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Drought explains variation in the radial growth of white spruce in western Canada

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ABSTRACT

Many studies have already addressed the existence of unstable and nonlinear relationships between radial growth of white spruce (*Picea glauca*) and climate variables in boreal forests along the high latitudes (>60° N). However, along the mid-latitudes, the climate-growth relationship is still poorly understood. In this study, we used a network of ring-width chronologies from 40 white spruce sites along a wide latitudinal gradients from 52° N to 58° N in Alberta, Canada and attempted to understand the complicated response of tree growth to climatic variables and to identify the main limiting factor for the radial growth of white spruce. We combined the empirical linear statistics with the process-based Vaganov-Shashkin Lite (VS-Lite) model requiring only latitude, monthly mean temperature, and monthly total precipitation information together to better clarify growth-climate relationship. The linear statistical methods indicated that the previous summer temperature imposed a strong negative impact on the radial growth of white spruce while the precipitation and climate moisture index in prior and current summer both had significant positive effects on the radial growth. Similarly, the VS-Lite model showed that the radial growth of white spruce was limited by soil moisture. This suggests that temperature-induced drought is the main limiting factor for the radial growth of white spruce. Furthermore, climate-growth relationship varied along different elevations, latitudes, and growing degree days (GDD >5 °C). The radial growth of white spruce in northern stands was often more strongly limited by temperature-induced drought due to the higher temperature and lower precipitation. As the global climate change is in progress, we suggest that more large-scale and continuous investigations are needed to address the spatial variation in growth-climate relationship due to the temperature-induced drought.

1. Introduction

The global surface temperature increased approximately 0.85 °C from 1880 to 2012, and the period from 1983 to 2012 is thought to be the warmest 30-year period of the last 14 centuries in the Northern Hemisphere (IPCC, 2014). It is not well understood how these dramatic changes in climate will affect terrestrial biomes (Ma et al., 2012). The largest of these terrestrial biomes is the boreal forest, which is predominantly distributed across northern Eurasia and North America, and covers 11% of the earth's land surfaces (Dixon et al., 1994; Lindahl et al., 2007). Climate warming will not only influence the function and structure of these boreal forests but also may affect the frequency and severity of abiotic and biotic feedbacks of boreal forests, including outbreaks of forest insects, droughts and wild fires (Stocks et al., 1998; Volney and Fleming, 2000; Kasischke and Stocks, 2012; Price et al., 2013). Therefore, it is critical to understand the response of boreal tree species to climate warming for better predicting potential changes and monitoring in boreal forest ecosystems.

Tree rings provide a high-resolution proxy of climate, and have been successfully used by many studies to reconstruct past climatic change (Mann et al., 2002; Esper et al., 2002; Cook et al.,

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2004; D'Arrigo et al., 2006, 2008), and to better understand the relationship between tree growth and climate (Hughes et al., 2010; Speer, 2010; Fritts, 2001). Traditional statistical calibration methods assume a linear relationship between tree growth and climatic factors and it is constant through time (Jones et al., 2009; Tolwinski-Ward et al., 2011). As a result of climate warming over the last few decades, various studies (D'Arrigo et al., 2008; Esper and Frank, 2009; Zhang and Wilmking, 2010; Visser et al., 2010) have considered the existence of unstable and nonlinear relationships between tree growth and climate. In particular, it has been shown that white spruce (*Picea glauca* (Moench) Voss) has a complex nonlinear response to climate, at least in parts of Alaska and Yukon, Canada (Wilmking et al., 2004; D'Arrigo et al., 2004; Lloyd et al., 2013). For example, many studies have demonstrated a reduction in the sensitivity of the growth of white spruce to temperature in high altitude boreal forests, especially in Alaska and northern Canada (Jacoby and D'Arrigo, 1995; Lloyd and Fastie, 2002; Wilmking et al., 2004; Andreu-Hayles et al., 2011; Porter and Pisaric, 2011; Chavardès et al., 2013; Lloyd et al., 2013), which is referred to as the divergence problem (D'Arrigo et al., 2008). Except for the temporal change in the climate-growth relationship, the response of radial growth to climate variables also varies along latitudinal gradients in boreal forests (Mäkinen et al., 2002; Huang et al., 2010; Lloyd et al., 2011). Therefore, large spatial scale tree-ring study is needed to clearly address how radial growth responds to climatic factors.

The process-based Vaganov–Shashkin (VS) model that estimates tree-ring growth using environmental inputs has the ability to resolve the non-stationary and nonlinear feature of the climate-growth relationship (Vaganov et al., 2006, 2011; Zhang et al., 2011; Touchan et al., 2012). However, the application of the VS model is limited due to its complex structure and required parameter inputs. Tolwinski-Ward et al. (2011) proposed a simplified version of the VS model (VS-Lite), which only requires latitude, monthly temperature and precipitation as inputs. Recent studies have shown that the nonlinear VS-Lite model can capture the growth trajectories of tree-ring series for a variety of environmental conditions and species (Tolwinski-Ward et al., 2011; Breitenmoser et al., 2014). Although the nonlinear response of white spruce growth to climate has been investigated in several high-latitude boreal forests, the climate-growth relationship of white spruce in mid-latitude forests is still poorly understood.

In this study, we used a network of ring-width chronologies from 40 white spruce sites in the boreal forest along mid-latitudinal gradient from 52° N to 58° N in Alberta, Canada. The objectives of this study were to: (1) clarify the response of the radial growth of white spruce to climate variables by comparing the results of traditional empirical linear function analysis and growth estimates from the VS-Lite model; (2) investigate the potential spatial variability in the radial growth of white spruce along the latitudinal gradient. As the western Canadian boreal forest is sensitive to climate change (Peng et al., 2011), in which elevations, latitudes and site effects could lead to spatial variability in climate change (Gewehr et al., 2014), we hypothesized that impacts of drought on the radial growth of white spruce could also vary along latitudinal gradients.

2. Materials and methods

2.1. Study area

The study area is located within the mixedwood forests in Alberta, Canada, which covers 75% of the forested area in the province. The dominant species in these forests are white spruce, trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), paper birch (*Betula papyrifera* Marshall), and balsam fir (*Abies balsamea* (L.) Mill.) (Cumming et al., 2000; Stadt et al., 2007). In addition, Lodgepole pine (*Pinus contorta* Douglas ex Loudon) exists within these mixed forests. Forty sample sites were distributed throughout these regions (Fig. 1), which are under typically dry continental climate conditions. The monthly mean temperature and total precipitation from 1930 to 2010 were around 1 °C and 460 mm, respectively (Appendix S1). The main soil types were brunisols and orthic gray luvisols (Beckingham et al., 1996).

2.2. Climate data

The interpolated climate data during the period of 1930–2010 for all the 40 sites were generated using ANUSPLIN (version 4.3) incorporated thin plate-smoothing splines to develop continuous climate surfaces across space based on the limited observed data (Hutchinson, 2004). In this study, the climate variables used include monthly mean temperature (T), monthly total precipitation, and growing degree days (GDD > 5 °C). The climate moisture index (CMI) (Hogg, 1994, 1997) has been successfully applied to predict impacts of drought on aspen forests in western Canada (Hogg et al., 2005, 2008, 2013; Michaelian et al., 2011). Therefore, the CMI was also calculated to explore the potential effect of drought on the radial growth of white spruce.

2.3. Tree-ring data

We randomly sampled accessible white spruce dominated mixedwood stands where over 2/3 trees were white spruce, the stand age ranged from 25 to 100 years according to the Phase 3 inventory database (AESRD, 2012). An average of 10 trees were sampled from each site. Trees for tree-ring analysis were either cored or felled. A disk of each sampled tree was collected from stump height (0.3 m). In addition, two 5.1 mm increment cores were collected at 1.3 m height from each sampled tree.

In the laboratory, all tree-ring increment cores were dried and polished with successively finer grits of sandpaper. All tree ring samples were visually crossdated, then measured using a Velmex measuring system with 0.001 mm resolution. Visual cross-dating was verified using COFECHA (Holmes, 1983). Age- and size-related growth trends were removed by detrending raw tree-ring series using a spline with a 50% frequency response (Cook and Kairiukstis, 1990). Standardized tree-ring series often contain low-frequency variation, such as biological persistence. An autoregressive (AR) model was used to remove the low-frequency persistence and enhance the residual common signal. Residual chronologies were developed using a biweight robust mean to reduce the effect of outliers. The chronology was constructed using the dplR package (Bunn, 2008) of R (R Core Team, 2015). In total, 40 white spruce residual ring-width chronologies were constructed.

2.4. Climate-growth analysis

2.4.1. Traditional statistical analysis

The climate-growth relationship was assessed by comparing climate data to the residual chronologies both in a correlation analysis and with a linear mixed model. Temperature and precipitation from previous May to August of current growing season were tested. In the correlation analysis, climate variables were correlated with residual chronologies. Bootstrapping was used to test the significance of Pearson's correlation values and increase the reliability. Then the linear regression was used to explore the variation in the correlation coefficients along different elevations, latitudes, and growing degree days (GDD > 5 °C).