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Carbon and oxygen isotopes of lakeshore black spruce trees in northeastern Canada as proxies for climatic reconstruction

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ABSTRACT

In the boreal zone of northeastern Canada, paleoclimatic reconstructions of millennial length are rare and long isotopic climatic records are unavailable. However, millennial tree-ring series could be constructed within the region by cross-dating sub-fossil stems preserved in the littoral part of lakes. Thus, there is a need to evaluate the potential of using stable isotopes of lakeshore black spruce trees (*Picea mariana* [Mill] *B.S.P.*) as proxies for climatic reconstruction. We collected four living riparian black spruce trees and we investigated the inter- and intra-tree correlations for four trees, at two different sampling heights (1 and 4 m), for their carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes, as a test for potential long-term reconstruction. A significant correlation (Pearson coefficient) for the isotopic series was found for the two sampling heights ($r = 0.92$ for $\delta^{13}C$; 0.65 for $\delta^{18}O$), and between the four trees. We further assessed the climatic significance of the mean of the four trees. The strongest correlation of the $\delta^{13}C$ series was with the mean of June to August vapor pressure deficit (VPD; $r = 0.50$), and the $\delta^{18}O$ values with the June to August climatic index and June to July maximal temperature ($r = -0.61$ and 0.55, respectively). This study suggests that $\delta^{18}O$ series of riparian black spruce trees, and eventually their sub-fossil counterparts, can be used as proxies for reconstructing long climatic series in northeastern Canada.

1. Introduction

Natural archives are useful for reconstructing past climatic conditions and to compensate for the lack of direct long-term meteorological measurements. Trees present several advantages in this regard as they offer the possibility of absolute dating at annual or sub-annual resolution, and their ring width, latewood maximum density or stable isotopes can largely be modulated by climatic variations. Although the dendroisotopic approach requires a considerable analytical effort for each tree, tree-ring isotope series present the advantage that they generally do not need to be detrended, can retain climatic low-frequency variations, and require fewer trees compared to classical dendrological methods (Robertson et al., 1997; Young et al., 2011; Loader et al., 2013a).

Where tree growth is controlled by either a single or combined environmental parameters, oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) ratios contained in tree rings can be used as records of past climatic variability (Craig, 1954; Gray and Thompson, 1977). The relationship between isotopes and climatic parameters is most easily understood for trees growing in limiting conditions, such as altitudinal/latitudinal treelines where temperature influences tree growth, or at under water-stressed conditions (McCarroll and Loader, 2004). Centennial or millennial climatic reconstructions require long-lived trees (Bale et al., 2011). Such trees are not widely distributed and, unfortunately, are not found in the boreal forest of northeastern Canada. An alternative method to obtain extended chronologies consists of using historical wood (Haupt et al., 2011), or subfossil trees preserved in peats (Csank et al., 2011) or lakes (Boettger et al., 2003; Mayr et al., 2003; Gagen et al., 2012; Savard et al., 2012), and cross-dating stems to build continuous timeseries (Arseneault et al., 2013). The advantage of subfossil stems extracted from lakes is that they are easily collected compared to those buried in peats, and the original stand where they have grown is known, a piece of information which is generally not available for historical woods used in man-made constructions.

Tree-ring $\delta^{13}C$ ratios are commonly used for long climatic reconstruction but only a few studies have documented long $\delta^{18}O$ series (Treydte et al., 2006; Edwards et al., 2008; Richter et al., 2008; Wang et al., 2013). In addition, trying to extract climatic information from subfossil stems presents several potential problems. The use of subfossil material can introduce an isotopic bias due to wood degradation, and diagenesis can affect the original isotopic signal (Yapp, 2001; Van Bergen and Poole, 2002). When there is visual textural degradation, $\delta^{18}O$ values may be first altered, but not necessarily $\delta^{13}C$ ratios even for wood several centuries old (Savard et al., 2012). However, it has been recently demonstrated that a textural screening of samples allows

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for pre-selection of sub-fossil stems with preserved isotopic integrity (Savard et al., 2012). This observation implies that a textural pre-screening of sub-fossil samples from boreal lakes is required prior to isotopic analysis. Other crucial aspects should also be considered prior to conducting a long isotopic reconstruction study. Indeed, the subfossil stems may come from various heights along lakeshore trees; possibly creating isotopic artifacts on long chronologies. To assess this, we need to know if there is a vertical isotopic variability along the stem of lakeshore living trees. A study has shown that δ^{13}C ratios of living *Pinus sylvestris* were significantly correlated with the ratios of subfossil stems from lakes in northern Finnish Lapland (Gagen et al., 2012). A few studies have determined the vertical variability for δ^{13}C ratios to be ~0.5–1‰ over 3 m in pine trees (*Pinus edulis*) from New Mexico (Leavitt and Long, 1986), ~1‰ over 28 m in beech trees (*Fagus sylvatica*) from Germany (Schleser, 1992), ~1‰ over 12 m in pine trees (*Pinus pinaster*) from France and Morocco (Nguyen-Queyrens et al., 1998), and an increase of 1.5‰ over 12 m in spruce trees (*Picea mariana*) from Canada (Marion et al., 2001). No study, however, has assessed if the δ^{13}C or δ^{18}O series of different stem heights are corresponding, or if they show similar sensitivities to climatic variations.

Considering these issues, and the lack of long climatic reconstruction using isotopes in northeastern Canada, the purpose of this study is to determine if δ^{13}C and/or δ^{18}O series from different heights in lakeshore black spruce trees of the boreal forest are suitable proxies for reconstructing climate in this region.

Our main objectives are to: (1) assess if the δ^{13}C and δ^{18}O ratios for two different stem heights are coherent and respond significantly to climatic variations; and (2) statistically evaluate which of δ^{13}C or δ^{18}O values represent the best climatic indicator for riparian black spruce trees from boreal lakeshores and find the climatic parameter that can be used for reconstruction.

2. Material and methods

2.1. Study area

The study site (Fig. 1) is located at the center of the Québec–Labrador peninsula in northeastern Canada. In this area, the forest is mainly dominated by black spruce trees (*Picea mariana* [Mill] B.S.P.), commonly as pure open lichen woodlands on well-drained sites and spruce-moss woodlands in depressions. Balsam fir (*Abies balsamea* (L.) Mill.) and tamarack (*Larix laricina* (Du Roi) Koch) also grow in this region. The regional forest has a natural fire rotation period estimated at about 250 to 500 years (Boulanger et al., 2012).

The climate is continental and subarctic with short, mild summers and long, cold winters. According to Environment Canada data, mean monthly temperature from 1981 to 2010 vary from −22.9 °C in January to 13.3 °C in July. Total annual precipitation averages 825 mm with up to 46% falling in summer (June to September). The mean duration of the frost-free period is 75 days from late June to mid September. The lakes are generally frozen from mid-October to early June, and the growth of trees is roughly extending from middle or late June to the end of August or early September.

2.2. Lake and living trees selection

The selected lake L20 (54°56′31″ N; 71°24′10″ W; Fig. 1) is part of the large network of lakes sampled by our group (Arseneault et al., 2013). Criteria have been developed to identify lakes with best potential for millennial-long climatic reconstruction (well-preserved sub-fossil trees) and presenting large amounts of subfossil samples. Such lakes have an abrupt lake/forest transition, a riparian forest that is undisturbed over several centuries (as indicated by the presence of the fire-sensitive balsam fir), accumulated tree remains in the lower littoral zone away from ice erosion and waves, and stems covered with fine sediment once fallen into water (Arseneault et al., 2013). Lake L20 selected for the present study has an altitude of 483 m and covers an area of 35.1 ha. This lake is bordered by open spruce-moss with lichen woodlands, well-drained podzolic soil and an important and homogeneous slope.

Four living black spruce trees were selected for isotopic analyses. They are considered as specimens typical of those falling into the lake, which could become subfossil material. They have grown under the same hydrological and ecological conditions at a distance from the lake varying between 1 and 2 m, and on a slope of the same orientation (60–80°NE). All trees were systematically sampled at the stem heights

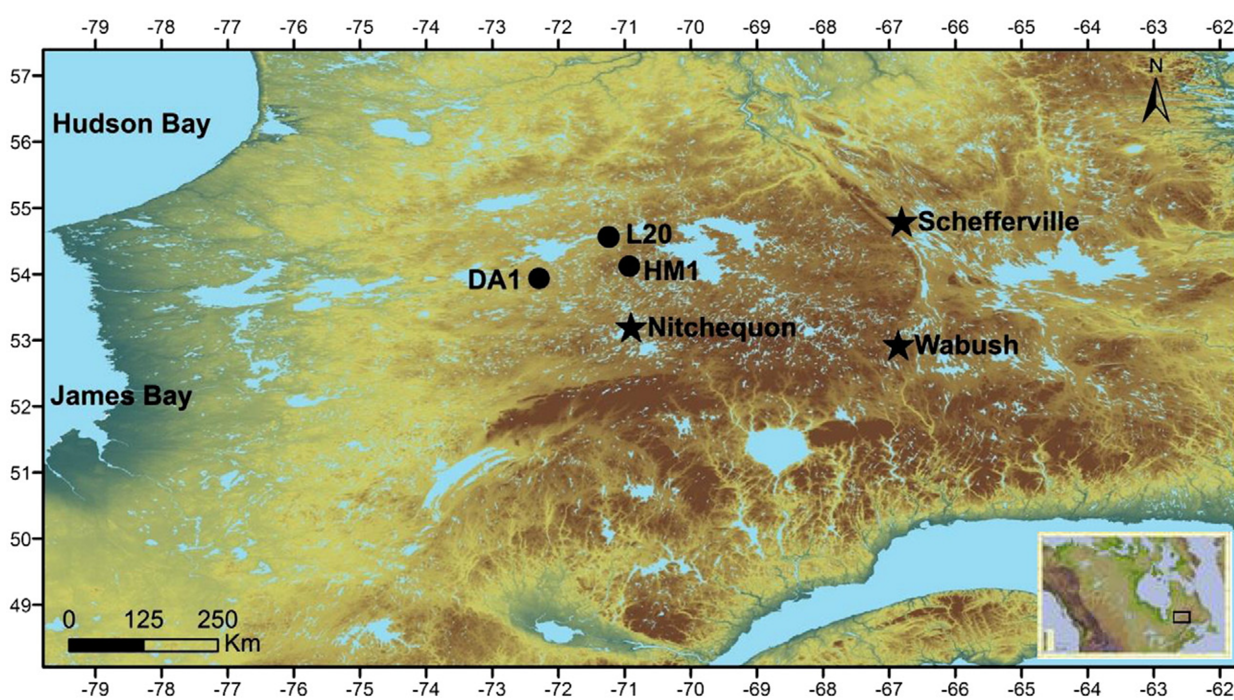

Fig. 1. Location of the study area in the northeastern Québec. Selected meteorological stations are represented with black stars and the lake L20 with a black circle.