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Relevance of using whole-ring stable isotopes of black spruce trees in the perspective of climate reconstruction

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ABSTRACT

Studies in dendroisotope chemistry suggested that latewood cellulose contains better climatic records than whole-ring cellulose. However, this approach has never been tested on northeastern Canadian spruce trees. This study compares dendroisotopic series of cellulose from late and whole ring, and analyses their statistical relationships with hydro-climatic variables with the aim of selecting the best suited protocol for future hydro-climatic reconstruction in the downstream sector of Churchill River basin of Labrador, Canada. To this end, $\delta^{13}C$ and $\delta^{18}O$ series from latewood (LW) and whole ring (WR) α-cellulose of black spruce trees (*Picea mariana* [Mill.] B.S.P.) were produced for the 1940–2010 period. The results show strong correlations between LW and WR isotopic series suggesting that there are no important variation in the isotopic ratios during the growing year and that black spruce trees use photosynthates of the current growing season to form their earlywood. Moreover, LW and WR $\delta^{13}C$ and $\delta^{18}O$ show similar relationships with both maximum temperature (T_{max}) and Churchill River discharge. Correlations are higher when combining $\delta^{13}C$ and $\delta^{18}O$ for LW and WR. Overall, those correlations support the indirect relationship between tree-ring isotopic series and river discharge, as they are integrators of several climatic variables and derived parameters (T_{max}, relative humidity, evapotranspiration, etc.). The LW and WR isotopic series give similar statistical relationships with hydro-climatic variables, and the WR treatment is faster (separation easier compared to LW). Thus, for black spruce the use of combined isotopic series in WR can be favored over LW for hydro-climatic reconstruction in the study region.

1. Introduction

In boreal and subarctic regions, tree-ring physical characteristics such as ring width and density are commonly used as proxies for paleoclimatic research (e.g. Briffa, 2000; D'Arrigo et al., 2006; Hughes, 2002; Porter et al., 2013). Beside physical characteristics, tree-ring chemical attributes such as stable isotope ratios can be used for climate reconstruction (McCarroll and Loader, 2004). They have the advantage of being controlled by physiological mechanisms that are relatively well understood and less affected by biological and/or ecological factors compared to tree-ring physical characteristics (Farquhar et al., 1982; Gagen et al., 2004; Sternberg et al., 1986). For example, while aging affects long-term ring width patterns that have to be removed by statistical detrending techniques, it has no effect on stable isotope series (Leavitt, 2010; Young et al., 2011). Therefore, annual tree-ring $\delta^{13}C$ and $\delta^{18}O$ analyses have been widely used to reconstruct hydro-climatic variables and improve understanding climate variability of the past (e.g. temperature, precipitation, moisture, drought, water supply, sunshine) from few centuries to millennia (Bégin et al., 2015; Edwards et al., 2017; Esper et al., 2017; Gagen et al., 2007; Gennaretti et al., 2017; Kress et al., 2014; Loader et al., 2013; Naulier et al., 2015; Nicault et al., 2014; Rinne et al., 2013; Waterhouse et al., 2000; Young et al., 2015).

As the dendroisotopic approach has been increasingly used in diverse fields of investigation, researchers have discussed several technical aspects related to sample preparation that may affect the meaning and the validity of isotopic results. In the context of hydro-climatic reconstructions, it is crucial to identify ring characteristics that best represent the hydrologic conditions, one of the first concerns being to tackle the significance of isotopic variations in various wood components (cellulose, lignin, bulk wood). For example, bulk wood versus cellulose analyses have been carried out to verify which component provides the most coherent isotopic signal and the question is still being debated (Battipaglia et al., 2008; Bégin et al., 2015; Cullen and

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Grierson, 2006; Guerrieri et al., 2017; Leavitt, 2010; Loader et al., 2003; Szymczak et al., 2011; Tei et al., 2013; Weigt et al., 2015). Tei et al. (2013) find a significant relationship between $\delta^{13}C$ values of cellulose and bulk wood in larch, suggesting to use bulk wood for rapid production of $\delta^{13}C$ values. Those results are in accordance with previous observations of isotopic ratios analyzed in oak and beech that do not required cellulose extraction (Borella et al., 1999; Loader et al., 2003). On the other hand, Bégin et al. (2015) results clearly show that climatic conditions are better reflected in $\delta^{13}C$ cellulose than in bulk wood for black spruce (*Picea mariana* (Mill.) BSP) possibly due to varying resin quantities in conifer stems that may particularly affect $\delta^{13}C$ values in bulk wood.

Other authors have raised the question of which portion of the rings should be analyzed for climatic reconstruction, either earlywood (EW), latewood (LW) or whole ring (WR) (e.g. An et al., 2012; Fu et al., 2017; Jäggi et al., 2002; Kagawa et al., 2006; Kimak and Leuenberger, 2015; Kress et al., 2009; Porté and Loustau, 2001). Many studies emphasized the importance of investigating and comparing the climatic signal of isotopic values obtained for EW versus those obtained for LW. One of the reasons is that stored starches in LW of the previous growing season, which are converted into soluble sugars during cambial activation in spring, contribute to EW formation of the year-of-growth ring. This could induce a bias when analyzing WR instead of LW. Thus, the isotopic value obtained for WR would include part of the isotopic signal of LW of the previous year as well as climatic information from the current year (An et al., 2012; Fu et al., 2017; Hill et al., 1995; Kagawa et al., 2006; Livingston and Spittlehouse, 1996; Rahman et al., 2016; Robertson et al., 1997). However, EW from conifer species are recognized to be almost entirely dependent on year-of-growth photosynthates production (Dickmann and Kozlowski, 1970; Glerum, 1980). On this basis, other studies have found that isotopic signals of conifers (1) in EW are not related to stored carbon reserves, and (2) in EW and LW are similar (Barbour et al., 2002; Jäggi et al., 2002; Kress et al., 2009). Overall, different criteria such as study objectives, study regions, species and tree ages (i.e. capacity for nutrient storage from the previous year, sensitivity to climatic conditions), LW width and ability to distinguish EW from LW, etc., influenced the selection of the ring part to be investigated (Leavitt, 1993; Leavitt, 2010). Therefore, it becomes relevant to determine which part of black spruce ring best integrates hydro-climatic conditions in the chosen study region. In that perspective, the specific objectives of this study are to (1) compare $\delta^{13}C$ and $\delta^{18}O$ values of LW and WR of black spruce trees from east-central Labrador, and (2) determine which isotopic signal best correlates with hydro-climatic variables and offers the highest potential for hydro-climate reconstruction with tree species from this part of North America.

2. Materials and methods

2.1. Study area and site selection

The study site (Lab 32) is located in the east-central part of Labrador (53° 36′ 35.64″N; 60° 53′ 07.08″W), 50 km northwest of Happy Valley-Goose Bay (Fig. 1). The area is underlain by igneous and metamorphic rocks of the Grenville Province in the Precambrian Shield (Roberts et al., 2006). During the last glaciation, the Laurentide Ice Sheet covered most of Labrador and shaped the regional topography by leaving drumlins and rocky hills covered by a thin layer of ablation till (Dyke et al., 2002).

The site lies in the High Boreal Forest ecoregion, which is part of the boreal forest biome. In this region, the boreal vegetation is mostly composed of spruce-lichen forests on river terraces and upland, and mixed forests with balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marshall), trembling aspen (*Populus tremuloides* Michx.) and black spruce (*Picea Mariana* (Mill.) BSP) on the valley slopes (Government of Newfoundland Labrador, 2017).

The region has a continental climate characterized by long and severe winters with heavy snow accumulation. However, Lake Melville subzone has warmer summers and shorter winters (Roberts et al., 2006). The regional climatic data have been continuously recorded by the Goose Bay meteorological station since 1942. The mean annual temperature is 0.2 °C while monthly mean temperatures vary from −17 °C in January to 16 °C in July. The mean annual precipitation is 1070 mm, 47% of which is rainfall (Government of Canada, 2017a). The growth season lasts 130 days on average from 1942 to 2010 (Government of Canada, 2017b).

Ecological and edaphic conditions are relatively homogeneous through the study site. The latter is characterized by an old-growth uneven age closed black spruce stand growing on a well-drained podzolic soil with a gentle slope (< 10°) and developed on compact stony till (Walker, 2012). The understory vegetation is typically boreal with abundant dead wood material on the forest floor indicating that this site has escaped fire for a long period.

2.2. Tree sampling and isotopic analysis

A total of 32 healthy spruce trees aged from 50 to 290 years were sampled at the selected site during the summer of 2009 and fall of 2010. Considering that the lifespan of black spruce trees in this part of the Canadian boreal forest rarely exceed 300 years, this site has a high potential for paleoclimatic studies. From this sample population, a subset of five trees was selected for isotopic analyses. They are all dominant in the stand, in good health condition and without any notable growth injuries. We also made sure that their radial growth pattern was representative of the general trend observed in the entire population. Three of the trees were older than 200 years and devoted to the production of long dendroisotopic series that served for climate reconstruction (results not presented here). The two other trees, which were younger than 150 years, were used to test the reliability of analyzing cellulose of the final part of the growth ring, the latewood (LW), relative to the whole ring (WR). Younger trees were specifically selected with that purpose in mind, as they usually showed larger rings in the external part of the stems, facilitating an accurate subsampling of latewood.

Two cross-sections per tree were taken at a height of about one meter. One section was used for classic dendrochronological analysis and the other for dendroisotopic analyses. The section devoted to dendrochronology was perfectly sanded until wood cells were visible under a binocular and scanned using a high resolution Epson 10000XL scanner. Tree-ring sequences were dated visually along four opposite radii according to standard techniques (Stokes and Smiley, 1996) and ring widths were measured using the LignoVision™ software (0.001 mm; Rinntech). Dating and cross-dating accuracy was verified by a statistical analysis with the COFECHA program (Holmes, 1983). Sections devoted to isotopic analysis was subsampled to obtain four radial wood strips from four opposite directions. Then, each strip was separated into two equally thick parts to ensure that the analyses of LW and WR are as comparable as possible. In total, sixteen strips were taken from the two sections. The surfaces of the eight wood strips that served for LW analysis were previously cut with a core-microtome to make ring and cell boundaries perfectly visible (Gärtner and Nievergelt, 2010). The latewood of each ring was carefully separated from 1940 to 2010 inclusively (n = 71), to cover the hydro-climatic instrumental record in the study area, using an electronic rotary microtome HM340E (Thermo Scientific). The tree WR were separated for the same period with a razor blade under Leica binocular lens.

For the WR samples, separated wood material from the four strips and corresponding to the same years were pooled and homogenized in a grinding 40 mesh Wiley mill and then placed in tightly sealed fiber filter bags (Ankom F57) for subsequent chemical treatments. The LW samples from the four strips were pooled in the same way and placed directly in fiber filter bags because of the small amount of available material. The α-cellulose from all samples was then extracted as it