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Climate-Sensitive Diameter Growth Models for White Spruce and White Pine Plantations

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Abstract: Global change in the climate is affecting tree/forest growth. There have been many studies that analyzed climate effects on tree growth. Results presented in these studies showed that the climate had both positive and negative effects on tree growth. The nature (positive/negative) and magnitude of the effects and the climate variables affecting growth depended on tree species. Climate-sensitive diameter growth models are not available for white pine (*Pinus strobus* L.) and white spruce (*Picea glauca* (Moench) Voss) plantations. These models are needed to project forest growth and yield and develop forest management plans. Therefore, diameter growth models were developed for white pine and white spruce plantations by incorporating climate variables. Four hundred white pine and white spruce trees (200 per species) were sampled from 80 (40 per species) even-aged monospecific plantations (five trees per plantation) across Ontario, Canada. Diameter–age pairs were obtained from these trees using stem analysis. A nonlinear mixed-effects modeling approach was used to develop diameter growth models. To make the models climate sensitive, model parameters were expressed in term of climate variables. Inclusion of climate variables significantly improved model fit statistics and predictive accuracy. For evaluation, diameters (inside bark) at breast height were estimated for three geographic locations (east, west, and south) across Ontario for an 80-year growth period (2021–2100) under three climate change (emissions) scenarios (representative concentration pathway or RCP 2.6, 4.5, and 8.5 watts m^{-2}). For both species, the overall climate effects were negative. For white spruce, the maximum pronounced difference in projected diameters after the 80-year growth period was in the west. At this location, compared to the no climate change scenario, projected spruce diameters under RCPs 2.6 and 8.5 were thinner by 4.64 (15.99%) and 3.72 (12.80%) cm, respectively. For white pine, the maximum difference was in the south. Compared to the no climate change scenario, projected pine diameters at age 80 under RCPs 2.6 and 8.5 at this location were narrower by 4.54 (13.99%) and 7.60 (23.43%) cm, respectively. For both species, climate effects on diameter growth were less evident at other locations. If the values of climate variables are unavailable, models fitted without climate variables can be used to estimate these diameters for both species.

Keywords: climate change; tree growth; DBH growth models; boreal tree species; nonlinear regression; mixed-effects model

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1. Introduction

Accurate information about forest stand development over time is essential for forest management planning [1–3]. This information is obtained using forest growth and yield models that are driven by certain measurable variables (e.g., diameter at breast height (dbh) and total height of a tree, site index, tree/stand age, basal area). These models are mainly classified into two categories: stand- and tree-scale [2]. Stand-scale models rely on stand-level attributes such as stand age, stand density, and site index for growth and yield calculations. On the other hand, tree-scale models rely on individual tree attributes (e.g., dbh, height) [3]. Stand-scale models are less comprehensive than tree-scale models for providing stand structure and its development over time [1]. Tree-scale models provide detailed information about stand dynamics and structure, including stand volume distribution by size classes [2].

Information about individual tree diameters and their growth is needed to determine current and projected product recoveries from trees growing in a stand under a range of management alternatives. Therefore, diameter growth models are key components of tree-scale growth and yield models. The models can be used to estimate individual tree growth rates, which can be summed to obtain stand-scale estimates [3].

Diameter growth is affected by climate change [4–11]. The nature (positive/negative) and magnitude of climate effects depend on tree species and geographic locations [3,12]. Pokharel and Frose [13] analyzed climate effects on basal area growth of black spruce (*Picea mariana* (Mill.) B.S.P.), jack pine (*Pinus banksiana* Lamb.), balsam fir (*Abies balsamea* (L.) Mill.), and trembling aspen (*Populus tremuloides* Michx.) grown in natural stands in eastern Canada. They reported that basal area of all these tree species was significantly affected by climate.

Maxime and Hendrik [5] examined climate effects on diameter growth of common beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.) grown in France. They reported that climate significantly affected diameter growth of these tree species. In another study, Subedi and Sharma [12] found positive effects of climate change on jack pine diameter growth but negative effects on black spruce grown in plantations across Ontario, Canada. For both species, the effects (positive or negative) were more pronounced in the west than the east. Similarly, Matisons et al. [8] reported that the radial growth of European (common) beech was sensitive to climate, with sensitivity depending on the method of establishment and social status of trees.

Sharma [3] recently analyzed climate effects on diameter growth of red pine (*Pinus resinosa Ait.*) plantations grown in eastern Canada. He reported that red pine diameter growth was significantly affected by climate, with positive effects in the southeast and southwest and negative effects in the central west of Ontario. No effect was evident in the far west. The magnitude (positive or negative) of the effect varied by geographic location. Oboite and Comeau [14] also found varying effects of climate on diameter growth of lodgepole pine (*Pinus contorta* Douglas ex Loudon), jack pine, trembling aspen, white spruce (*Picea glauca* (Moench) Voss), and balsam poplar (*Populus balsamifera* L.) trees grown in western Canada. Similarly, Bayat et al. [15] analyzed climate effects on diameter increment of various tree species of the Hyrcanian Forest of Northern Iran.

Most of the studies described above examined whether diameter/basal area growth of different tree species in various locations were affected by climate change. Since these studies reported significant effects (positive/negative of varying magnitude) of climate on diameter/basal area growth of various tree species, climate factors need to be accounted for to accurately project future tree growth [16]. Accurate growth projections are crucial for developing credible forest management plans. Therefore, in addition to analyzing climate effects on diameter growth of different tree species, Subedi and Sharma [12], Sharma [3], and Oboite and Comeau [14] also developed diameter growth models by incorporating climate variables. Similarly, Bayat et al. [15] modeled diameter growth in terms of climate variables.

White pine (*Pinus strobus* L.) and white spruce grow throughout much of Ontario. These species are the most commonly planted commercial tree species after jack pine and black spruce. The objectives of this study were to (1) examine climate effects on diameter growth of plantation-grown white pine and white spruce trees, (2) develop climate-sensitive diameter growth models for these species, and (3) analyze climate effects on their future diameter growth under three climate change scenarios.

2. Materials and Methods

2.1. Tree Data

For each species, forty even-aged monoculture plantations were selected from across Ontario, Canada (Figure 1) to sample trees for this study. In total, 400 white spruce and white pine trees (200 per species) were sampled from these plantations. White spruce and white pine trees were sampled in fall 2021 and 2022, respectively. For both species, the latitude of sample sites ranged from 42.38° N to 50.83° N and longitude varied from 75.06° W to 94.07° W. Similarly, the variation in elevation was from 83.0 m to 534.0 m. A circular temporary sample plot of 400 m^2 (11.28 m radius) was established, representing the tree population in the stand at each plantation site to sample the trees for each species. If required, the plot size was increased (up to 600 m^2) to ensure at least 40 planted live trees were in the sample plots.

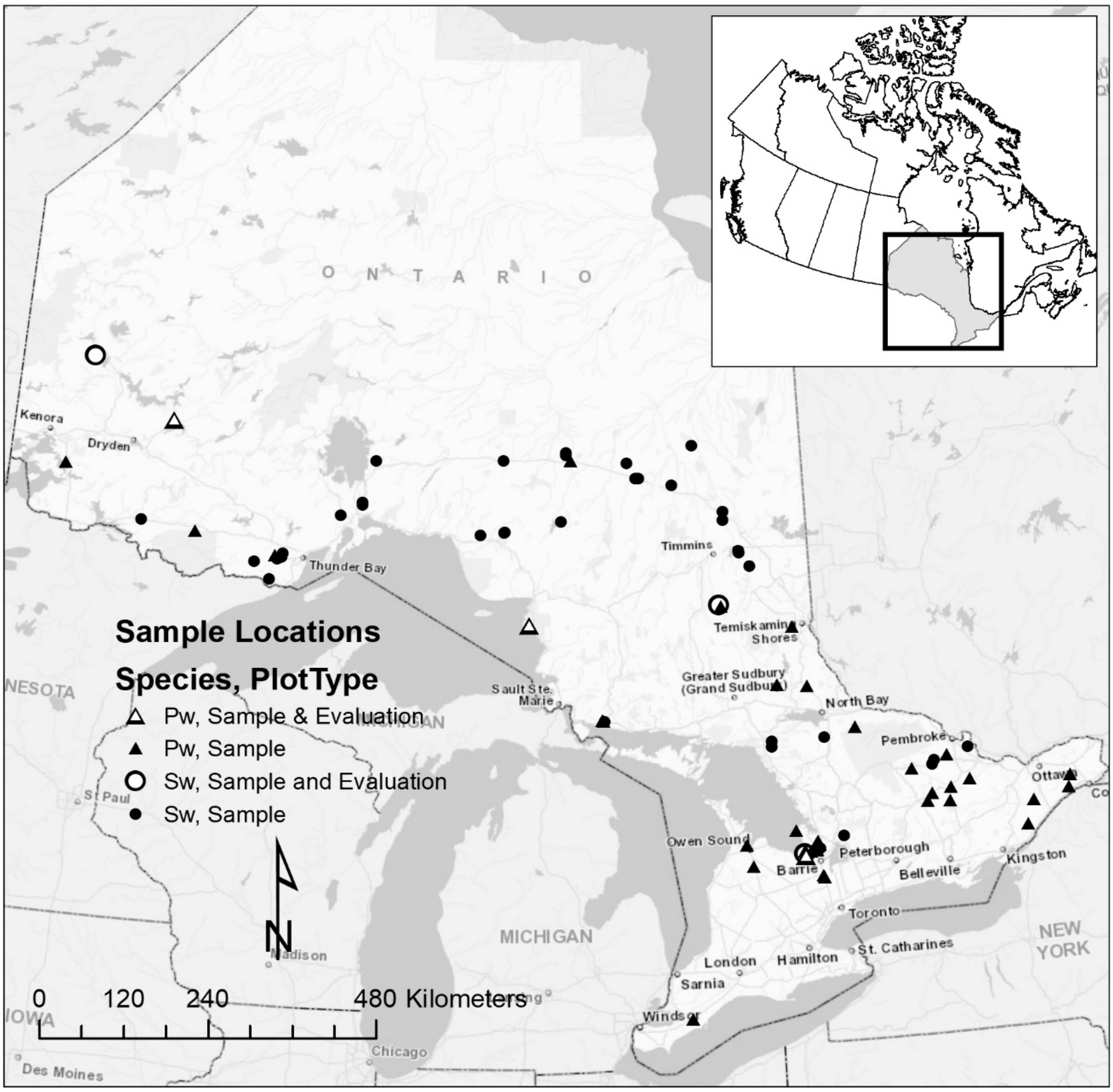

Figure 1. Distribution of white spruce (Sw) and white pine (Pw) plantation sites sampled across Ontario, Canada.

All live trees were measured in each sample plot, and stem density (trees ha^{-1}) and total basal area (BA ha^{-1}) were calculated by consecutively numbering all trees growing in the plot for each species. Total basal area of each tree species from each plot was divided into 5 BA classes. One tree was randomly selected from each BA class for each species at each plot and destructively sampled. Five trees without visible deformities (e.g., broken tops, forked, dead, injuries) were sampled from each plot (one tree from each BA class) for each species. This sampling resulted in 200 trees for each species.

Each sample tree was cut at 0.15, 0.5, and 0.9 m heights below breast height and one disk was sampled at 1.3 m (breast height). The rest of the height (tree height from breast height to tip) was divided by 10, with sections cut at the resulting interval. This approach resulted in 13 sections per tree for each species. The largest outside and inside bark diameters and those perpendicular to them passing through the pith were measured at each stem height where sections were cut. Mean inside and outside bark diameters were obtained by averaging these diameters at that stem height. Since this study involved diameter at breast height (DBH) growth, only the disks cut and measurements taken at breast height from each tree of each species were used for analysis. The sampling and other data collection protocols used in [3] were applied in this study. For details about the procedures used to measure mean annual radial growth by stem analysis and calculate mean annual diameter growth for each tree, refer to [3].

Although all trees of a particular tree species at a specific site were planted during the same year, erratic early height growth means not all of them reached breast height the same year. However, climate variable values are tied to a particular calendar year. Therefore, diameter growth of 5 trees from a site could not be combined to obtain a site-scale growth series to analyze climate effects on diameter growth. Hence, climate effects on diameter growth of a tree in a particular calendar year were analyzed using annual/seasonal values of climate variables from the same calendar year that the tree reached breast height. This analysis resulted in 200 diameter–age growth series for white pine plantations. For white spruce, one tree was missing from the final data set, resulting in 199 trees in the growth series.

The growth period used to analyze climate effects included the time between when the sample tree reached breast height and when it was sampled, ending in 2021 for white spruce and 2022 for white pine trees. Summary statistics of trees and stand characteristics used in this study are listed in Table 1.

Table 1. Summary statistics for measured tree and stand characteristics of plantation-grown white spruce and white pine trees and climate variables from across Ontario used in this study. DBH = diameter at breast height; BA = basal area ha^{-1}; trees ha^{-1} = density; TPGS = growing season total precipitation; MTGS = growing season mean temperature; CMI = climatic moisture index; Std Dev = standard deviation.

Attribute	N	Mean	Std Dev	Minimum	Maximum
White spruce					
DBH (outside bark) (cm)	199	24.83	7.03	10.10	48.80
DBH (inside bark) (cm)	199	23.20	6.82	9.48	45.53
Total height (m)	199	19.59	3.08	12.30	26.75
Breast height age (yr)	199	48.22	7.71	28.00	69.00
BA (m^2 ha^{-1})	40	41.65	11.16	22.76	81.50
Trees ha^{-1}	40	1134.14	451.22	533.33	2625.00
White pine					
DBH (outside bark) (cm)	200	27.78	8.84	11.50	55.10
DBH (inside bark) (cm)	200	25.42	8.01	10.82	49.23
Total height (m)	200	21.09	4.59	8.60	34.90
Breast height age (yr)	200	51.31	15.67	21.00	88.00
BA (m^2 ha^{-1})	40	44.00	12.15	23.09	78.84
Trees ha^{-1}	40	975.08	451.72	366.67	2425.00
Climate variables					
TPGS (mm)	9680	459.43	95.86	108.20	960.40
MTGS (°C)	9680	13.41	1.04	9.65	17.20
CMI for June (cm)	9680	−1.29	3.58	−10.57	13.87
Sum of growing months (April to August) CMIs (cm)	9680	−1.78	8.26	−27.35	29.94
Annual CMI (sum of 12 months CMIs) (cm)	9680	30.61	13.69	−15.47	94.72

2.2. Climate Data

Climate variable values for each sample site were estimated using Canadian climate models [17]. Estimates of annual/seasonal values of these variables were calculated for each year, starting when the sample tree reached breast height and ending in 2022. In this study, 68 climate-related variables were used including mean, minimum, and maximum values of total precipitation and air temperatures estimated for each month and quarter of the year and annually (see [3] for a detailed description of climate variable calculations).

In addition, climatic moisture index (CMI) was computed by subtracting potential evapotranspiration (PET) from mean monthly precipitation (MMP) for each month of each year (see [18]). Climate variable values were taken from [16]. Summary statistics of climate variables used in this study (climate variables that significantly explained diameter growth of trees in white spruce and white pine plantations) are shown in Table 1.

2.3. Diameter Growth Models

In general, basal area/diameter growth models are developed using composite models [19–22]. These models include individual tree size, competition effects (tree vigor), and a measure of site productivity [14,23]. Recently, growth functions commonly used to model stand height growth have also been used to model diameter growth.

Sharma et al. [24] used a variant (algebraic-difference type) of the Chapman–Richards function to model diameter growth of Norway spruce (*Picea abies* (Linnaeus) H. Karsten). Similarly, Sharma [3] used the McDill and Amateis growth model (see [25]) to describe diameter growth of red pine in plantations across Ontario, Canada. Comparing this model to the variant of the Chapman–Richards function used by Sharma et al. [24] for red pine plantation diameter growth data, he found the McDill and Amateis model had better fit statistics and predictive ability. The mathematical form of the McDill and Amateis model was:

$$D = \frac{\beta_0}{1 - \left(1 - \frac{\beta_0}{D_0}\right)\left(\frac{A_0}{A}\right)^{\beta_1}} + \varepsilon \quad (1)$$

where D and D_0 are diameters at ages A and A_0, respectively, β_0 and β_1 are the parameters to be estimated, and ε is the model error term. In this model, β_0 and β_1 determine the asymptote and shape, respectively, of the curve.

Equation (1) can be easily modified to analyze climate effects on diameter growth by expressing its parameters in terms of climate variables [3]. Therefore, Equation (1) was used as the base function to describe diameter growth of trees in white spruce and white pine plantations. Climate effects on diameter growth of these tree species were analyzed by expressing the asymptote and the shape parameters as a function of climate variables. Three site-related variables (longitude, latitude, and elevation) were added to climate variables to account for site effects on tree diameter growth in white spruce and white pine plantations.

2.4. Methods

Diameter growth data of white spruce and white pine trees were obtained by measuring annual ring widths along the radius of the disks sampled at breast height from each tree at each plot (site). These data have hierarchical structures (i.e., rings within trees, trees within plots/sites). Among trees, diameter measurements can be considered independent, but within a tree they are correlated. Within-tree correlation (autocorrelation) can be addressed by using a mixed-effects modeling technique [26]. Therefore, in this study a diameter growth model was fit using a mixed-effects modeling technique. Random effects at stand and tree scale were added to both asymptote and rate parameters.

Climate- and site-related variables were incorporated into diameter growth models by dividing them into 3 categories: temperature, precipitation, and site-specific. First, all temperature-related variables were introduced one at a time and fitted using the NLINMIXED procedure in SAS. The variable that significantly explained the variation in diameter growth (alpha = 0.05) and produced the lowest Akaike information criterion (AIC) value was selected as the first climate (temperature) variable to be included in the model.

Precipitation-related variables were then introduced one by one in the presence of the first temperature-related variable. The one that was significant in the regression and resulted in the lowest AIC value was selected to be included in the model. All other climate- and site-related variables were introduced individually in the presence of the first 2 variables. Similarly, derived variables obtained by making quadratic and/or exponential transformations of climate- (temperature and precipitation) and site-related variables were introduced in the model. Variables that significantly explained the variation in diameter growth and reduced the AIC value were added to the model.

Random effects were added to fixed-effects parameters at site and tree scales as required. Estimated values of residuals (observed − predicted) from the diameter growth model were calculated for all 1-year growth periods for each diameter growth series. Heteroscedasticity in the data was checked by plotting these residuals against predicted diameter growth.

Climate effects on future diameter growth were evaluated by randomly selecting 3 sites from eastern, central, and western (1 site from each area) Ontario (Figure 1). Inside bark diameters of white spruce and white pine trees were estimated using the model with projected values of climate variables for each area for each species under 3 climate change scenarios. These scenarios include emissions trajectories with 2.6, 4.5, and 8.5 watts m^{-2} of warming projected for the end of the century [27]. These scenarios were chosen as these represent the mildest, an intermediate, and an extreme case of projected climate change scenarios. These trajectories are known as representative concentration pathways (RCPs). Since projected values of climate variables were available for 80 years beginning in 2021, diameters were estimated for an 80-year growth period. These diameters were plotted against breast height age (BHA).

3. Results

To check whether Equation (1) is appropriate to model diameter growth of trees in white spruce and white pine plantations, this equation was fit to diameter growth data collected from these species (Table 2). Nonlinear regression in SAS was used to fit the equation for both species. Annual diameter growth was determined with the parameters estimated using regression. Initial values used to estimate the diameters were average diameter values at age 1 (0.52 and 0.72 cm, for white spruce and white pine, respectively).

Table 2. Parameter estimates and fit statistics (σ^2 = mean squared error and AIC = Akaike's information criterion) for the base model (Equation (1)) fitted to diameter growth data collected from trees in white spruce and white pine plantations across Ontario. NA = not applicable.

Parameters	White Spruce		White Pine	
	Estimates	SE	Estimates	SE
β_0	43.9032	0.36930	51.8574	0.64230
β_1	1.2177	0.00581	1.0898	0.00613
σ^2	0.18866	0.00054	0.05236	0.00075
AIC	−4309	NA	−1073	NA

Estimated diameters were plotted against breast height age (BHA) for both species (Figure 2). Observed diameters across BHA were also overlaid in the plot. Diameter growth profiles generated using Equation (1) closely followed the trend of observed values for both species. These results confirmed that Equation (1) was appropriate to model diameter growth of both white spruce and white pine grown in plantations.

Equation (1) was modified to include climate- and site-related variables. Parameters of Equation (1) were expressed in terms of climate- and site-related variables. The equation was fit to diameter growth data by expressing each parameter in terms of temperature-related variables individually for both species. Although many temperature-related variables were significant in the regression, the rate parameter (β_1) expressed in terms of the mean growing season temperature (MTGS) resulted in the best fit (lowest AIC value) for both tree species.

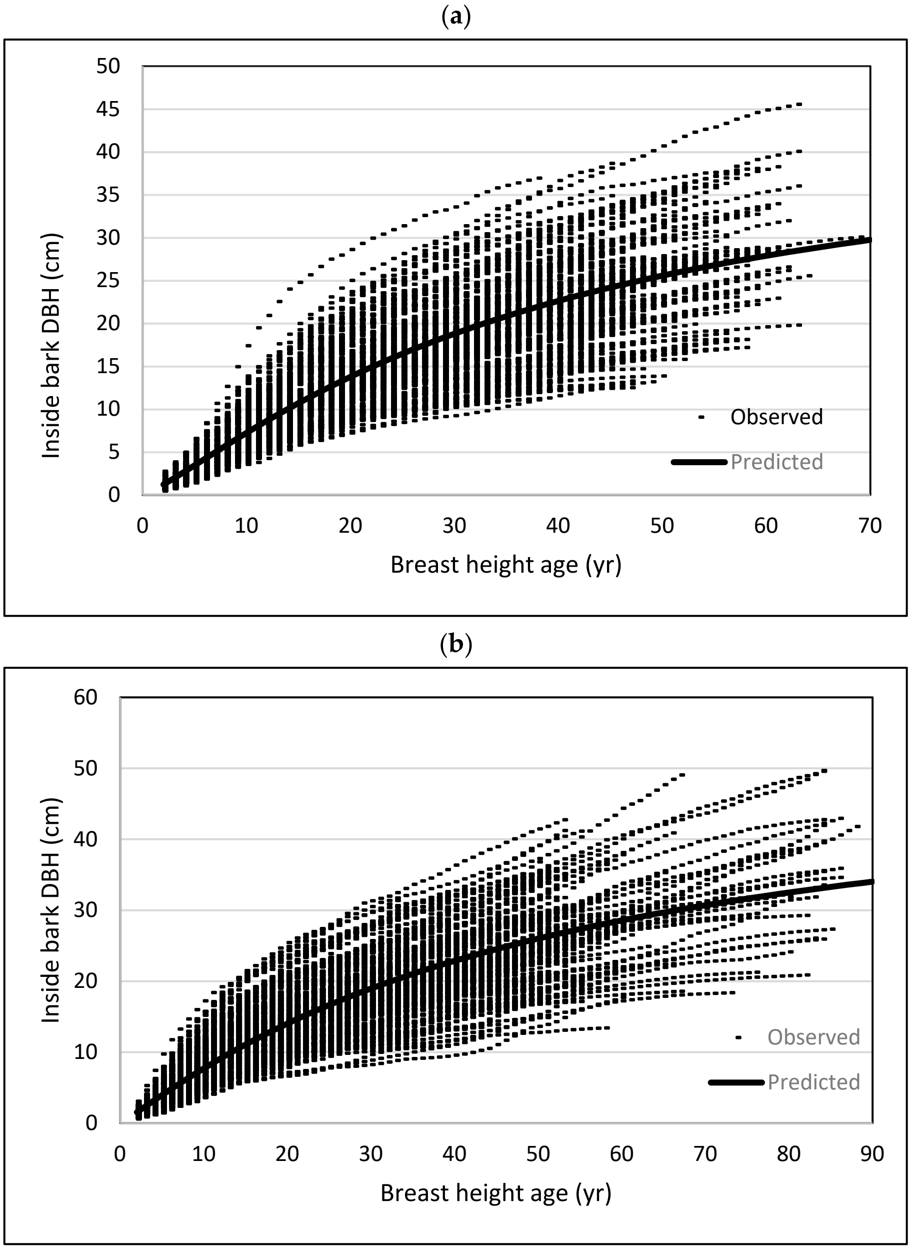

Figure 2. Inside bark diameters at breast height (DBH) of all trees across breast height age (observed) and diameter profiles (predicted) generated using Equation (1) for plantation-grown (**a**) white spruce and (**b**) white pine in Ontario fitted without climate variables.

Precipitation-related variables were then introduced in the model in the presence of MTGS. The asymptote (β_0) expressed in terms of annual climatic moisture index (ACMI), defined as the sum of the monthly moisture indices, and GMCMI, defined as the sum of April to August (growing months) moisture indices, explained the variations in diameter growth more than other variables from this category for white spruce and white pine, respectively. Other temperature and precipitation variables were then introduced in the presence of MTGS and ACMI and GMCMI.

In the presence of MTGS and the sum of climatic moisture indices, total growing season precipitation (TPGS) and June climatic moisture index (JCMI) were also significant in expressing the rate parameters for both species. No site-related variables (elevation, latitude, longitude) were significant for both species. For transformations and interactions, only the quadratic transformation of JCMI was significant for white pine. The AIC value decreased significantly for both species when climate variables were introduced.

The diameter growth models that include climate variables can be written as:

White spruce

$$D_{ij} = \frac{\beta_0 + \beta_2 ACMI}{1 - \left(1 - \frac{\beta_0 + \beta_2 ACMI}{D_{ik(k \neq j)}}\right)\left(\frac{A_0}{A}\right)^{\beta_1 + \beta_3 MTGS + \beta_4 TPGS + \beta_5 JCMI}} + \varepsilon_{ij} \quad (2)$$

White pine

$$D_{ij} = \frac{\beta_0 + \beta_2 GMCMI}{1 - \left(1 - \frac{\beta_0 + \beta_2 GMCMI}{D_{ik(k \neq j)}}\right)\left(\frac{A_0}{A}\right)^{\beta_1 + \beta_3 MTGS + \beta_4 TPGS + \beta_5 JCMI + \beta_6 JCMI^2}} + \varepsilon_{ij} \quad (3)$$

where D_{ij} is the diameter at breast height of ring j and tree i, β_2 to β_6 are fixed-effects parameters associated with climate-related variables, ε_{ij} is the error term associated with the jth ring of tree i, and other variables/parameters are as defined earlier. Random effects were then introduced to fixed-effects parameters. Only random effects associated with intercepts in the expressions for asymptote and the rate parameter were significant at tree level. However, introduction of these random effects resulted in very unstable and inconsistent parameter estimates for both species.

For example, estimates for β_3 and β_4 were both negative for the model without random effects but turned positive when the random effects were introduced for white spruce. Additionally, the estimated standard error for β_3 was zero for the model with random effects for this tree species. Moreover, diameters estimated using the parameters with random effects were negative for some trees. Results for white spruce were also inconsistent. Therefore, random effects were not included in the final model for either species. Table 1 includes the summary statistics for climate variables (TPGS, MTGS, JCMI, GMCMI, and ACMI) that were significant in the regression.

Table 3 displays the estimated values of parameters for Equations (2) and (3). The asymptote was expressed as a linear function of ACMI and GMCMI for white spruce and white pine, respectively. Similarly, the rate parameter was a linear function of MTGS, TPGS, and JCMI for white spruce, and of MTGS and TPGS and a quadratic function of JCMI for white pine. The asymptote for the white spruce is negatively correlated with ACMI. On the other hand, it is positively correlated with GMCMI for white pine.

Table 3. Parameter estimates and fit statistics (σ^2 = mean squared error and AIC = Akaike's information criterion) for diameter growth models incorporating climate variables (Equations (2) and (3)) fitted to diameter growth data collected from white spruce and white pine trees in plantations from across Ontario. NA = not applicable.

Parameters	White Spruce		White Pine	
	Estimates	SE	Estimates	SE
β_0	49.7726	0.93160	52.9072	0.7130
β_1	1.5247	0.06365	1.3601	0.06869
β_2	−0.1585	0.02286	0.3975	0.06065
β_3	−0.03690	0.004823	−0.01308	0.00482
β_4	0.000381	0.000054	−0.00015	0.00004
β_5	0.005878	0.001331	0.00687	0.00133
β_6	NA	NA	−0.00071	0.00025
σ^2	0.03596	0.000531	0.05161	0.00074
AIC	−4464	NA	−1203	NA

The rate parameter was negatively associated with MTGS for both species. However, the association of the rate parameter with TPGS was positive for white spruce and negative for white pine. JCMI was positively correlated with the rate parameter for both species. Its quadratic term ($JCMI^2$) was only significant for white pine and its association with the rate parameter was negative. The magnitude of the coefficient for the linear term of JCMI for white pine was almost 10 times larger than the one for its quadratic term. This result implies that the positive effect of JCMI on the rate parameter diminishes as the value of JCMI increases.

Residual plots were made by predicting inside bark diameters of all trees using Equations (2) and (3) for white spruce and white pine, respectively, at all breast height ages (Figure 3). These plots indicated that heteroscedasticity was not a concern in fitting the models. However, diameters larger than 35 cm seemed slightly underestimated for both species. Residual plots were also made against tree breast height age for both species. All residuals were clustered around the zero line and there was no bias at any point across the breast height age for both species.

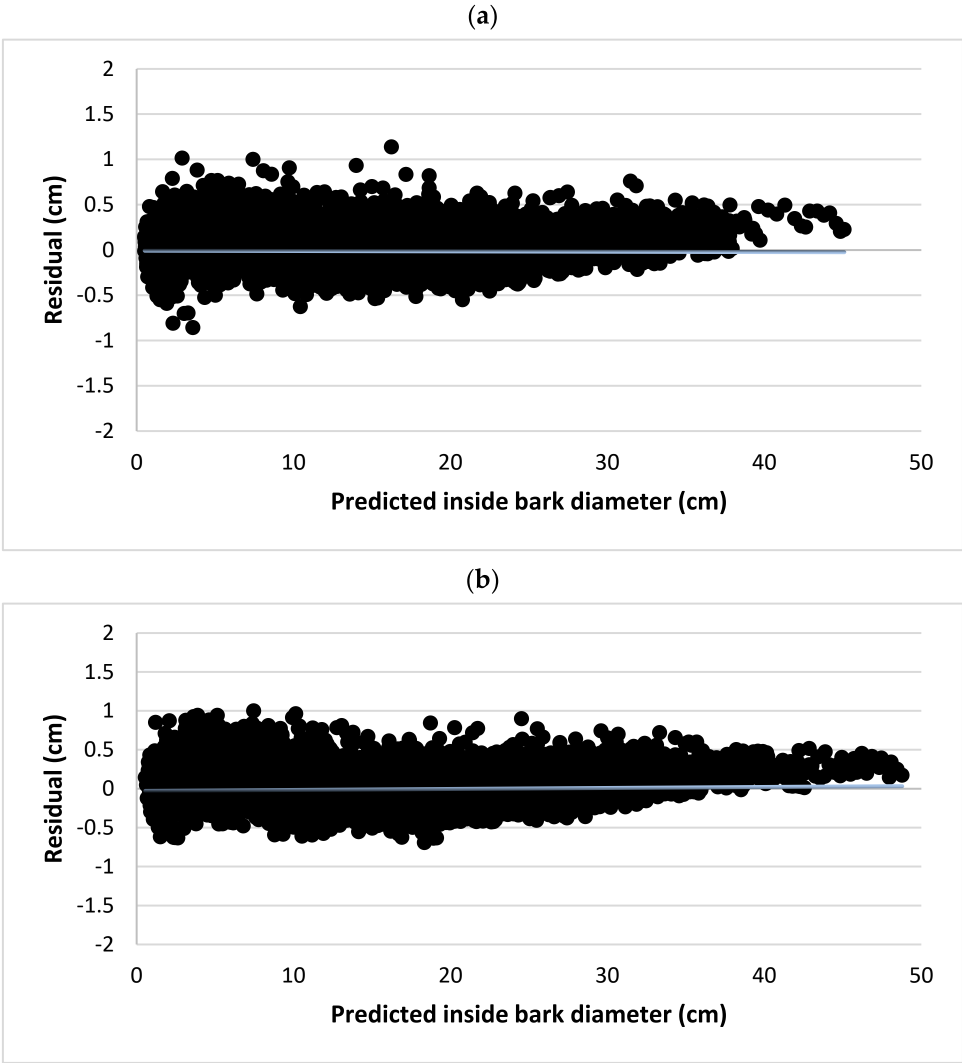

Figure 3. Residuals (observed—predicted) of inside bark diameter at breast height (DBH) estimated using Equation (2) for plantation-grown white spruce (**a**) and Equation (3) for white pine (**b**) in Ontario plotted against predicted inside bark diameters.

Equations (2) and (3) were further analyzed by computing bias across breast height age and diameter classes for both species. Predicted diameters were subtracted from their observed counterparts to calculate residuals. Bias was obtained for each age and diameter class by averaging residuals in those classes. Standard deviation of the bias was also obtained for each age and diameter class. These biases and standard deviations are provided in Tables 4 and 5 for white spruce and white pine, respectively. The maximum bias was 0.1316 cm for diameters larger than 45 cm for white pine, with a standard deviation of 0.2302 cm. Most of the biases were less than 0.09 cm for both species.

Table 4. Bias (observed—predicted) and its standard deviation (Std Dev), minimum, and maximum of the residuals for diameter at breast height (DBH) class and age class that resulted from fitting Equation (2) for white spruce trees in Ontario, Canada. (N = number of sample trees).

DBH (cm)	N	Bias	Std Dev	Min	Max
<15	626	0.1070	0.1282	−0.4102	0.3816
15–20	1661	−0.0880	0.1521	−0.5379	0.6449
20–25	2390	−0.0473	0.1626	−0.7024	0.7316
25–30	2374	0.0056	0.1835	−0.8580	1.0140
30–35	1137	−0.0473	0.1941	−0.5168	0.9998
40–45	721	0.1141	0.2197	−0.5915	1.1369
>45	280	0.1235	0.1875	−0.5004	0.8356
Age (Years)					
<10	1791	0.0713	0.2197	−0.8580	1.1369
10–20	1990	0.0131	0.2016	−0.5495	0.8356
20–30	1987	−0.0849	0.1601	−0.4884	0.6388
30–40	1883	−0.0549	0.1570	−0.3814	0.6272
40–50	1123	−0.0083	0.1537	−0.2738	0.7589
50–60	388	0.0332	0.1546	−0.2242	0.7089
>60	27	0.0257	0.0883	−0.1506	0.2247

Table 5. Bias (observed—predicted) and its standard deviation (Std Dev), minimum, and maximum of the residuals for diameter at breast height (DBH) class and age class that resulted from fitting Equation (3) for white pine trees in Ontario, Canada. (N = number of sample trees).

DBH (cm)	N	Bias	Std Dev	Min	Max
<15	474	−0.1274	0.1826	−0.6106	0.7236
15–20	1049	−0.0660	0.1982	−0.5861	1.0820
20–25	1918	−0.0558	0.2097	−0.8363	1.2187
25–30	1878	0.0368	0.2285	−0.7897	1.0537
30–35	1822	−0.0141	0.2151	−0.7197	1.0113
40–45	1266	0.0559	0.2213	−0.8960	1.4841
>45	1254	0.1316	0.2302	−0.5750	1.1761
Age (years)					
<10	1800	0.1128	0.2892	−0.8960	1.4841
10–20	1999	−0.0711	0.2131	−0.7197	0.8433
20–30	1900	−0.0953	0.1755	−0.4930	0.8103
30–40	1630	0.0548	0.1708	−0.4117	0.9912
40–50	1240	0.0394	0.1823	−0.2799	0.6525
50–60	532	−0.1264	0.2180	−0.2043	1.1761
60–70	291	0.0894	0.1684	−0.1952	0.6819
70–80	229	0.0814	0.1578	−0.1612	0.5978
>80	40	0.1126	0.1686	−0.1161	0.4775

Climate effects on future diameter growth were evaluated by estimating inside bark diameters at breast height using Equations (2) and (3) for white spruce and white pine, respectively. Estimates were made for three sites in Ontario under three emissions scenarios (RCPs 2.6, 4.5, and 8.6 watts m^{-2} trajectories). Average diameters of sample trees from those sites measured at BHA 1 year were used as initial values for these estimations. These diameters were plotted against BHA for each climate change scenario for each site for each species (Figures 4 and 5).

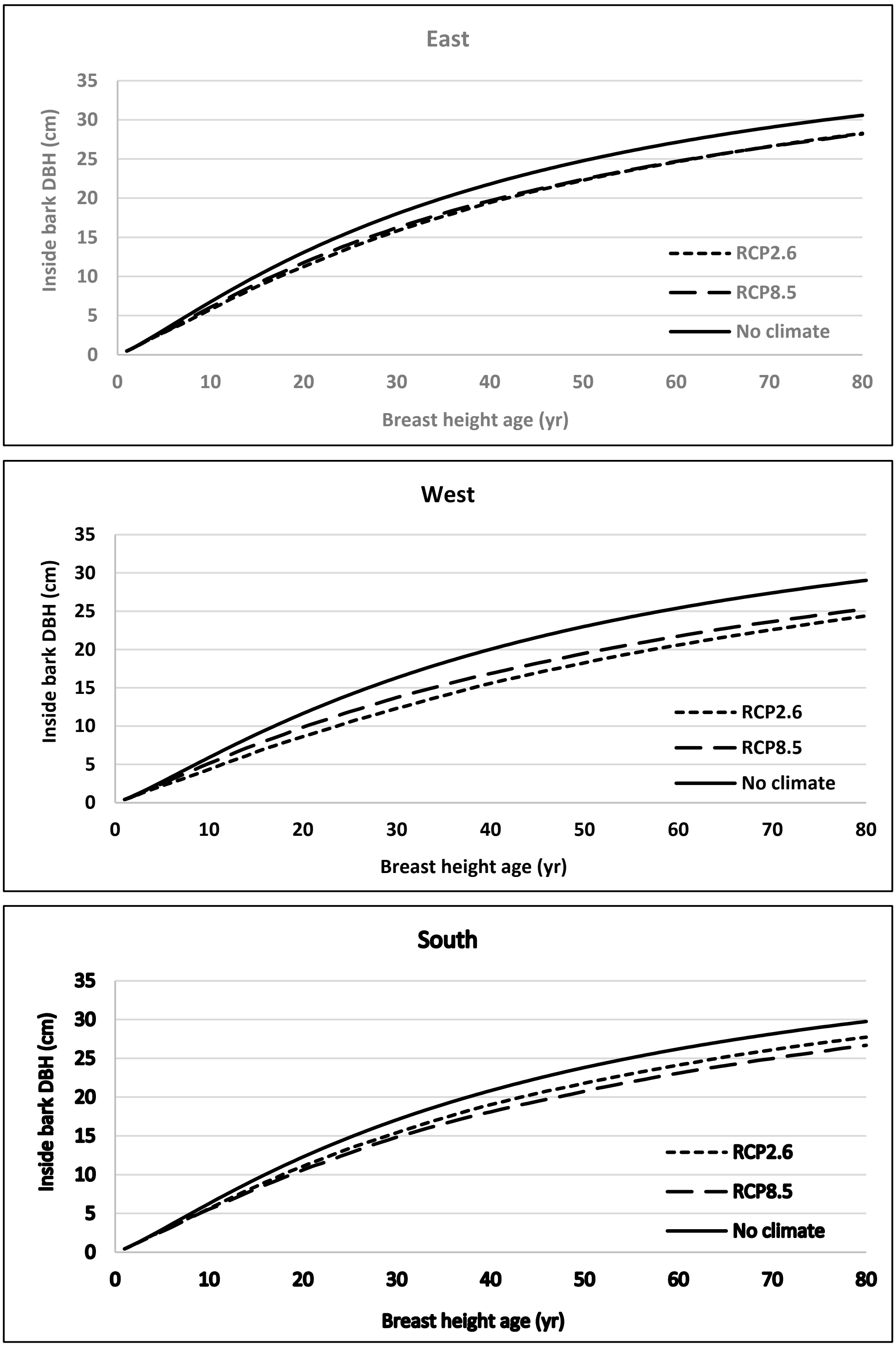

Figure 4. Diameter growth profiles for plantation-grown white spruce trees generated using the models without climate variables (Equation (1)) (no climate) and with climate variables (Equation (2)) under representative concentration pathway (RCP) 2.6 and 8.5 for eastern, western, and southern parts of Ontario, Canada.

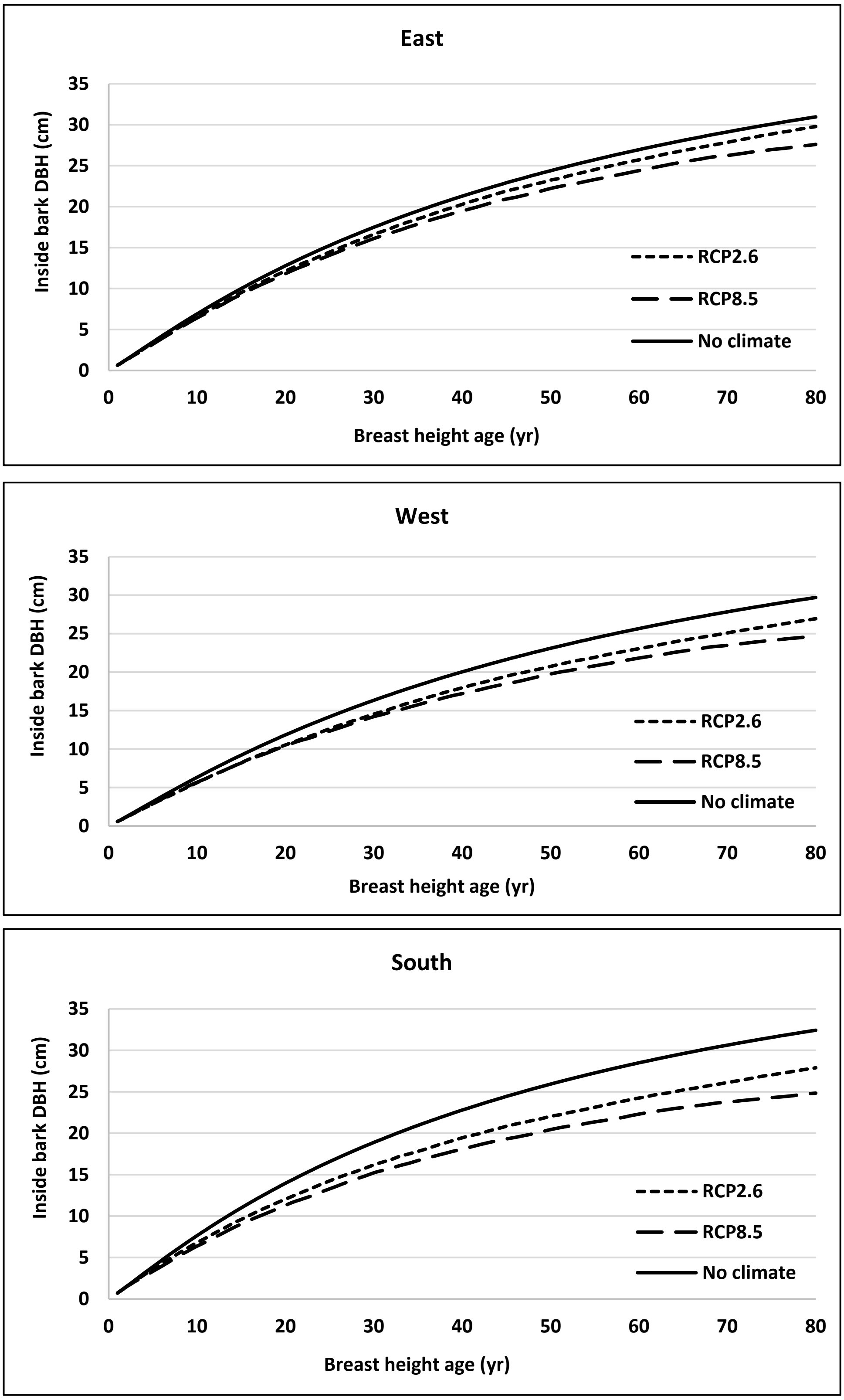

Figure 5. Diameter growth profiles for plantation-grown white pine trees generated using the models without climate variables (Equation (1)) (no climate) and with climate variables (Equation (3)) under representative concentration pathway (RCP) 2.6 and 8.5 for eastern, western, and southern parts of Ontario, Canada.

Projected diameter growths under RCP 2.6 were very similar to those under RCP 4.5 for both tree species. Therefore, RCP 4.5 growth profiles were not included in Figures 4 and 5. Annual and seasonal values of all climatic variables were used in Equations (2) and (3) to estimate future diameter growth for white spruce and white pine, respectively. Diameter growth was projected from 2021 through 2100 (80-year growth period) for all climate change scenarios for both species. Diameters were also estimated using Equation (1) without climate variables.

The climate effects were negative and varied with species and location. The maximum difference in projected diameters at age 80 for white spruce was in the west. Projected diameters under RCPs 2.6 and 8.5 were thinner by 4.64 (15.99%) and 3.72 (12.80%) cm, respectively, compared to those under no climate change scenario. In the east, diameter differences under RCP 2.6 and 8.5 scenarios were minimal. However, the difference in diameters with and without climate change was significant. Under climate change scenarios, diameters at age 80 were thinner than those under no climate change by 2.30 cm (8.00%). In the south, diameters at age 80 under RCP 2.6 and 8.5 were thinner than those under no climate scenario by 2.02 (6.79%) and 3.07 (10.33%) cm, respectively.

Climate effects on diameter growth were more consistent for white pine than for white spruce. These effects were more pronounced under RCP 8.5 than under RCP 2.6 for all three locations for this tree species. The maximum difference in projected diameters was in the south and the minimum difference was in the east. At age 80, projected diameters under RCPs 2.6 and 8.5 in the south were narrower than those under no climate change scenario by 4.54 (13.99%) and 7.60 (23.43%) cm, respectively. In the east, these diameters under RCPs 2.6 and 8.5 were thinner than those under the no climate change scenario by 1.17 (3.79%) and 3.36 (10.85%) cm, respectively. In the west, however, projected diameters under RCPs 2.6 and 8.5 were narrower than those under the no climate change scenario by 2.76 (9.28%) and 4.96 (16.71%) cm, respectively. Summary statistics of projected climate variables under three climate change scenarios for the 80-year (2021–2100) growth period used in this study are presented in Table 6.

Table 6. Summary statistics of projected climate variables significant in explaining the variation of diameter growth of white pine and white spruce plantations of sample sites used in this study for the 80-year (2021–2100) growth period. TPGS = growing season total precipitation; MTGS = growing season mean temperature; CMI = climatic moisture index; Std Dev = standard deviation.

Attribute	N	Mean	Std Dev	Minimum	Maximum
	RCP 2.6				
TPGS (mm)	6400	570.85	147.86	225.90	1257.30
MTGS (°C)	6400	14.97	1.10	11.89	18.84
CMI for June (cm)	6400	−3.27	4.25	−12.69	15.59
Sum of growing months (April to August) CMIs (cm)	6400	0.60	7.68	−23.49	28.94
Annual CMI (sum of 12 months CMIs) (cm)	6400	33.01	18.33	−24.68	111.98
	RCP 4.5				
TPGS (mm)	6400	569.71	128.33	234.00	1038.10
MTGS (°C)	6400	15.36	1.11	11.90	19.26
CMI for June (cm)	6400	−4.72	4.45	−14.97	13.36
Sum of growing months (April to August) CMIs (cm)	6400	−1.93	7.09	−22.32	31.17
Annual CMI (sum of 12 months CMIs) (cm)	6400	28.84	17.48	−31.15	103.06
	RCP 8.5				
TPGS (mm)	6400	587.72	135.52	242.70	1225.80
MTGS (°C)	6400	16.64	1.74	12.21	22.66
CMI for June (cm)	6400	−6.13	5.00	−20.35	13.91
Sum of growing months (April to August) CMIs (cm)	6400	−3.23	9.84	−38.15	30.26
Annual CMI (sum of 12 months CMIs) (cm)	6400	22.46	19.88	−52.11	92.22

4. Discussion

Climate has both positive and negative effects on tree growth. The nature (positive/negative) and magnitude of the effects and the climate variables affecting growth depend on tree species and location. Even for a given species, the nature and magnitude of the effects can vary from one location to another [28]. Goldblum and Rigg [29] found that temperature and precipitation had positive effects on the growth of white spruce and sugar maple (*Acer saccharum* Marsh.), but temperature had no significant effects on diameter growth of balsam fir grown in the boreal forest near the coast of Lake Superior in Ontario, Canada. Similarly, Pokharel and Froese [13] reported that including average annual temperature in modeling basal area growth of natural stand-grown trembling aspen, balsam fir, jack pine, and black spruce trees improved the fit statistics and predictive accuracy.

Subedi and Sharma [12] examined climate effects on diameter growth of jack pine and black spruce trees grown in plantations in Ontario. Overall, they found effects of climate were positive for jack pine but negative for black spruce. The climate variables that explained the variation in diameter growth were total precipitation of growing season, precipitation of wettest quarter, and the mean temperature of the growing season for both species. Negative climate effects on black spruce were more evident than the positive climate effects on jack pine trees. They used average values of climate variables over a 30-year growth period (1971–2000) to examine climate effects.

Sharma [3] used seasonal/annual values of climate variables to examine climate effects on diameter growth of red pine in plantations. He reported that diameter growth was affected by climate and varied by location. The overall effect was positive and pronounced more in southern than in eastern Ontario. It was neutral in the far west. However, the effects were negative and less pronounced in the central west. The climate variables that significantly explained variation in the diameter growth of red pine trees in plantations were the total growing season precipitation (TPGS) and the range of mean diurnal temperature (MDTR). Diurnal temperature range is the difference between the maximum and minimum temperatures on the same day.

In this study, the overall climate effects on diameter growth of white spruce and white pine trees in plantations were negative. The magnitude of negative effects depended on tree species and location. The effects were more pronounced for white pine than for white spruce trees at all locations. For white spruce, the asymptote decreased as the sum of monthly CMIs for the whole year (January to December) (ACMI) increased. For white pine, the sum of monthly CMIs of growing months (April-August) (GMCMI) explained more variation in the asymptote than ACMI and the asymptote increased as the value of GMCMI increased.

The rate parameter increased as growing season total precipitation and JCMI increased but decreased as mean temperature of growing season increased. On the other hand, the rate parameter increased as JCMI increased to a certain limit (the coefficient of the quadratic term of JCMI was negative) and decreased if the values of both total precipitation and mean temperature of the growing season were elevated.

In other studies, Matisons et al. [8] and Adhikari et al. [11] found June weather corelated with radial growth of European beach and post oak (*Quercus stellata* Wangenh.) grown in Europe and Oklahoma, United States, respectively. Similarly, Oboite and Comeau [14] reported positive effects of CMI on diameter growth of lodgepole pine, jack pine, trembling aspen, white spruce, and balsam poplar grown in western Canada. They also reported that a longer frost-free period (FFP) had positive effects on the diameter growth of balsam poplar and trembling aspen trees. However, the FFP had negative effects on the diameter growth of lodgepole and jack pine trees. On the other hand, Bayat et al. [15] found that the impact of climate change on diameter growth of several tree species in the Hyrcanian Forest was not very pronounced. They reported that the diameter growth under climate change decreased by 7% at the end of 2070 as compared to the beginning of the growth period.

Climate effects varied among species. Even for the same species, effects varied by location even within a province (Ontario). The projected values of diameter growth under different climate change scenarios showed that climate had positive effects on diameter growth of jack pine [12] but negative effects on that of black spruce [12], white spruce, and white pine (this study). Climate had both positive and negative effects on red pine. It was positive in the east and west but negative in the south. Effects on black spruce were most evident, followed by those on red pine, white pine, and white spruce. Among red pine, white spruce, and white pine, white spruce growth was least affected. Effects on red pine and white pine growth were similar, with red pine affected slightly less.

Competitive interactions can modify the growth responses to climate change [28]. Similarly, the response may vary from its northern to southern boundary [3]. It was not possible to cover the native range and stand density in sampling white pine and white spruce trees. Additionally, Sharma [30] reported that the climate effects on height growth of black spruce in mixed stands depended on the tree species that it grew with. Therefore, caution should be applied in utilizing the diameter growth models presented here to determine the climate effects on growth of all white pine and white pine populations.

5. Conclusions

Climate-sensitive diameter growth models were developed for white pine and white spruce plantations. The McDill–Amateis growth function was used as the base function to model diameter growth of these tree species. To make the model climate sensitive, the asymptote and rate parameter of the function were expressed in terms of climate variables. The climate variable that explained the variation in the asymptote of white spruce trees was the sum of monthly climatic moisture index (CMI) for the whole year. For white pine, variation in the asymptote was explained by the sum of monthly CMI of the growing months.

For the rate parameter, mean temperature and total precipitation of the growing season and June CMI significantly explained the variation for both species. Climate effects were evaluated at three geographic locations across Ontario (east, west, and south) for each species under three climate change (emissions) scenarios. The overall effects of climate were negative, with magnitude depending on tree species and growing location. The negative effect of climate on diameter growth was more pronounced for white pine than for white spruce.

Inside bark diameters at breast height of white spruce and white pine plantations can be estimated using the models presented here. Projected seasonal/annual values of climate variables under the most accurate emissions (climate change) scenario are needed for accurate estimations. Forest management plans developed using climate-sensitive models should provide forest managers with more accurate information about forest growth than traditional models. If the values of climate variables are unavailable, the models fitted without climate variables can be used to estimate the diameters of the tree species used in the study.

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Data Availability Statement: Summary statistics of the data used in this study are presented in Table 1.

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References

1. Vanclay, K. *Modelling Forest Growth and Yield: Application to Mixed Tropical Forests*; CAB International: Wallingford, UK, 1994.
2. Avery, T.E.; Burkhart, H.E. *Forest Measurements*; McGraw-Hill: New York, NY, USA, 2002; 456p.

3. Sharma, M. Modelling climate effects on diameter growth of red pine trees in boreal Ontario, Canada. *Trees For. People* **2021**, *4*, 100064. [CrossRef]
4. Chhin, S.; Hogg, E.H.; Lieffers, V.J.; Huang, S. Potential effects of climate change on the growth of lodgepole pine across diameter size classes and ecological regions. *For. Ecol. Manag.* **2008**, *256*, 1692–1703. [CrossRef]
5. Maxime, C.; Hendrik, D. Effects of climate on diameter growth of co-occurring Fagus sylvatica and Abies alba along an altitudinal gradient. *Trees* **2011**, *25*, 265–276. [CrossRef]
6. Toledo, M.; Poorter, L.; Pena-Clara, M.; Balkazar, A.A.J.; Leano, C.; Licona, J.C.; LIanque, O.; Zuidema, V.V.P.; Bongers, F. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. *J. Ecol.* **2011**, *99*, 254–264. [CrossRef]
7. Hökkä, H.; Salminen, H.; Ahti, E. Effect of temperature and precipitation on the annual diameter growth of Scots pine on drained peatlands and adjacent mineral soil sites in Finland. *Dendrochronologia* **2012**, *30*, 157–165. [CrossRef]
8. Matisons, R.; Puriņa, L.; Adamovičs, A.; Robalte, L.; Jansons, Ā. European beech in its northeasternmost stands in Europe: Varying climategrowth relationships among generations and diameter classes. *Dendrochronologia* **2017**, *45*, 123–131. [CrossRef]
9. Rubio-Cuadrado, Á.; Bravo-Oviedo, A.; Mutke, S.; Del Río, M. Climate effects on growth differ according to height and diameter along the stem in Pinus pinaster Ait. *iForest* **2018**, *11*, 237–242. [CrossRef]
10. Jiao, L.; Xue, R.; Qi, C.; Chen, K.; Liu, X. Comparison of the responses of radial growth to climate change for two dominant coniferous tree species in the eastern Qilian Mountains, northwestern China. *Int. J. Biometeorol.* **2021**, *65*, 1823–1836. [CrossRef]
11. Adhikari, A.; Masters, R.E.; Adams, H.D.; Will, R.E. Radial growth responses of post oak (Quercus stellata) to climate variability and management in southeastern Oklahoma, USA. *Can. J. For. Res.* **2022**, *52*, 209–219. [CrossRef]
12. Subedi, N.; Sharma, M. Climate-diameter growth relationships of black spruce and jack pine trees in boreal Ontario, Canada. *Glob. Chang. Biol.* **2013**, *19*, 505–516. [CrossRef]
13. Pokharel, B.; Froese, R.B. Representing site productivity in the basal area increment model for FVS-Ontario. *For. Ecol. Manag.* **2009**, *258*, 657–666. [CrossRef]
14. Oboite, O.F.; Comeau, P.G. Climate sensitive growth models for predicting diameter growth of western Canadian boreal tree species. For. *Int. J. For. Res.* **2021**, *94*, 363–373. [CrossRef]
15. Bayat, M.; Knoke, T.; Heidari, S.; Hamidi, S.K.; Burkhart, H.; Jaafari, A. Modeling Tree Growth Responses to Climate Change: A Case Study in Natural Deciduous Mountain Forests. *Forests* **2022**, *13*, 1816. [CrossRef]
16. Yeh, H.Y.; Wensel, L.C. The relationship between tree diameter growth and climate for coniferous species in northern California. *Can. J. For. Res.* **2000**, *30*, 1463–1471. [CrossRef]
17. McKenney, D.W.; Hutchinson, M.F.; Papadopol, P. Customized spatial climate models for North America. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 1161–1622. [CrossRef]
18. Hogg, E.H. Climate and the southern limit of the western Canadian boreal forest. *Can. J. For. Res.* **1994**, *24*, 1835–1845. [CrossRef]
19. Wykoff, W.R. A basal area increment model for individual conifers in the northern Rocky Mountains. *For. Sci.* **1990**, *36*, 1077–1104.
20. Murphy, P.A.; Shelton, M.G. An individual-tree basal area growth model for loblolly pine stands. *Can. J. For. Res.* **1996**, *26*, 327–331. [CrossRef]
21. Weiskittel, A.R.; Garber, S.M.; Johnson, G.P.; Maguire, D.A.; Monserud, R.A. Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock, and red alder. *For. Ecol. Manag.* **2007**, *250*, 266–278. [CrossRef]
22. Leites, L.P.; Robinson, A.P.; Crookston, N.L. Accuracy and equivalence testing of crown ratio models and assessment of their impact on diameter growth and basal area increment predictions of two variants of the Forest Vegetation Simulator. *Can. J. For. Res.* **2009**, *39*, 655–665. [CrossRef]
23. Subedi, N.; Sharma, M. Individual-tree diameter growth model for black spruce and jack pine plantations in northern Ontario. *For. Ecol. Manag.* **2011**, *261*, 2140–2148. [CrossRef]
24. Sharma, R.P.; Vacek, Z.; Vacek, S.; Jansa, V.; Kucera, M. Modelling individual tree diameter growth for Norway spruce in the Czech Republic using a generalized algebraic difference approach. *J. For. Sci.* **2017**, *63*, 227–238. [CrossRef]
25. Burkhart, H.E.; Tome, M. *Modeling Forest Trees and Stands*; Springer: Dordrecht, The Netherlands, 2012; 457p.
26. Pinheiro, J.C.; Bates, D.M. *Mixed-Effects Models in S and S-PLUS*; Springer: New York, NY, USA, 2000; 528p.
27. Vuuren, D.P.; Edmonds, J.A.; Kainuma, M.; Riahi, K.; Weyan, J. A special issue on the RCPs. *Clim. Chang.* **2011**, *109*, 1. [CrossRef]
28. Buechling, A.; Martin, P.H.; Martin, P.H.; Canham, C.D. Climate and competition effects on tree growth in Rockey Mountain forests. *J. Ecol.* **2017**, *105*, 1636–1647. [CrossRef]
29. Goldblum, D.; Rigg, L.S. Tree growth response to climate change at the deciduous-boreal forest ecotone, Ontario, Canada. *Can. J. For. Res.* **2005**, *35*, 2709–2718. [CrossRef]
30. Sharma, M. Climate effects on black spruce and trembling aspen productivity in natural origin mixed stands. *Forests* **2022**, *13*, 430. [CrossRef]