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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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ or $\delta^{18}O$ 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 $\delta^{13}C$ and/or $\delta^{18}O$ 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 $\delta^{13}C$ and $\delta^{18}O$ ratios for two different stem heights are coherent and respond significantly to climatic variations; and (2) statistically evaluate which of $\delta^{13}C$ or $\delta^{18}O$ 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

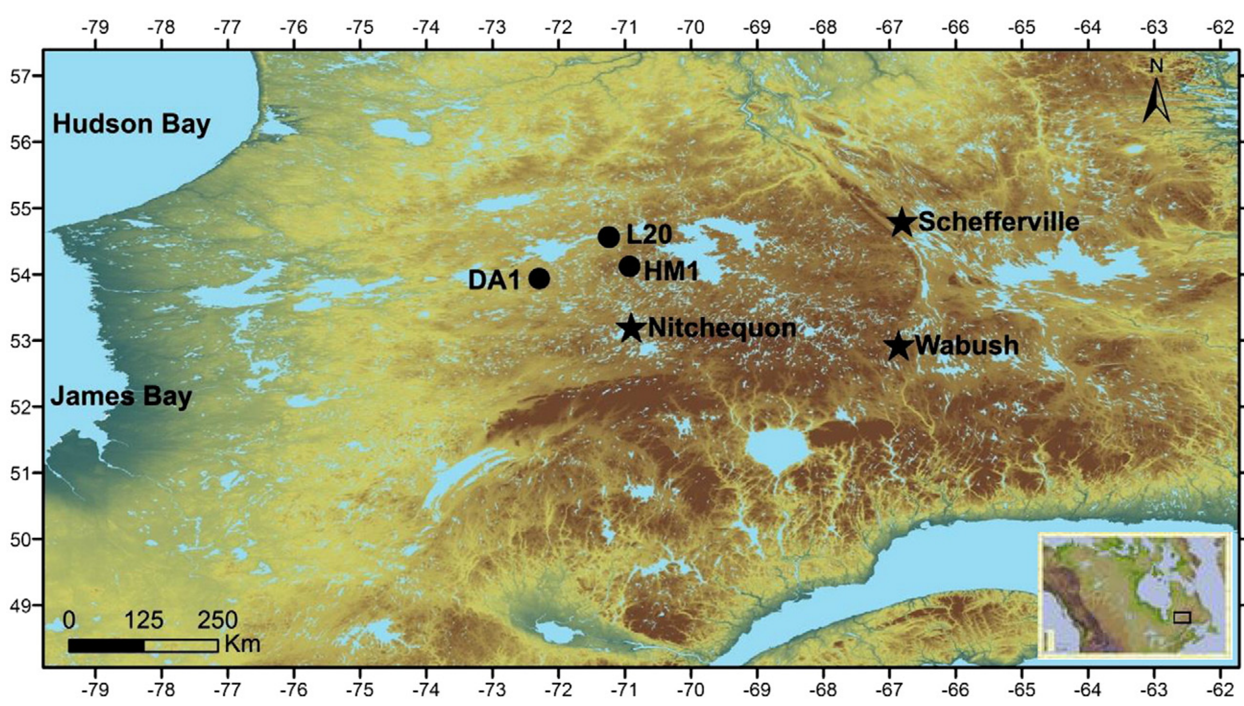


**Fig. 1.** Location of the study area in the northeastern Québec. Selected meteorological stations are represented with black stars and the lake L20 with a black circle.

of 1 and 4 m. For each sampling height, the length of the ring series varies according to the age of tree and the sampling height. Their series lengths varied between 124 and 104 rings for the 1 m level, and between 95 and 87, for the 4 m level. All series are included in the 1880–2010 time period.

### 2.3. Laboratory treatment and isotopic analyses

Stem samples of the four trees were cut along four perpendicular radii, and throughout the complete procedure the samples from 1 and 4 m were treated separately. Rings were mechanically separated at a one- (1940–2010) and two-year resolution (<1940) using razor blades. Corresponding tree rings from the different radii were combined into a single sample and α-cellulose was extracted according to a proven protocol (Green, 1963; Loader et al., 1997; Rinne et al., 2005) modified for small samples at Delta-lab laboratory of the Geological Survey of Canada. The final α-cellulose sub-samples were dried at 55 °C for 12 h. As a result, 813 subsamples of α-cellulose were obtained.

Subsamples were analyzed for $\delta^{18}O$ values using a pyrolysis-CF-isotope ratio mass spectrometer (IRMS; Delta plus XL) with a precision of 0.2‰ ($n = 252$), and for $\delta^{13}C$ using a Carlo Erba combustion elemental analyzer on-line with an IRMS (Prism-III), giving a precision of 0.2‰ ($n = 89$). Four standards (international and internal) were used to calibrate $\delta^{13}C$ and $\delta^{18}O$ analyses, and the measured values were referenced against the Vienna Standard Mean Ocean Water (VSMOW) value and Vienna Pee Dee Belemnite (VPDB) value, respectively.

Several studies demonstrate that $\delta^{13}C$ tree-ring records generally show a downward trend of 1–2‰ starting around 1800–1850 AD resulting from a $\delta^{13}C$ depletion in atmospheric $CO_2$ caused by fossil fuel emissions (McCarroll et al., 2009; Treydte et al., 2009). Thus, all $\delta^{13}C$ values reported here are mathematically corrected for industrial changes of $\delta^{13}C$ values in atmospheric $CO_2$ (Suess effect) (McCarroll and Loader, 2004). A supplementary correction called “PIN-correction” is necessary in order to take account of changes in plant response as a consequence of increasing atmospheric $CO_2$ concentrations. We have chosen to show $\delta^{13}C$ values with no correction, correction for Suess effect, and PIN correction proposed by McCarroll et al., 2009. The values were normalized for the four trees to remove metabolic discrepancies.

### 2.4. Climate variables and statistic treatments

For statistical treatment, the isotopic series of the four trees were averaged for each sampling height to compare the intra-tree isotopic series, and on the two sampling heights to evaluate the strength of the relationships between climatic parameters and isotopic series. The results are presented for the common period between the two sampling heights (1890–2010). The correspondence of the dendroisotopic series is calculated using the expressed population signal (EPS as in Wigley et al., 1984).

The meteorological data from three stations located near the study lake were used: Nitchequon (1943–1985), Wabush Lake (1961–2005) and Schefferville (1949–2005). Data from the stations were normalized on the overlap period (1961–1985) before they were averaged to produce a regional climate time series. Correlations were calculated between normalized isotopic ratios and several normalized climatic parameters: maximal (Tmax), minimal (Tmin), and mean (Tmean) temperature, precipitation, relative humidity and inflows to the Caniapiscau reservoir for the 1949–2005 periods.

In previous studies, several climatic index were developed to characterize dry periods, including soil water deficit index (SWDI as in Lévesque et al., 2013), self-calibrated Palmer drought severity index (sc-PDSI as in Wells et al., 2004), or the standardized precipitation evapotranspiration index (SPEI as in Vicente-Serrano et al., 2010). Considering that more than one climatic parameter can play a role in inducing isotopic responses in lakeshore trees, we used the sc-PDSI, the vapor pressure deficit which is the difference between the amount of moisture in the air and how much moisture they can hold when they are saturated (VPD, Ferrio and Voltas, 2005), and we developed a simple “climatic index” specific to our region. Another climatic index was used previously along with a dendrochronological series, but for normalized (rather than standardized) ring width values in Alaskan trees (Barber et al., 2000).

Our index is normalized with a z-score taking into account the standardized July to August precipitation minus standardized June to August maximal temperature (coming from our regional climate time series), as these are the most important months and climatic conditions for the studied series (Eq. (1)).

$$C.I. = \sum\left(Precipitation_{jja}/\sigma\right) - \mu\left(Tmax_{jj}/\sigma\right). \quad (1)$$

Hence, the climatic index characterizes different climatic regimes for the summer: if the climatic index is positive, the summer is wetter and/or colder than average, if it is negative; the summer is warmer and/or drier. The normalization with a z-score allows to us give the same weight to temperature and precipitation in the calculation of the index.

## 3. Results

### 3.1. Inter-tree comparisons

The carbon isotopic series show significant correlation between the four trees at 1 and 4 m heights ($R_{mean} = 0.64$ and 0.74, respectively with $P > 0.01$; Fig. 2A and B). The EPS is strong for the two sampling heights: 0.87 for 1 m and 0.92 for 4 m series. The 4 m level shows more inter-tree variability than the 1 m height (Fig. 2).

The oxygen isotopic series also show significant correlation at the 1 and 4 m heights ($R_{mean} = 0.51$ and 0.34, respectively, for $P > 0.01$; Fig. 2C and D). The EPS for oxygen isotope values are 0.81 for 1 m and 0.67 for 4 m.

The average $\delta^{13}C$ values are between −25.5‰ and −22.0‰ for both heights. The values are relatively stable between 1890 and 1925 (~−24.5‰; Fig. 3A), and increase by ~1.5‰ from 1926 to 1985. After the $\delta^{13}C$ series fluctuates. The two sampling heights show the same long-term trend and a good high-frequency correspondence, with an EPS obtained for the two heights and four trees of 0.94 (SE = 0.22).

The $\delta^{18}O$ series of the two sampling heights show long-term stability, and several variations in the shorter term, during the twentieth century. Relevant variations in the $\delta^{18}O$ series include increases and decreases between 1923 and 1990 (with maximum of 22.6‰ and minimum of 19.2‰; Fig. 3B). After an increase between 1990 and 2005, the last five years (2006–2010) show an abrupt decline of $\delta^{18}O$ values. Notably, only the first fifteen years (1890–1905) at the two heights show a relative $\delta^{18}O$ difference of 1‰. The complete range of $\delta^{18}O$ values for the two heights and four trees is within +19.2 and +22.6‰, with an EPS of 0.85 (SE = 0.35).

### 3.2. Statistical analysis between isotopic ratios and climatic parameters

The Pearson correlation was calculated for the isotopic values averaged for the two sampling heights against and the various normalized monthly meteorological parameters from 1949 to 2005. Correlations between the isotopic values for the 1 m and 4 m sampling heights with climatic parameters were similar (not shown), but the combined series gave the strongest correlations. These combined correlations were specifically tested against the climate variables established for the regional series (Section 2.4) for the period of June of the previous year (t − 1) to September (t) of the year of tree-ring formation from 1949 to 2005. The combination of several months for the growth period (summer) provides the best correlations (Table 1).

We also show $\delta^{13}C$ corrections (Fig. 4) with correlations between climatic parameters and $\delta^{13}C$ series with PIN correction and without

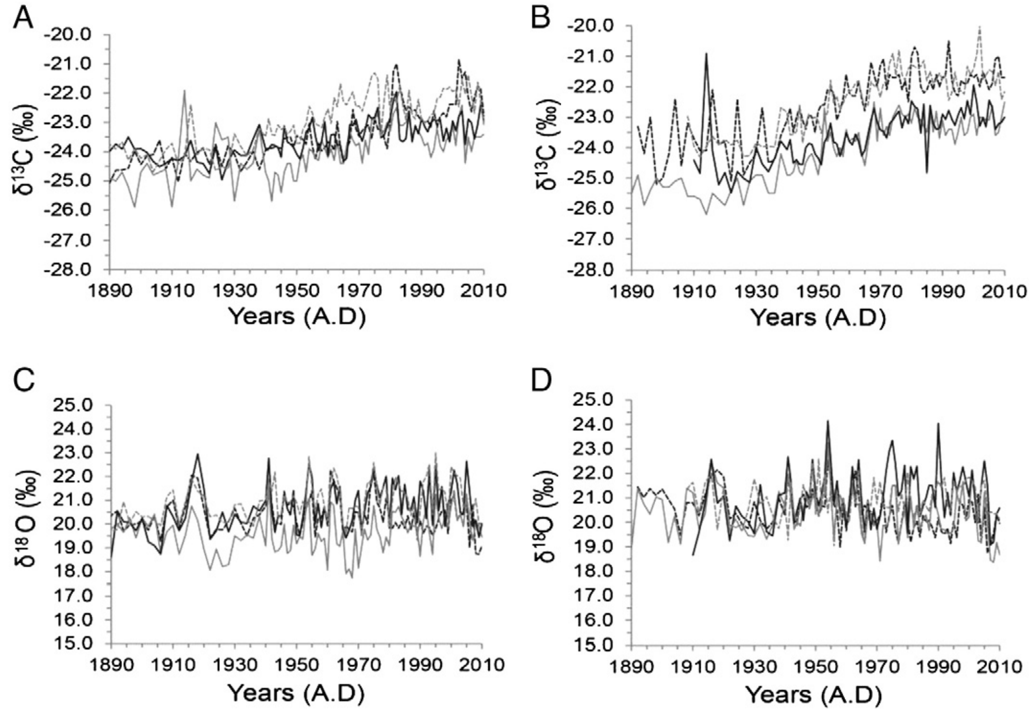

Fig. 2. Comparison between the four individual black spruce trees (dotted black, gray, black, and dotted gray lines) on two heights for $\delta^{13}C$ series with PIN correction (A: 1 m, B: 4 m) and $\delta^{18}O$ series (C: 1 m, D: 4 m).

(Table 1). The $\delta^{13}C$ series with PIN correction give the best correlations with climatic parameters even though it does not change significantly the trend of $\delta^{13}C$ series in the last decades.

The best climate versus $\delta^{13}C$ correlations are positive and are for June to August VPD of the year of tree-ring formation ($r = 0.50$). Maximal and mean temperature of summer months (July to August for mean and June to August for maximal temperature) are also significant ($r = 0.39$). There is no correlation between $\delta^{13}C$ series and precipitation for the summer months.

The average $\delta^{18}O$ values correlate with annual climatic parameters for the years of the tree-ring formation. Negative correlations are obtained with the total of July to August precipitation ($r = -0.41$), the mean of June to August climatic index ($r = -0.61$) and with the June to July VPD ($r = 0.45$). There is also a positive correlation with the mean of maximal June to July temperature ($r = 0.55$).

These correlations show that the local summer climate is the dominant control on the assimilation rate of oxygen and carbon isotopes in black spruce trees. The $\delta^{18}O$ series shows the strongest correlation with the summer climatic index, whereas the $\delta^{13}C$ values present the strongest correlation with the VPD. Overall, the $\delta^{18}O$ series shows a wider sensitivity to climate, as expressed by its numerous and higher, significant correlations with several climatic parameters at the investigated site.

## 4. Discussion

### 4.1. Inter-tree isotopic variations

The strong correlations obtained for the $\delta^{13}C$ and $\delta^{18}O$ series between the two different heights in the four living lakeshore trees indicate that the isotopic trends are expected to be coherent among pieces of fallen stems from different heights. Thus, we may infer that sampling sub-fossil remnants of black spruce trees from boreal lakes will generate reliable long series for climatic reconstruction, provided that the metabolic effects are removed by normalizing each series.

In this study, four trees permitted an average series that was representative of the selected site ($EPS \geq 0.85$). These results support the fact that the $\delta^{18}O$ and $\delta^{13}C$ series from only a few black spruce trees may be used to reconstruct climate of annual to multi-decadal frequencies.

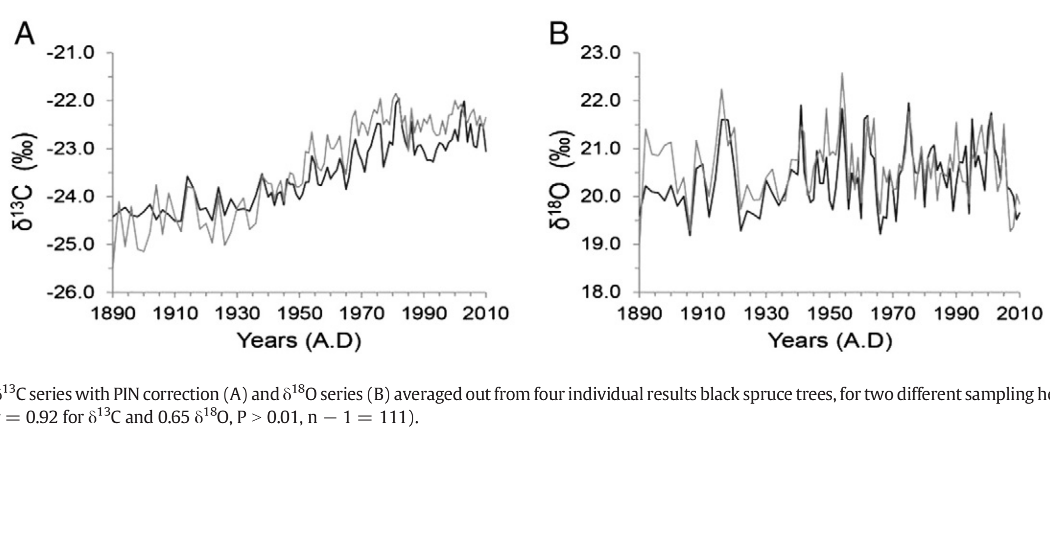

Fig. 3. Comparison of $\delta^{13}C$ series with PIN correction (A) and $\delta^{18}O$ series (B) averaged out from four individual results black spruce trees, for two different sampling heights: 1 m (black line) and 4 m (gray line) ($r = 0.92$ for $\delta^{13}C$ and 0.65 $\delta^{18}O$, $P > 0.01$, $n - 1 = 111$).

**Table 1**
Pearson correlations between $\delta^{13}C_{cor}$ (Suess effect corrected), $\delta^{13}C_{PIN}$ (PIN corrected) and $\delta^{18}O$ values (mean of series from two heights) and climatic parameters for the instrumented period (1949–2005). The significant correlations are in bold (99% confidence level).

| Climatic parameters | Months | $\delta^{13}C_{cor}$ | $\delta^{13}C_{PIN}$ | $\delta^{18}O$ |
|---|---|---|---|---|
| Tmax | June–August | 0.29 | **0.39** | **0.54** |
| | June–July | 0.26 | 0.29 | **0.55** |
| Tmean | July–August | **0.32** | **0.39** | **0.46** |
| Precipitation | July–August | −0.03 | 0.12 | **−0.41** |
| VPD | June–July | **0.38** | **0.40** | **0.45** |
| | June–August | **0.46**[a] | **0.50**[a] | **0.44** |
| Climatic index | June–August | −0.19 | −0.21 | **−0.61**[a] |
| Sc_PDSI | July–September | 0.04 | 0.01 | **−0.37** |

[a] Best correlations.

## 4.2. Responses of $\delta^{13}C$ and $\delta^{18}O$ series to climate

Depending on the location of the study site and the selected tree species, one or more climatic parameters (i.e. temperature, solar radiation, relative humidity, precipitation) can indirectly influence the isotopic variations. Despite different sources and fractionation processes driving $\delta^{13}C$ and $\delta^{18}O$ values, both correlate to summer climatic conditions. However, they did not respond to the climatic parameters in the same way.

The major controls on $\delta^{18}O$ ratios are the isotopic signature of source water (itself linked to the isotopic ratio of rain water), the evaporative enrichment in the leaf due to transpiration, and exchange with xylem water during cellulose synthesis (Anderson et al., 2002; Barbour et al., 2004; Barbour, 2007). The $\delta^{18}O$ values correlate significantly with the mean June–July maximal temperature, total July–August precipitation and the mean June–August climatic index. These results show that for the study site, $\delta^{18}O$ values depend on the climatic factors that influence stomatal opening like temperatures and moisture (McCarroll and Loader, 2004). The strong correlation with climatic index shows that $\delta^{18}O$ series are sensitive to changes of boreal climatic ambiances and indicates that low $\delta^{18}O$ values corresponds to cold and wet conditions. The weaker correlation with sc-PDSI shows that the climatic index is more appropriate to describe boreal climatic regimes. However, the negative correlation with sc-PDSI proves also that $\delta^{18}O$ values are sensitive to changes in drought conditions. Finally, the positive correlation with the daily VPD ($r = 0.45$) also confirms the influence of temperature and humidity on evapotranspiration, and thus, on the $^{18}O$ discrimination (Ferrio and Voltas, 2005).

Tree-ring $\delta^{13}C$ values depend on the diffusion of $CO_2$ from ambient air through the stomata and on the mechanisms operating during photosynthetic $CO_2$ fixation, both leading to an isotopic discrimination linked to the internal (*ci*) and external (*ca*) $CO_2$ pressure (Farquhar et al., 1982). Increasing $\delta^{13}C$ ratios commonly observed in the early rings of juvenile trees can be caused by recycling respired $CO_2$ from the air or changes in hydraulic conductivity as trees gain height (Gagen et al., 2007). We assume that this effect was removed from the $\delta^{13}C$ series by discarding the pre-1890 rings (i.e. by restricting the statistical analysis to the period common to the two heights).

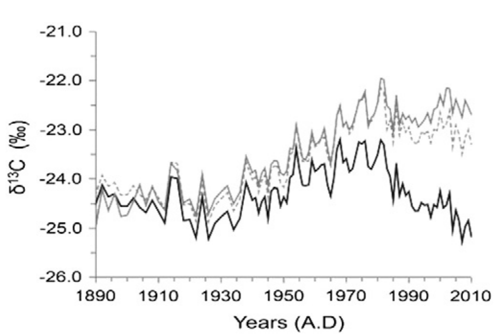


**Fig. 4.** Correction for changes in atmospheric $CO_2$. A comparison between the raw (black), Suess corrected (dashed gray), PIN corrected (gray). The PIN adjustment for climate reconstruction was applied to the individual series which were subsequently combined.

The average $\delta^{13}C$ series correlates positively with the mean June–August maximal temperature and VPD which is in agreement with our understanding of the mechanisms controlling carbon fractionation (Robertson et al., 1997; McCarroll and Pawellek, 2001; Young et al., 2010; Haupt et al., 2011; Loader et al., 2013a,b). With a higher summer VPD, the observed increase in $\delta^{13}C$ ratios between 1940 and 1980 likely reflects a decrease in *ci*, i.e. lower stomatal conductance or an increase in the photosynthetic rate and thus, leads to an increase in the $\delta^{13}C$ ratio (Scheidegger et al., 2000). The combination of temperature and moisture (VPD) seems to partly control the $\delta^{13}C$ ratios in black spruce trees from this region ($r = 0.50$). It is impossible to evaluate if other factors such as solar radiation influence the $\delta^{13}C$ values as this type of data is not available for the investigated region. However, the weaker correlation between $\delta^{13}C$ values and precipitation shows that $\delta^{13}C$ values are not sensitive to changes in precipitation which could be explained by the site location. Indeed, summer precipitations in the boreal zone are abundant and consequently, the absorption of soil water by black spruce trees is not limited. These conclusions have already been found in other studies, i.e. Porter et al., 2009; Saurer et al., 2004. All results confirm that $\delta^{13}C$ values are mostly controlled by temperature rather than by precipitation in north eastern Canada. In addition, the correlation between VPD and $\delta^{13}C$ values is much weaker than that obtained for the climatic index with $\delta^{18}O$ ratios. Note that the summer VPD and climatic index are parameters that both integrate maximum temperature and moisture (related to precipitation). This finding is in agreement with several studies which have found that $\delta^{18}O$ and $\delta^{13}C$ ratios are statistically linked to temperature and/or air moisture (Treydte et al., 2007; Loader et al., 2008; Porter et al., 2009; Daux et al., 2011).

Consequently, any climatic reconstruction using lakeshore trees in the studied area should be realized with the $\delta^{18}O$ series.

## 4.3. Implication for future climatic reconstruction

The northeastern Canadian boreal forest contains an enormous number of lakes. Some of these lakes are ideal for sub-fossil stem studies, providing series covering 1500 years or more (Arseneault et al., 2013), and well-preserved sub-fossil stems can retain their isotopic integrity (Savard et al., 2012). In this study of riparian black spruce trees, we have further developed the approach by indicating that lake material from various stem heights harbor similar trends in response to climatic variations. Significant correlations between $\delta^{18}O$ series and climatic index may allow depicting changes of climatic "ambiances" or reconstructing maximal temperature in millennial series. This last approach could allow extending the climatic record for northeastern Canada, and comparing summer temperature with other millennial such records as for other circum-Atlantic regions.

# 5. Conclusions

The results of the present study demonstrate that:

1- series from different heights along stems of riparian trees provide similar isotopic trends, inferring that using different stems of riparian black spruce trees and subfossil stem segments will not introduce artifacts in $\delta^{18}O$ and $\delta^{13}C$ series, and thus permit their use for climatic reconstruction;

2- average $\delta^{13}C$ ratios show good correlation with June to August VPD; but average $\delta^{18}O$ series presents stronger correlations with several climatic parameters, the strongest with the summer climatic index and Tmax;

3- combined $\delta^{18}O$ and $\delta^{13}C$ series of lake sub-fossil segments also show strong correlations with summer VDP and Tmax; and
4- although the best correlation is obtained for $\delta^{18}O$ series and the summer climate index, a practical approach dictates reconstructing summer Tmax as it would permit comparing our reconstruction with these of other regions.

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