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ORIGINAL ARTICLE

Predicted short-term radial-growth changes of trees based on past climate on Vancouver Island, British Columbia

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Abstract

Tree-ring radial expansion estimator (TREE) is an integrated radial growth model that allows users to define short-term climate change scenarios to anticipate the impact upon mature trees found growing at high elevation on Vancouver Island, British Columbia. Five individualistic models were built to represent the radial growth behaviour of mountain hemlock (*Tsuga mertensiana* (Bong.) Carr), yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), western red-cedar (*Thuja plicata* Donn), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. The models were developed on climate-radial growth relationships incorporating Nanaimo climate station data, and were able to explain from 55 to 68 per cent of the variance in radial growth. The models can be run with modifications to yearly precipitation and temperature variables, giving the user the ability to investigate the radial-growth impacts of a wide range of possible climate change scenarios. Results from eight such scenarios show that species growing within their ecological limits illustrate a limited change in radial growth to forecasted climate, while species growing at an ecotonal boundary are usually very sensitive to a specific climate variables (e.g., July temperature). A forecasted alteration to this key variable will then radically alter the radial-growth rate of the species.

Keywords: Radial-growth model; Climate change; High-elevation conifers; Vancouver Island

Introduction

The radial-growth of various trees has been modelled using various approaches, including ecosystem-wide studies (e.g., Scuderi et al., 1993; Keane et al., 1996), site- or species-specific studies (e.g., Sutherland et al., 1991; Fritts and Dean, 1992) and even physiological models that predict specific cambial activities (e.g., Fritts et al., 1991; Deleuze and Houllier, 1997). These models require either site-specific climate data or detailed physiological data and, as a result, can be of limited practical utility. An infrequently used approach is to model future perturbations in the climate of a region and use this forecasted data to predict changes in radial tree growth based on past tree-growth–climate relationships (e.g., Laroque and Smith, 2003).

As the magnitude of future climate changes is uncertain, most researchers now agree that defining future climate and its probable effects on radial growth

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will not be a straightforward process. Given this inherent uncertainty, we developed a modelling approach whereby individual users select future climatic parameters and use the model to determine the effect these changes will have on the radial growth of trees. Radial-growth data were obtained from tree-ring chronologies of conifer species growing at high-elevation sites on Vancouver Island (Laroque and Smith, 2003). These chronologies were used to develop five robust, biologically based, deterministic subroutines held within the Internet-based model tree-ring radial expansion estimator (TREE).

This paper summarizes the potential future growth regimes of the five species by predicting the impact of short-term (<20 years) climate-change scenarios upon the radial-growth rate. We believe that the TREE model has considerable potential application to future planning in the British Columbia forest industry. Current annual allowable cut estimates have no climate change variables built into their long-term sustainability criteria. Incorporation of the TREE model would allow forest managers to begin to anticipate the likely effects of climatic perturbations on future forest yields.

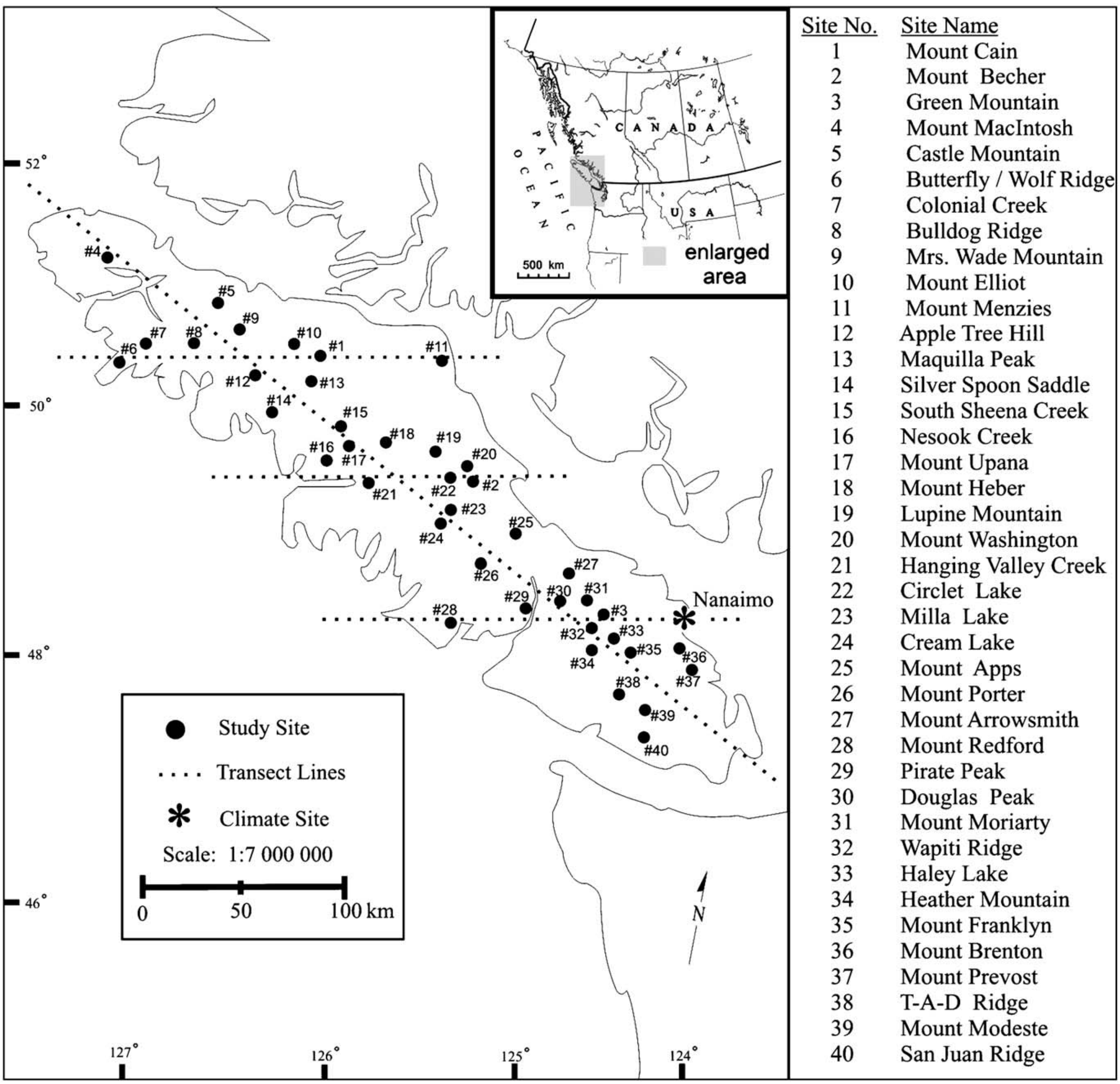

Fig. 1. Location of the 40 study sites on Vancouver Island, British Columbia, Canada.

Study sites and species

Forty individual study sites were sampled on Vancouver Island, British Columbia, Canada (Fig. 1). The Insular Mountain Range runs parallel to the long axis of the island, with maximum elevations reaching 2200 m asl. A network of 88 chronologies (Laroque and Smith, 2003) was collected from five species at high-elevation sites between 696 and 1433 m asl in the Mountain Hemlock Zone (MHZ). In the MHZ, cool summers and cool winters with a deep snowpack are common (Klinka et al., 1991). Co-dominant species are mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) and yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach). In the transition area between the MHZ and the biogeoclimatic zone downslope, western red-cedar (*Thuja plicata* Donn.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) are also present. All of these species are represented in the chronologies, with the majority sampled being mountain hemlock and yellow-cedar (>30 each), with limited numbers of chronologies for the other three species (11 for western hemlock and two each for Douglas-fir and western red-cedar).

Samples were collected from dominant trees along transects set out to capture variation in growth due to localized site characteristics (Fig. 1). Sites were located equidistant along a northwest–southeast "longitudinal" transect and three east–west "latitudinal" transects. Treeline sites and species were selected because stronger climate signals are commonly retained at these sites than in the tree-ring records from trees growing at lower elevations on Vancouver Island (Laroque, 1995; Smith and Laroque, 1996, 1998a, b; Zhang, 1996; Laroque and Smith, 1999).

Methods

The TREE model was developed to forecast the impact of short-term climate changes on radial-growth trends. TREE uses species-specific climate/radial-growth relationships and selected temperature and precipitation variables to predict radial-growth trends within the next 20 years. Predictions are based upon stepwise multiple regression equations that reflect, for each species, the relationship between radial-growth increments and 41 independent variables – 40 monthly temperature and precipitation variables (previous May to current December) and a 1-year lag variable representing prior year's growth.

Radial growth data

Spatial patterns within the chronology network were examined using a correlation matrix over a common interval from 1793 to 1993. The analysis resulted in over 7700 cross-correlations, with most within-species correlations being highly significant ($p<0.0001$) and very few site-to-site comparisons failing to show the same 200-year pattern (Laroque, 2002). The strongest correlations were usually from nearby sites of the same species. Between-species tests often showed high correlations and statistically significant relationships, especially when the two chronologies came from the same or nearby locations. The strongest correlations between species pairs were for mountain hemlock and western hemlock, and between mountain hemlock and yellow-cedar. An examination of the chronologies from 28 randomly selected sites containing both a mountain hemlock and a yellow-cedar chronology, showed there was a very strong similarity between species at different sites, with most chronologies significant at $p<0.0001$ level (Laroque, 2002). Strong common patterns of variation were found both between and amongst species over the entire range of sites (Laroque, 2002), providing a rationale for combining the regional data into species-specific master chronologies (Laroque and Smith, 2003). The five resultant chronologies form island-wide master chronologies representing the general radial growth pattern for each species on the island.

Climate data

Climate data are needed to develop regression models establishing the mathematical relationship between radial growth and climate for each tree species. Homogenized climate data from the Nanaimo station from 1900 to 1995 ($n=96$) were used to calibrate the models as this station is the most representative single site of all the long-term station data on Vancouver Island. In addition, a 1-year-prior growth variable was added to the analyses because of high autocorrelation values in the data set and because previous research strongly suggested that the prior year's growth has a strong bearing on current radial growth production in these conifer species (Laroque and Smith, 1999; Laroque, 2002).

A stepwise multiple regression was used to determine which of the 41 variables had the largest partial correlation with ringwidth. For each species the most significant variables were selected using confidence limits of 0.10 ("F to Enter") and 0.15 ("F to Remove"). The number of variables in the final regression equations ranged from 7 to 13. The five regression models explained from 55 to 68 per cent of the variance in radial growth. As expected with the high amount of variance explained, all models were significantly verified (Laroque, 2002).

Results

TREE uses an HTML interface to model future radial growth variations by comparing historical radial-growth responses to changing climates, and assuming that future annual radial-growth responses will respond to climate in the same way. The model allows a user to examine the growth response of individual tree species by selecting the expected temperature/precipitation variation over the interval of interest, after which the predicted radial-growth increments are displayed as annual standardized measurements. The current version of TREE (Version 2.1 [http://cgrg.geog.uvic.ca/tree.htm]) is able to explain over half of the variance in the radial-growth of all of the species studied. The models work in a simple three-step process:

1. The user selects any or all of the five tree species for modeling.
2. The user selects the climate parameters to be altered, with the amount of alteration allowed based upon the standard deviation of known seasonal climatic normals for Vancouver Island (Environment Canada, 1996). For example, the user is able to make scaled precipitation adjustments of ±3 to a maximum of 75 mm (one standard deviation) in January to ±1–30 mm (one standard deviation) for August. If no selection is made, future growth is predicted using the 100-year temperature and precipitation averages from the Nanaimo climate station data.
3. Finally, the user selects a time interval (up to 20 years) for prediction. For the first year of a run, the previous year's climate parameter is based on the 100-year average of each parameter; for successive years the calculated increment is saved for use in the next year's calculation. Since all trees grow at different rates, based on age and species, the calculations are standardized so that average growth is equal to one. Departures above and below one standard deviation from the average signify growth above or below normal rates, with symbols signifying this in the output.

The outputs of TREE are presented as schematic tree symbols, which increase or decrease in size depending upon the predicted annual enhancement or reduction in radial growth, and also as standardized ring-width values. Iterations are performed for the user-defined number of years and appropriate image sizes are displayed beside each year. Since the climate changes induced by the operator are static (i.e., they are altered from the past, but do not change in the future), most dramatic changes in radial-growth persist for only a few years, stabilizing in most cases by the fifth or sixth year. The year in which this stabilization occurs is also displayed in the output.

Discussion

Although short-term forecast models can never adequately illustrate the natural ecological amplitude or plasticity inherent in every tree or individual tree species, experimentation with the TREE model highlights the capacity of trees to respond to potential future climate changes. Table 1 shows results from TREE simulations of eight common climate-change scenarios that differ from the current climate. The year of stabilization and the degree of alteration are listed for each species. Changes in temperature were set at 1.0 °C above or below the 100-year average for all months in each climate change scenario, while changes in precipitation were altered the maximum one standard deviation allowed for each month in each scenario.

Table 1. Results from eight climate change scenarios for all five upper elevation species available from the tree model

Seasonal climate scenario	MH	YC	WH	WRC	DF
Cooler (1°) – wetter spring (+1 SD, MAM)	0.91 (4*)	0.99 (5)	0.99 (1)	0.97 (2)	1.09 (5*)
Warmer (1°) – drier spring (−1 SD, MAM)	1.09 (4*)	1.01 (5)	1.01 (1)	1.03 (2)	0.91 (5*)
Cooler (1°) – wetter summer (+1 SD, JJA)	1.17 (6*)	1.09 (6*)	1.41 (10*)	1.40 (2*)	1.28 (4*)
Warmer (1°) – drier summer (−1 SD, JJA)	0.83 (6*)	0.91 (5*)	0.59 (10*)	0.60 (2*)	0.72 (4*)
Cooler (1°) – wetter autumn (+1 SD, SON)	1.00 (1)	0.91 (7*)	0.95 (4)	0.89 (3*)	1.06 (6*)
Warmer (1°) – drier autumn (−1 SD, SON)	1.00 (1)	1.09 (7*)	1.05 (3)	1.11 (3*)	0.94 (6*)
Cooler (1°) – wetter winter (+1 SD, DJF)	0.97 (3)	0.97(3)	1.03 (5)	0.97 (3)	0.97 (1)
Warmer (1°) – drier winter (−1 SD, DJF)	1.03 (3)	1.03 (3)	0.97 (5)	1.03 (3)	1.03 (1)

The ultimate alteration in radial growth is defined for species, with average growth represented by 1.0 and deviations above or below this number representative as above or below normal growth. The year of stabilization of the growth increment is displayed in brackets after each growth increment. An asterisk (*) within this bracket signifies a significant alteration in radial growth under the selected climate scenario. Individual tree species are defined as MH = mountain hemlock, YC = yellow-cedar, WH = western hemlock, WRC = western red-cedar, DF = Douglas-fir. Seasons are defined as, MAM = March, April and May, JJA = June, July, and August, SON = September, October, and November, DJF = December, January, and November.

Table 1 shows that generalist species such as yellow-cedar (Antos and Zobel, 1986; Russell, 1993) are better able to adjust to climatic changes, since no single factor limits their growth to a high degree compared to other species in this study. Conversely, the response of a more specialist species like western hemlock or western red-cedar varies, depending on timing and the specific climate changes. For example, drier-warmer or wetter-cooler springtime conditions have little effect on western hemlock as it is still generally dormant at that time in its radial growth cycle (Laroque, 2002). However, wetter-cooler or drier-warmer environments during the critical radial growth period for this species (summer, Laroque, 2002), result in dramatic changes in the response of radial growth (Table 1).

The derived relationships do not take into account the form of the forecasted precipitation (i.e., whether it falls as snow or rain). This is important for species such as mountain hemlock since snow or rain in spring has been shown to have different effects on radial growth (Peterson and Peterson, 2001): a large spring snowpack plays an important role in setting up the upcoming year's radial growth for many of the species in this environment (Graumlich and Brubaker, 1986; Smith and Laroque, 1998a; Laroque, 2002).

In general, this analysis also suggests that the trees found at key ecotonal boundaries are more apt to do better or worse depending upon the direction that their ecotonal gradient would move with the change in climate.

Conclusion

TREE is a short-term forecasting model that allows users to develop climate-change scenarios and visualize their potential effects for up to 20 years. Five species-specific algorithms are built into TREE, developing relationships based on local climate station data, and are able to explain from 55 to 68 per cent of the variance in radial growth. Changes in precipitation and temperature variables may be introduced into the model to investigate the radial-growth impacts of a wide range of possible climate-change scenarios.

TREE highlights the radial-growth potential that each species could yield under a variety of user defined climate change scenarios. Generalist species or species growing well within their ecological limits show a more limited alteration to their radial growth. Non-generalist species or species growing at an ecotonal boundary are usually sensitive to specific climate variables (e.g., July temperature) and changes to one of these key variables can radically alter the radial-growth rate of the species.

The model accepts a wide range of possible climate inputs that result in alterations to radial growth that vary considerably in amount and duration of the alteration. Given these complexities, models such as TREE should be increasingly useful as foresters face managing resources under the varied scenarios predicted by future climate models.

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