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Integrating climatic response in competition dependent tree-level growth models for northern hardwoods

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A B S T R A C T

With increased rates of climate change, it is imperative for forest managers to have access to models that can take into account the expected effects of climate change on tree growth. To this end, growth function are sometimes used that include climatic variables such as mean annual temperature or precipitation averaged over decades. Such growth models are usually relatively easy to develop but they do not take into account the fact that tree diameter growth on a given year is determined not by climatic conditions that prevailed up to 30 years before but mainly by climatic conditions that prevailed during the current and previous year. Our objective is determine if including climatic variables obtained from dendroclimatic response function will lead to growth models having a better fit to data than versions with 30-year average climatic conditions, or no climate at all. Growth models were developed for *Betula alleghaniensis*, *Acer saccharum*, *Acer rubrum* and *Fagus grandifolia* using data from south-eastern Quebec. Three types of growth function were compared. A first set of growth function was developed in which the potential growth of a tree was modeled as a function of tree size and site characteristics (vegetation type and drainage) to be further modified as a non-linear function of plot basal area. The effect of climate was not explicitly accounted for in this fort set of growth function, therefore they will be refered to as Climate-implicit models. A second set of growth function was developed in which we explicitly accounted for the effect of climate by incorporating 30-year mean annual temperature and precipitation in the growth function. In a third type of growth function, also climate-explicit, we incorporated the most significant recent climatic variables identified using climatic response function developed for each species based on dendrochronological and climatic data. The three types of models were compared based on the Akaike information criterion (AIC). Our results showed that Climate-explicit growth models with climatic variables obtained from response function analysis outperformed other growth models for three out of four species (*B. alleghaniensis*, *A. saccharum* and *F. grandifolia*). Incorporating climate in the form of 30-year average climatic conditions brought some improvement over a non-climatic function for *A. rubrum*, but this was not the case for other species. Accounting for growth dependency on climate by including recent monthly climatic variables provided by response function could be a potentially useful approach for the development of a new lineage of tree growth models dealing with climate change.

1. Introduction

Given the current and anticipated changes in climatic conditions, tree growth models need to account for the influence of climate on growth, especially if models are intended to be used to predict growth over several decades. Several tree growth models do account for the effect of climate on growth. Moreover, growth models which explicitly incorporate climate effects on growth generally show a better fit to data than models withtout climate terms. For instance, Huang et al. (2013) showed that the inclusion of a 30-years climate variable significantly improved model fit for two deciduous species (*Populus tremuloides* Michx. and *Betula papyrifera* Marshall.) in eastern Canada. Mixed models using climatic input were computed by Laubhann et al. (2008) and Rayamajhi and Kush (2006) for deciduous species in Europe and

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USA. They found that including climatic variables improved growth model predictions compared to growth models that did not account explicitly for climate effects. However, in all of these studies, climate was represented by a 20–30 year average of annual or seasonal climatic data.

Assessment of climate change impacts on predicted growth trends need to be derived from models which explicitly incorporate the effects of climate on growth. Dendrochronology, which deals with long-term records of tree growth under natural environmental conditions, can be used to evaluate the impacts of climatic change on forest productivity (Schweingruber, 1996). Dendroclimatic analysis (e.g. response function) can be useful as an exploratory tool for determining which climatic variables are relevant to use and for identifying periods (months and/or seasons) when climatic conditions (temperature and/or precipitation) are more likely to influence tree growth (Schweingruber, 1996; Hofgaard et al., 1999; Tardif et al., 2001; Deslauriers et al., 2003; Girard et al., 2011a). For example, dendroclimatic response function have been found to give good results in modeling past and future radial growth (Tardif et al., 2001).

According to International Panel on Climatic Change workgroup (IPCC) scenarios, southern Québec will experience increased rates of climate change for the 21st century (Solomon et al., 2007). Not only are changes expected in terms of mean annual temperatures, but also in terms of monthly variations and frequency of extreme climatic events. This is crucial to consider since diameter growth of most North American trees is mainly influenced by prevailing climatic conditions during a few months of the previous and current year, because of pre- and neoformation of cambial cells (Schweingruber, 1996; Hofgaard et al., 1999; Tardif et al., 2001; Deslauriers et al., 2003; Girard et al., 2011a). Therefore, including climatic variables such as mean annual temperature and precipitation in tree growth models, especially when the value of these variables is obtained from averaging several decades of data, may not capture the effects that expected changes in monthly temperatures and precipitation may have on tree ring growth. Using climatic response function (Schweingruber, 1996) to identify the monthly climatic variables most important to a species diameter growth, and including these combinations of monthly climatic variables in tree growth models might prove to be a promising approach to account for climatic change in competition-dependent tree growth models, for example the USDA's Forest Vegetation Simulator or 3-PG (Landsberg and Waring, 1997).

The objective of this study is to test the hypothesis that including climatic variables obtained from dendroclimatic response function will lead to tree growth models having a better fit to data than model versions in which climate is only represented by 30-year average conditions, or not represented at all. To address our objective, tree growth models were developed for four deciduous tree species found in northern hardwood forests in southern Québec: *Betula alleghaniensis* Britton (yellow birch), *Acer saccharum* Marsh. (sugar maple), *Acer rubrum* L. (red maple) and *Fagus grandifolia* Ehrh. (American beech). Growth models were calibrated using forest inventory data as well as dendrochronological material. Model development was performed in three steps. First, Climate-implicit models (i.e., models in which climate is not explicitly accounted for) were calibrated for each species with plot-level basal area (used as the competition variable), tree size and site conditions (vegetation type and drainage). Second, dendroclimatic response functions were established for each species from an analysis of tree cores taken on a subset of trees. The response functions were used to identify the suites of climatic variables (temperature and precipitation of specific months of the current and/or previous growing season) that most significantly influenced annual ring formation for each species. Third, Climate-explicit versions of growth models were developed by incorporating the suites of climatic variables identified in the response function. An alternative approach to include climate in growth models was also considered in which 30-year mean annual climate variables (temperature and precipitation) were used.

2. Methods

2.1. Study area

The study area is located in southeastern Québec and is part of the sugar maple-basswood bioclimatic domain (Robitaille and Saucier, 1998) (Fig. 1). The study area extends from 72°W 45.25°N to 70.3°W 46°N, for a total of 10 845 km^2. Mean elevation of the plots is 431 m above sea level (range: 214–639 m). For the period 1980–2010, climatic conditions were characterized by a mean annual temperature of 4.7 °C and annual precipitation averaging 1335 mm, of which 20% falls as snow. The growing season length varies between 180 and 190 days (Environnement Canada, 2012).

2.2. Database

We used a forest inventory database provided by Domtar Inc., which included data from 4592 permanent plots sampled at different times between 1963 and 2010. Most of the plots were circular (radius of 11.28 m) but some were square (20 m $\times$ 20 m), and they all covered an area of 400 m^2. We selected plots that met the following criteria: (1) plots located in landscape units 8, 30, 31 or 32 (Robitaille and Saucier, 1998); (2) plots with a potential vegetation type that was either deciduous or mixed (based on forest maps); (3) plots which comprised >75% of total basal area as deciduous trees; (4) plots which were sampled at an interval of $\geqslant$5 years; and (5) plots with drainage ranging from poor to moderate.

A total of 590 plots met our criteria, corresponding to 15 742 tree measurements. The main tree species found in the selected plots were: *B. alleghaniensis* (3346 measurements on 2213 trees), *A. rubrum* (3180 measurements on 2315 trees), *A. saccharum* (8368 measurements on 5278 trees) and *F. grandifolia* (848 measurements on 504 trees). In the dataset, mean diameter at breast height (dbh) was 187 mm (91–735 mm) for *B. alleghaniensis*, 208 mm (91–622 mm) for *A. rubrum* , 201 mm (91–704 mm) for *A. saccharum* and 185 mm (91–515 mm) for *F. grandifolia*. Plot-level basal area (BA) ranged from 8 to 58 m^2 ha^{-1}. Soils were typically brunisols (occasionally podzols) covered by a Moder humus layer.

For each dbh measurement *i* recorded in the database, we estimated the proportion of the growing season (Pseason$_i$) elapsed at the sampling date (date$_i$) using the logistic function presented in Duchesne and Ouimet (2008):

$$\text{Pseason}_i = \frac{1}{(1 + \exp^{(12.54 - 0.066 \cdot \text{date}_i)})} \quad (1)$$

where Pseason$_i$ ranges from 0 to 1 and where date$_i$ is expressed in Julian days.

The interval between two measurements was then calculated as:

$$\text{Interval}_{0-1} = (\text{Year}_1 - \text{Year}_0) + (1 - \text{Pseason}_0) - (1 - \text{Pseason}_1) \quad (2)$$

where Interval is expressed in number of growing seasons, Year$_i$ is the measurement calendar year and Pseason$_i$ is from Eq. (1).

Annual diameter growth (mm year^{-1}) of each tree between two measurements was calculated by dividing the total increase in dbh (dbh$_1$ – dbh$_0$) by the interval length between measurements (Interval$_{0-1}$). Occasionally, negative dbh increments were