Forest Ecology and Management 262 (2011) 863–872

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Modelling day-to-day stem diameter variation and annual growth of balsam fir (*Abies balsamea* (L.) Mill.) from daily climate

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ARTICLE INFO

*Article history:*
Received 11 January 2011
Received in revised form 12 May 2011
Accepted 18 May 2011

*Keywords:*
Boreal forest
Growth models
Balsam fir
Dendrometers
Heat stress

## ABSTRACT

In the present context of global climate changes and the continuous development of forest management strategies based on the concept of sustainable use, it is important to develop a better understanding of the climatic factors controlling the growth of boreal forests. In this study, we report the results of a five-year field research within which day-to-day balsam fir (*Abies balsamea* (L.) Mill.) stem diameter variation was measured with dendrometers and examined in relation with various daily climatic variables. A model built with data from three growing seasons that included solar radiation, relative humidity, temperature and precipitation explained 84% of the variance in day-to-day stem diameter variation from June to September. The model has approximately the same predictive capability when validated with independent daily data from two other growing seasons. The model captured both the cumulative increment associated with the irreversible growth and the high frequency variation of day-to-day fluctuations associated to changes in the stem water content. In general, rainy days during which relative humidity was high and solar radiation was low favored stem diameter expansion (growth and swelling) while stem diameter decreased during periods of low relative humidity and high solar radiation. Similar models were obtained when the June–September period was divided into two parts (June–July and August–September) to better represent the period during which most of the cumulative annual stem increment is observed (June–July). Inter-annual variation in stem growth computed from the modeled day-to-day variation in stem diameter was significantly correlated to the inter-annual variation in annual growth determined from tree core measurements over a 10 year period ($p = 0.023$). The model was notably able to capture a particularly poor growing year (2006) presumably due to a short-term heat stress period. Results suggest that the inclusion of daily data in growth–climate models may contribute to improve predictions of the potential tree growth response to climate by identifying particular climatic events that may escape to a classical dendroclimatic approach.

## 1. Introduction

The boreal forest, which includes balsam fir and black spruce dominated forests, has a huge economic value and is a key factor for the maintenance of the regional economic sustainability of rural populations (Burton et al., 2003). In the context of the contemporary climate changes, increasing our knowledge of the growth–climate relationships becomes particularly important. Also, forest management strategies based on the concept of sustainable use require a good knowledge of the factors affecting forest growth and their sensibility to climatic variables (Worbes, 1999). In this context, it is generally recognized that more modeling efforts are necessary to establish species and community responses to climate (Aber et al., 2001; Dale et al., 2001; Hansen et al., 2001). Detailed studies are needed in a variety of environments to detect recurrent patterns and underlying processes and to improve our comprehension of the interactions between climate, disturbances and tree growth (Dale et al., 2001; Scheffer and Carpenter, 2003).

However, modeling complex growth–climate relationships is an imposing challenge. Historically, classical dendroclimatic analysis, in which tree ring width measurements from wood samples were modeled from climatic variables, was the most common technique to determine the effect of climate on tree growth (Fritts, 1976). Despite that, causality links between tree growth dynamics and climatic variables are sometimes difficult to establish. Monthly air temperature and precipitation generally explain approximately 60% of inter-annual growth variation (as measured by tree ring chronology) for many species (Fritts, 1976). However, in northeastern North America, lower sensitivities of tree growth to climate were generally observed (Fritts, 1976; Phipps, 1982; Huang et al., 2010).

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doi:10.1016/j.foreco.2011.05.027

The lack of fit of models obtained with dendroclimatic analysis may be due to the high variability of growth rates within a given growing season. Moreover, the same amount of growth can be achieved through a faster growth rate or a longer growing period. The use of sensitive dendrometer and multivariate statistical analysis can provide useful insights into short term, physiological based responses of whole tree to changing external environmental and internal physiological and structural factors (McLaughlin et al., 2003). This technology opened a wide range of possibilities and has been successfully used to increase our comprehension of the diurnal and seasonal stem diameter variation of many species in Europe and North America (e.g. Deslauriers et al., 2003b; Dünisch and Bauch, 1994; Kozlowski and Winget, 1964; Tardif et al., 2001; Worbes, 1999). Some studies have focused on the relationship between stem diameter variation and climatic variables on a daily basis (e.g. Bouriaud et al., 2005; Deslauriers et al., 2003b; Downes et al., 1999; Drew et al., 2008; Pietarinen et al., 1982; Zweifel et al., 2005). These studies were made with different tree species at diverse development stage (juvenile and mature tree) in control and in field conditions. The type of model (process-based, multiple regression, response function, and correlation) as well as the variables used to characterize growth or stem diameter variation (averages, maximum, standardized vs non-standardized values, extraction of expansion and contraction phase in diurnal stem diameter variation) vary widely among those studies. Also, proposed models have been calibrated over relatively short periods of time (commonly over one growing season) with few repetitions (1–4 years) and were generally not validated on independent data sets which would limit their predictive capabilities. To our knowledge, no study has tested the capability of daily models to predict annual growth of mature trees *in situ* over many years. One may expect that models capable of relating daily climate to day-to-day stem diameter variation with high variance explanations would lead to the development of quantitative models capable of predicting annual tree growth based on daily climate data. It is expected that models using daily data will be more efficient to identify specific climatic events that could last only a few days but that may have dramatic impacts on growth, than classic dendroclimatic models, dealing with monthly climatic variables, may do. In this study, a first attempt is made to test the capability of a predictive stem increment model feed by daily climate to adequately predict total annual growth. Our objectives were to (1) identify the climatic variables (or the product of their interactions) controlling day-to-day changes in the stem diameter of mature balsam fir (*Abies balsamea* (L.) Mill.) trees for complete growing seasons using the results of a five-year field study and (2) to verify the potential of a daily model of stem diameter variation to accurately predict inter-annual variation in annual growth estimated independently from tree core measurements.

## 2. Materials and methods

### 2.1. Study site

The study site is located in Québec, Canada (47°19′41″N; 71°07′37″W; 771–864 m a.s.l.), 70 km north of Québec City. The canopy vegetation is mainly dominated by even-aged balsam fir with a small component of white spruce (*Picea glauca* (Moench) Voss) and paper birch (*Betula papyrifera* Marsh.). In 1999, a study plot (25 × 50 m) was established in a mature stand to monitor nutrient fluxes and vegetation dynamics. Diameter at breast height (dbh) and basal area were 14.5 ± 3.7 cm (mean ± SE), and 18.6 $m^2$ $ha^{-1}$, respectively, with balsam fir accounting for 88% of basal area. The groundcover consists mainly of mosses and *Oxalis montana*, with small lichen patches. The vegetation rests on Precambrian charnockitic gneiss covered by sandy till, classified as Spodosols (Haplorthods) (Soil survey staff, 1998) or Orthic Humo-Ferric Podzol (Canadian soil survey committee, 1992). The mean slope is 8%. Between 1999 and 2008, mean annual temperature and precipitation were 1.2 °C and 1355 mm, respectively. More details on site characteristics can be found in Duchesne and Houle (2008).

### 2.2. Dendrometric and climatic data

The microvariations in the stem diameters of three co-dominant balsam fir trees were measured at breast height (1.3 m above ground level) with automatic strain gauge dendrometers. Selected trees had well-developed crowns and a healthy trunk with no visible wounds. The dendrometers (DEX70, Dynamax Inc., Houston, TX; accuracy over 20 °C range = 0.05 mm) are made of two aluminum bars fixed to a flexible stainless steel band on which the strain gauge is attached (Link et al., 1998). As the stem diameter changes, differences in the relative tension experienced by the strain gauges are measured as a millivolt signal. Data were recorded every 30 min with a datalogger (CR10, Campbell Scientific, Logan, UT). Millivolt signals were converted to millimeter units after calibration. Calibration was performed on each dendrometer by altering the spacing of an internal micrometer and recording the millivolt signal following the procedure described in Link et al. (1998). Data were acquired continuously from mid June 2003 to October 2008.

In April 2009, 12 co-dominant balsam fir trees were sampled nearby the trees equipped with the dendrometers. Two increment cores were extracted from each tree at breast height (1.3 m above the highest root) from opposite sides of the bole (same geographic orientation as the instrumented trees). Cores were dried, mounted in wooden blocks and sanded for dendrochronological measurements. Ring widths of the last ten years (1999–2008) of all cores were cross-dated by visual examination of tree-ring sequence before measurement (Yamaguchi, 1991). Ring widths were measured to the nearest 0.01 mm with a WinDendro Image Analysis System for Tree-Ring Measurement (Regent Instruments Inc.).

Climate parameters were measured at a clearing site located approximately 600 m from the instrumented trees. Air temperature and relative humidity (HMP35CF, Campbell Scientific, Logan, UT) sensors were installed at a height of 3.3 m while a solar radiation sensor (LI190SB, Campbell Scientific, Logan, UT, light spectrum 400–700 nm) was installed at the top of a 14 m tower. Precipitation data was the average of values measured by two different pluviometers types: a tipping bucket rain gauge (TE-525, Texas Electronics, Dallas, TX) and a precipitation gauge (35-1558, Fisher and Porter, Albany, NY). All data were collected at 15 min intervals and hourly averages were recorded.

### 2.3. Data analysis

Within a given year, three distinct phases have been described in the seasonal pattern of stem diameter variation of many tree species in Canada (Belyea et al., 1951; Tardif et al., 2001; Turcotte et al., 2009). They consist of an initial period of swelling in early spring, followed by active cell division indicating the period of growth, and finally a third period, characterized by the cessation of growth, cell dehydration and preparation for winter. Growth initiation in the early spring may be readily confused with rehydration of internal tissues before the beginning of cambial growth (Kozlowski and Peterson, 1962; Winget and Kozlowski, 1964). It is however recognized that the majority of the annual growth coincides with the general upward trend found in the cumulative growth increments from early June through the end of July for many boreal species including balsam fir and black spruce (Tardif et al., 2001; Deslauriers et al., 2003a). From August to September, stem diameter generally reaches a plateau although small diurnal variation is