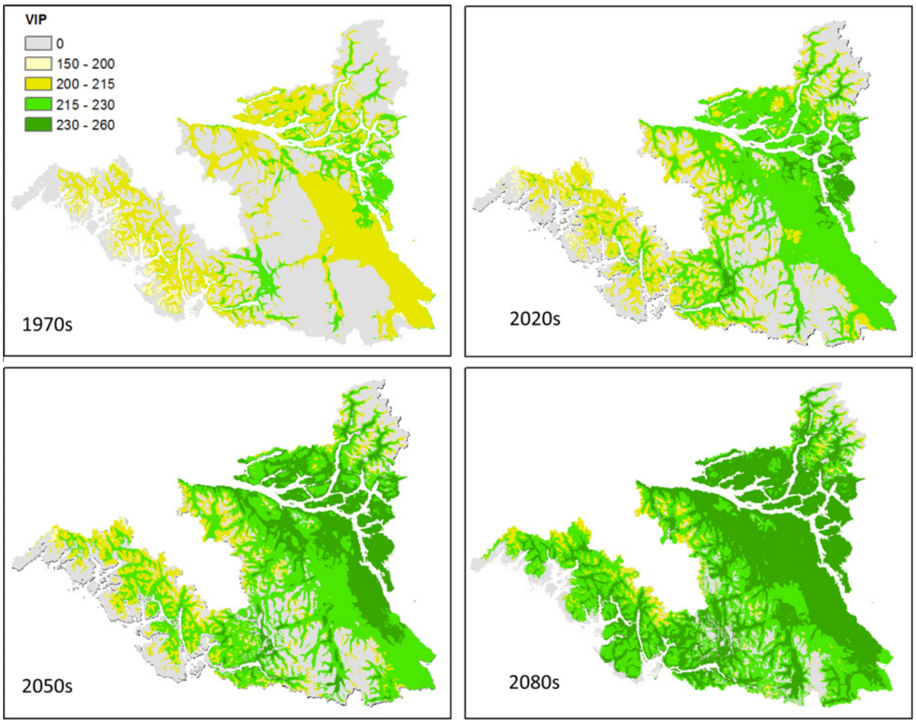

Fig. 4. Predicted volume increment potential (VIP; $cm^3 \times 10^{-2}$) of red alder for the Campbell River Forest District for the reference normal period 1961–1990 (1970s) and the three time periods (2020s, 2050s and 2080s) based on the warm and wet climate scenario (cccma_cgcm3_A2-run4).

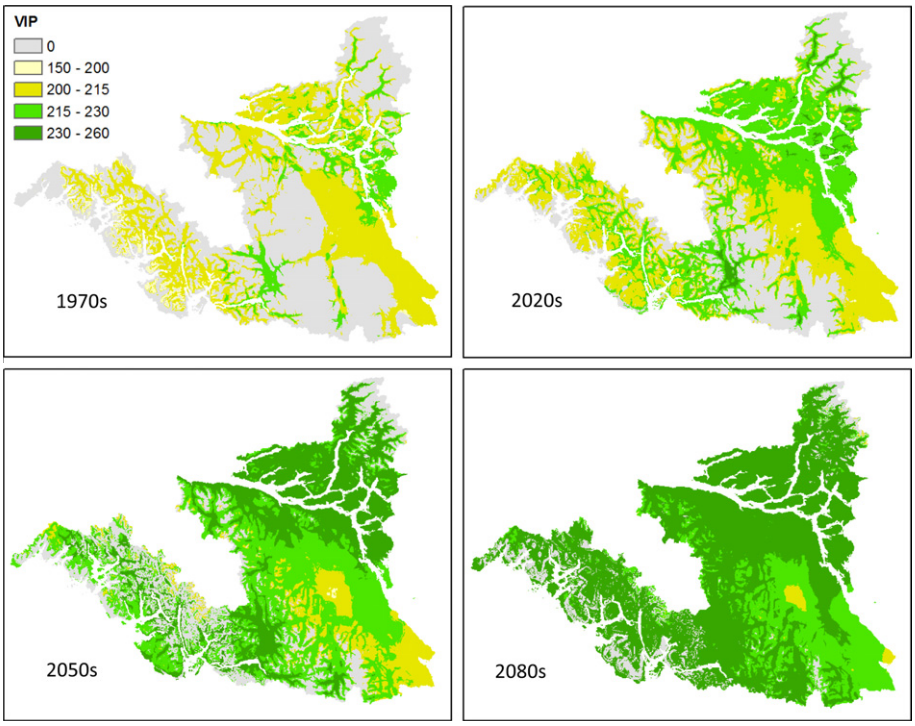

Fig. 5. Predicted volume increment potential (VIP; $cm^3 \times 10^{-2}$) of red alder for the Campbell River Forest District for the reference normal period 1961–1990 (1970s) and three future periods (2020s, 2050s and 2080s) based on the hot and dry scenario (ukmo_HadGEM1_A1B-run1).

Wang (2006) who indicated that red alder will increase in frequency and will expand its distribution in B.C. as a consequence of climate change. Similarly, a paleoecological study of red alder pollen abundance in the north Cascades area indicates that the range of red alder expanded between 9000 and 4800 YBP as climate became warmer and drier (Cwynar, 1987).

Our results also indicate that alder volume increment will change in response to climate change (average value = +7%). While there is evidence that increasing levels of CO_2 will improve future growing conditions for red alder (Hibbs et al., 1995), our study also suggests a potential increase in productivity under future climatic conditions based solely on climate variables.

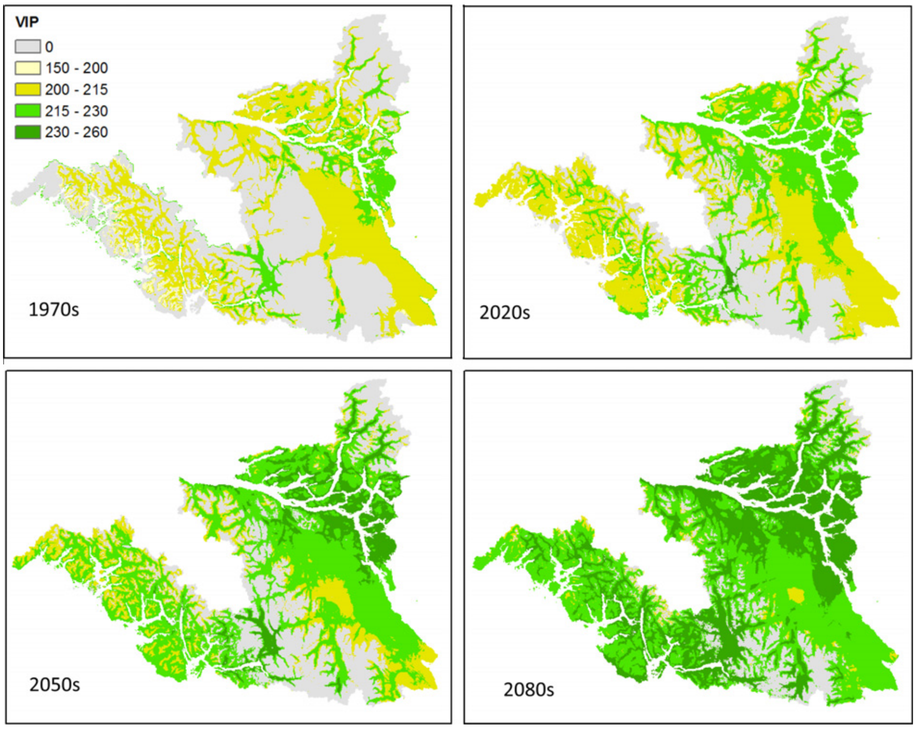

Fig. 6. Predicted volume increment potential (VIP; cm^3 × 10^{-2}) of red alder for the Campbell River Forest District for the reference normal period 1961–1990 (1970s) and three future periods (2020s, 2050s and 2080s) based on the cool and moist scenario (ukmo_hadcm3_B1-run1).

The model developed in this study explains about 78% of the variation in volume increment of red alder. Thus, a substantial portion of variation is still not explained by the variables included in our model. The negative coefficient related to spring precipitation is likely because the overall precipitation levels are more than adequate to meet alder needs at our sites during the drier years. We do, however, expect that alder may increase in vigour in drier parts of the region with increasing levels of spring precipitation. Red alder growth is influenced by soil moisture and, while it can tolerate poor drainage conditions, it does not grow well on droughty soils (Harrington et al., 1994). Variation in soil moisture related to topographic position, soil depth, soil texture, and other factors may account for some of this residual variation. It should also be noted that, since the most northerly HSC site in BC is at latitude 49° 46′, the data available for this analysis represent only the southern portion of the range of red alder in BC.

Despite an overall increase in projected growth for red alder for both biogeoclimatic variants over the three scenarios and time periods that we have examined, the results indicate local differences within the Campbell River District depending on the future climate scenario selected. Many studies have also suggested that climate change will increase the severity of fires, insect and disease epidemics, and drought-related mortality of forest trees (e.g., Gillett et al., 2004; Ebata, 2004), which could all impact the growth and survival of red alder.

Our analysis includes both the response of individual stands to climate changes, as well as the species level responses across the range of sampled stands (ranging from the central coastal region of Oregon to Bowser BC). Consequently, our results are being strongly influenced by the wider range of climate across the region sampled as opposed to the narrower range in climatic conditions seen at each site. In addition, the range of climates at the individual measured sites over the available period of the measurements is much narrower than we anticipate with climate change. In addition, since the results presented here are based on local populations the potential of using provenance effects to adapt to climate change revealed in other studies (Griesbauer et al., 2011; Wang et al., 2012) is not explored in this study. Given the substantial genetic variation in growth and adaptive traits across red alder's range, other research suggests that maladaptation of red alder provenances may be problematic when climatic changes are of sufficient magnitude (as predicted by these models) (Hamann, 2001). Thus, a comprehensive set of environmental and geographic predictors should be considered before transferring seed to a different area (Hamann et al., 2011).

The results from this analysis should be viewed as providing an indication of the potential changes in the range of suitable climate and productivity of red alder with climate change. To explore this potential, climate-based seed transfer systems are under development in BC and will consider the shift of the local climate of the current Seed Planning Units.

This study indicates that the range of suitable climate and the growth rates of red alder will potentially increase in the future in relation to the warming trend considering that climate will not limit alder over a larger range. Our results suggest that red alder could be grown more extensively in the future in the PNW, either as a short rotation, high value crop, or in mixed wood plantations. Since red alder has the potential to improve site productivity (through symbiotic fixation of nitrogen) and biodiversity, it may be useful in this role in the future. However, since the climate models do not currently provide information on climate agents that can damage or reduce the value of alder stands – such as spring and fall frost, freezing, outflow winds or severe freezing events (that can cause frost cracking of stems and lead to development of redheart) caution must be exercised when alder is being established in new areas. It must also be noted that growth improvements are only likely on moist sites, and are unlikely to be achieved on sites that have fresh or drier soil moisture regimes since soil moisture deficits are likely to increase dramatically on these sites in the warmer and drier variants, and most notably under the hot and dry scenario.

5. Conclusions

Our results indicate that climate change will likely lead to expansion of the potential range and potential increases in the growth of red alder in conjunction with assisted migration of provenance in the Pacific Northwest and in the Campbell River Forest District. While these results indicate substantial increased opportunities for extension of the range of red alder and opportunities for its management, care must be taken to avoid planting alder on sites with high risk of damaging agents such as cold outflow winds or frost.

Our results also indicate the potential to incorporate climate in tree growth models. Further research and additional data are needed to explore ways to include ecological site (i.e., soil and moisture regime) and genetic information in these models and to explore the application of such information in providing forest level estimates of the effect of climate change on red alder distribution and growth and to explore the effects of climate on the interactions between red alder and other species.

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