Effects of climate on the radial growth of *Thuja occidentalis* northern marginal populations in Québec

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Introduction

Current evidence indicate that boreal forest and tundra are exposed to warming. One of the expected results of projected climatic change on trees is a northward shift of biogeographic ranges. In boreal ecosystems, the effects of climate change are expected to be most visible at the species northern margin. Global warming should allow a relaxation of the cold related climatic constraints, as suggested by studies conducted at high latitude tree-lines. Housset et al. (submitted.) assessed the interannual and interdecadal climate variability response of the boreal gymnosperm eastern white cedar *Thuja occidentalis* L. (hereafter "cedar") over a latitudinal gradient encompassing its northern marginal, discontinuous and continuous distribution areas. This study analysed a network of annually-resolved tree growth increment multi-century data combined with meteorological data covering 1953 to 2010. Cedar is an evergreen long-lived and shade-tolerant species of the eastern side of North America. The following hypothesis was tested: growth variability of cedar is positively correlated with variations of temperature and growth increases over time in link to the recent climate warming. This increase would be expected to be the greatest in the northern marginal area.

Materials and methods

The study area is located in the western regions of Quebec. A latitudinal transect was established from 47.3ºN to 50ºN and divided into three zones based on cedar abundance: the continuous zone (CZ) where cedars are common, the discontinuous zone (DZ) that marks the northern edge of the continuous distribution and where cedars become less common in the forest matrix, and the marginal zone (MZ) where only a few isolated patches of cedars are found (Fig. 1a.). Sampling was concentrated on poorly drained lowland sites as it is the most representative edaphic conditions of the species northern margin in Québec.

In 2010, up to 30 dominant and co-dominant cedar trees were randomly sampled in 27 sites across the study area (Fig.1). Two cores per tree were collected at 1.3 m above ground, sanded and tree-ring widths were measured. Crossdating was verified visually and statistically with the software COFECHA. The ring-width measurement series were normalized and averaged for each biogeographic zone using power transformations and exponential detrending to eliminate noise caused by site- and biological-related effects. This procedure preserves the variance in low frequencies necessary for the study of long-term growth trajectories (Cook & Peters 1997). These low-frequency cedar Tree Growth Index (hereafter called TGI) chronologies were used for the study of low-frequency growth variations in the recent past. Each raw ring-width series was also detrended using 60-year splines with a 50% frequency response using the R package dplR (Bunn 2008) and a residual chronology was computed for each site using a biweight robust mean for the dendroclimatic analysis (Cook & Kairiūkštis 1990).

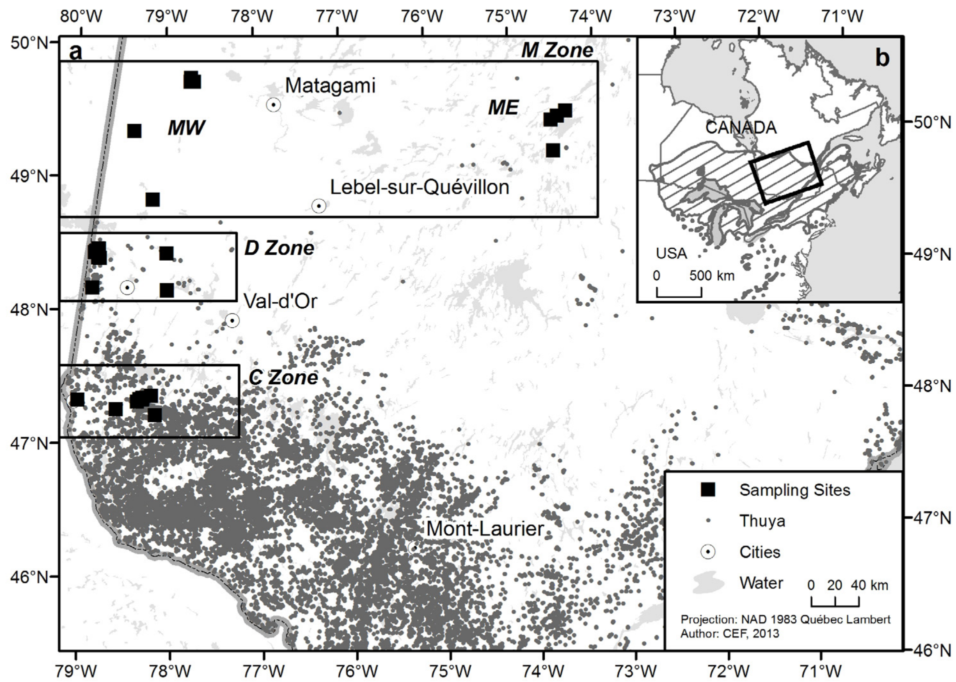

Figure 1: (a) Location of Thuja occidentalis sample sites (black squares). Background represents the known occurrences of Thuja occidentalis from the forest inventories of the province of Québec. Sampling was stratified between the continuous zone of distribution (C Zone), the discontinuous zone (D Zone) and the marginal zone (M Zone). (b) Location of the study area (black box) in the northern part of the species range (hatched area).

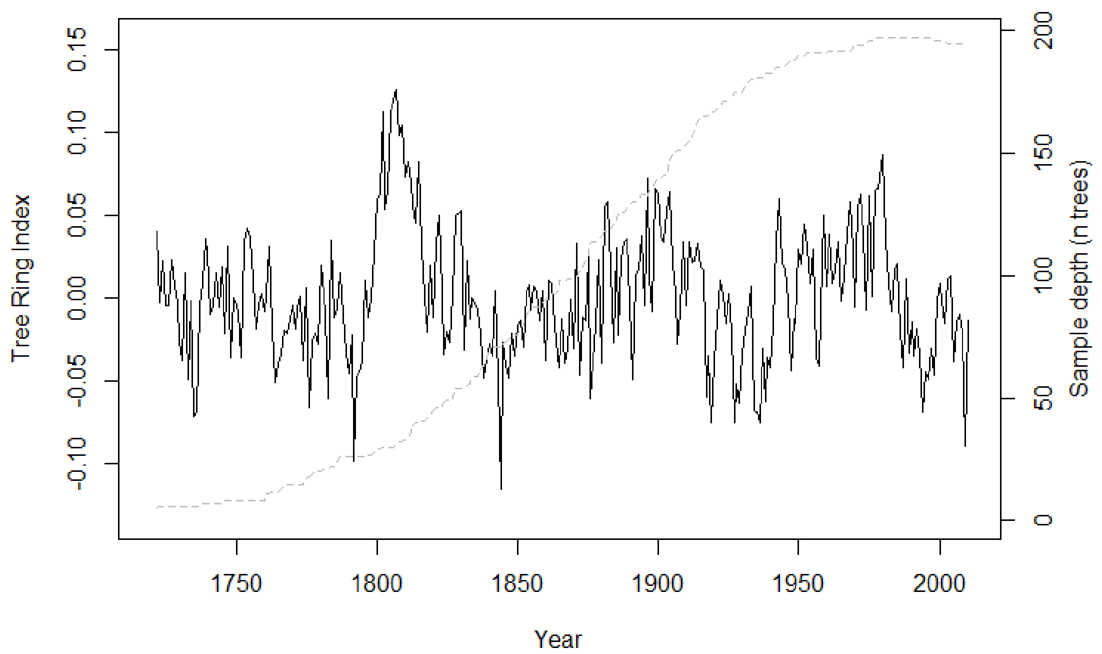

Figure 2: Low-frequency growth variations for Thuja occidentalis marginal populations. Tree growth index (TGI) chronology is compiled from the mean of all single tree detrended tree-ring width measurement series (black line). The gray dashed lines represent the sample depth, corresponding to the tree numbers.

Monthly mean temperatures and total monthly precipitation were interpolated for 1953–2010 at each sampling sites using the BioSIM software (Régnière & Bolstad 1994). Long-term trends in climatic series were linearly detrended using the period 1953-2010 to obtain unbiased data of interannual climatic variations. The relationship between climatic variability and residual chronologies of cedar was examined using bootstrapped correlation analyses over the period covered by observations. Analyses were conducted from May of the year preceding ring formation to October of the year current to ring formation using the R package bootRes (Zang & Biondi 2009).

Results

The recent warming did not result in a growth increase in the marginal zone (Fig. 2). On the contrary, a growth decline was observed with an onset starting ca. 1980. In more southern areas, the recent growth is not markedly different from past variations.

Interannual variations of cedar growth between 1953 and 2010 were positively correlated with spring temperature (March, April, mostly May). In contrast, growth was negatively correlated with warm summer (July and August) temperatures of the year preceding ring formation. A negative correlation was also observed for most sites, with June temperature of the year current to ring formation. While high temperatures are favourable to cedars at the beginning of the growing season, they become a limiting factor as the season progresses towards the end. Radial growth was positively correlated with precipitation in June of the year preceding ring formation, especially in the DZ. Radial growth was also positively correlated with precipitation in August of the current year in both the CZ and DZ but not in the MZ. Besides, excesses of precipitation during October of the year preceding ring formation had negative impacts on growth in the CZ. A negative effect of precipitation was also observed in the MZ during May of the current year.

Discussion

Contrary to the working hypothesis, Housset et al. (submitted) found that the warming has not caused a growth rise at cedar cold margins. Results suggest that the cold climate was not limiting growth at the northern edge of the cedar distribution. Surprisingly, a radial growth reduction was observed between 1980 and 2010. This slowing of cedar growth rates in the northern boreal forest during the last 30 years is consistent with reported evidences of productivity declines in these regions detected through remote sensing (Hicke et al., 2002; de Jong et al., 2012) or tree-ring analyses (Girardin et al. 2014). Drought stress may limit productivity despite the relatively wet environment in which cedar is growing at its northern margin.

Dendroclimatic analysis allowed to better identify the impact of drought stress on cedar growth over the gradient. Growth appeared to be positively influenced by May temperatures during the year of ring formation all over the gradient. However, summer temperatures have a negative consequence on radial growth, primarily indicated by the negative correlation with July and August temperatures of the year previous to ring formation. The drought stress constraint on radial growth is also suggested by a positive correlation with precipitation of August during the year of ring formation and June of the previous year. The negative effect of June temperature could be explained by the higher loss of carbohydrates due to maintenance respiration during warm episodes (Lavigne & Ryan 1997).

The negative effects of current May and previous October precipitation on radial growth is most likely linked to the soil hydrology. An increase in spring rain during the snow melting could cause a rise of the water table in swamps or a flooding event in lakes and rivers resulting in tree roots asphyxia. A wet soil in fall likely delays the soil warming up in the next spring, that could indirectly cause a growth delay. The paradoxal transition from spring water excess to summer drought is probably due to the shallow roots system developed by the cedars in hydric soils (Musselman et al. 1975). During summer's lowering of the water table, the upper layer of organic soils becomes dry and cedar shallow roots cannot supply water. Cedar growth is thus dependent on the precipitation seasonality and on local soil hydrology.

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