Riparian influences on carbon isotopic composition of tree rings in the Slave River Delta, Northwest Territories, Canada

William Mark Buhay[a,*], Sandra Timsic[b], Danny Blair[a], Jennifer Reynolds[a], Suzanne Jarvis[c], Deanna Petrash[a], Marlin Rempel[b], Dan Bailey[a]

[a] Department of Geography, University of Winnipeg, Winnipeg, Manitoba, Canada
[b] Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, Canada
[c] Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario, Canada

Abstract

Tree-ring cores from two white spruce (*Picea glauca*) trees at each of three sites within the Slave River Delta, Northwest Territories, Canada, were separated, processed for α-cellulose and analyzed for their carbon isotope composition. The three carbon isotope ($\delta^{13}C_{cellulose}$) time series, collectively covering the time period from 1689 to 2003, were statistically correlated with average Historical Monthly Climate Grid temperature and precipitation for the period 1901–2000. The results suggest that the trees from all three sites show a distinct trend towards more enriched $\delta^{13}C_{cellulose}$ values with time, implying more stressful environmental conditions possibly related to the overall 20th Century drying of the Slave River Delta. Anthropogenic impacts of heavy logging and the construction of a large upstream dam may also be present in the $\delta^{13}C_{cellulose}$ time series. The main focus of the study relates to the different nature of the three riparian sites. The $\delta^{13}C_{cellulose}$ values of the trees from the two sites ≥ 50 m from the river at higher elevation suggest a relationship with moisture-deficit-stress (MDS) emanating from hydroclimate effects during the non-growing and growing seasons. The $\delta^{13}C_{cellulose}$ values from a site adjacent to the river at lower elevation, however, suggest that these same effects can manifest as moisture-excess-stress (MES) on the trees. The relationships between these two types of moisture stress and the $\delta^{13}C_{cellulose}$ values of the trees from the sites with obvious riparian differences are discussed in detail.
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Keywords: Stable isotopes; Hydrology; Climate; Drought; Flooding

1. Introduction

Isotope dendroclimatology is a widely applied sub-discipline of traditional dendrochronology. It does not use ring width or density to assess a tree's history, but instead uses the isotopic composition of tree-ring wood and its various components (McCarroll and Loader, 2004). Typically, cellulose and lignin extracted from whole tree-ring wood are used to evaluate the stable isotopic composition of carbon, oxygen, hydrogen and, most recently, nitrogen (Schleppi et al., 1999; McCarroll and Loader, 2004; Gagen et al., 2004, 2006, 2008-this volume).

Overall, the most widely utilized component is α-cellulose, which can be extracted from the wood in a relatively pure form (Ried, 1997; McCarroll and Loader, 2004; Gaudinski et al., 2005). Cellulose is composed of the elements carbon, hydrogen, and oxygen, making it ideal for isotopic analyses of these components.

The main objective of this study is to assess whether, under the same climatic influences, dissimilar carbon isotopic signatures developed in trees growing at sites distinctively different in their proximity (riparian zone setting) to the active channel of the Slave River (SR). The study assesses variations in stable carbon isotopic compositions derived from white spruce (*Picea glauca*) tree rings from three sites within the upper Slave River Delta region, Northwest Territories, Canada, in conjunction with monthly precipitation and temperature data.

Fig. 1. Map showing the location of the Slave River Delta (box) on the south coast of the Great Slave Lake, Northwest Territories (grey shading), Canada.

The anthropogenic effects on the tree-ring $\delta^{13}C_{cellulose}$ values are also discussed in the context of the different riparian zone settings.

2. Background

2.1. The Slave River Delta, Northwest Territories, Canada

The Slave River has a course 434 km in length and a watershed of approximately 630,000 km². Approximately 20 km northeast of the community of Fort Resolution, Northwest Territories (NWT) (N61° 10.284′, W113° 40.476′), the river drains into Great Slave Lake, where it splits into multiple channels to form the Slave River Delta (Prowse et al., 2002; Prowse et al., 2006) (Fig. 1). The complex channel network in the delta is shaped by regular and frequently intense flooding, and can be divided into three discrete sub-regions delineated by differences in geomorphological foundation and vegetative succession: the apex, the mid-delta, and the outer delta regions (English et al., 1997). The elevated apex sub-region, with infrequent flood occurrences, is dominated by older white spruce forests accompanied by extensive bryophyte communities (English et al., 1997; Petrash, 2006).

The Slave River Delta has a continental subarctic climate characterized by long, cold winters, short, cool summers and relatively low precipitation amounts. The mean annual temperature is approximately −2 °C, while the mean winter and summer temperatures are −17.5 °C and 13 °C, respectively. The total annual precipitation is commonly in the range of 300–400 mm, a third of which occurs as snow (Prowse et al., 2002). The length of the mean annual growing season, which usually starts in May and ends in September (average monthly temperature >0 °C for the period 1901–2000; McKenney et al., 2006), varies between 120 and 160 days. About 50% of the precipitation falls during the growing season. July, August and September are the wettest, warmest months. The mean annual water flow rate for the Slave River is approximately 3400 m³/s (recorded in the outer delta region of the Slave River Delta) and the highest water flow rates usually occur in June and July (Prowse et al., 2002).

2.2. Carbon isotopes in tree rings

The carbon incorporated into tree rings enters the tree through leaf stomata as CO_2 and is subsequently utilized during carboxylation. A mass difference between the two main carbon isotopes (carbon-12, ^{12}C; and carbon-13, ^{13}C) results in discrimination (fractionation) between them during these processes. Discrimination against $^{13}CO_2$ molecules during stomatal diffusion and carboxylation results in tree-ring carbon isotopic compositions that are distinctly depleted in ^{13}C relative to the ambient air. The magnitude of the ^{13}C discrimination in trees is a direct function of the ratio of intracellular concentration of CO_2 in the leaf to the concentration of CO_2 in the
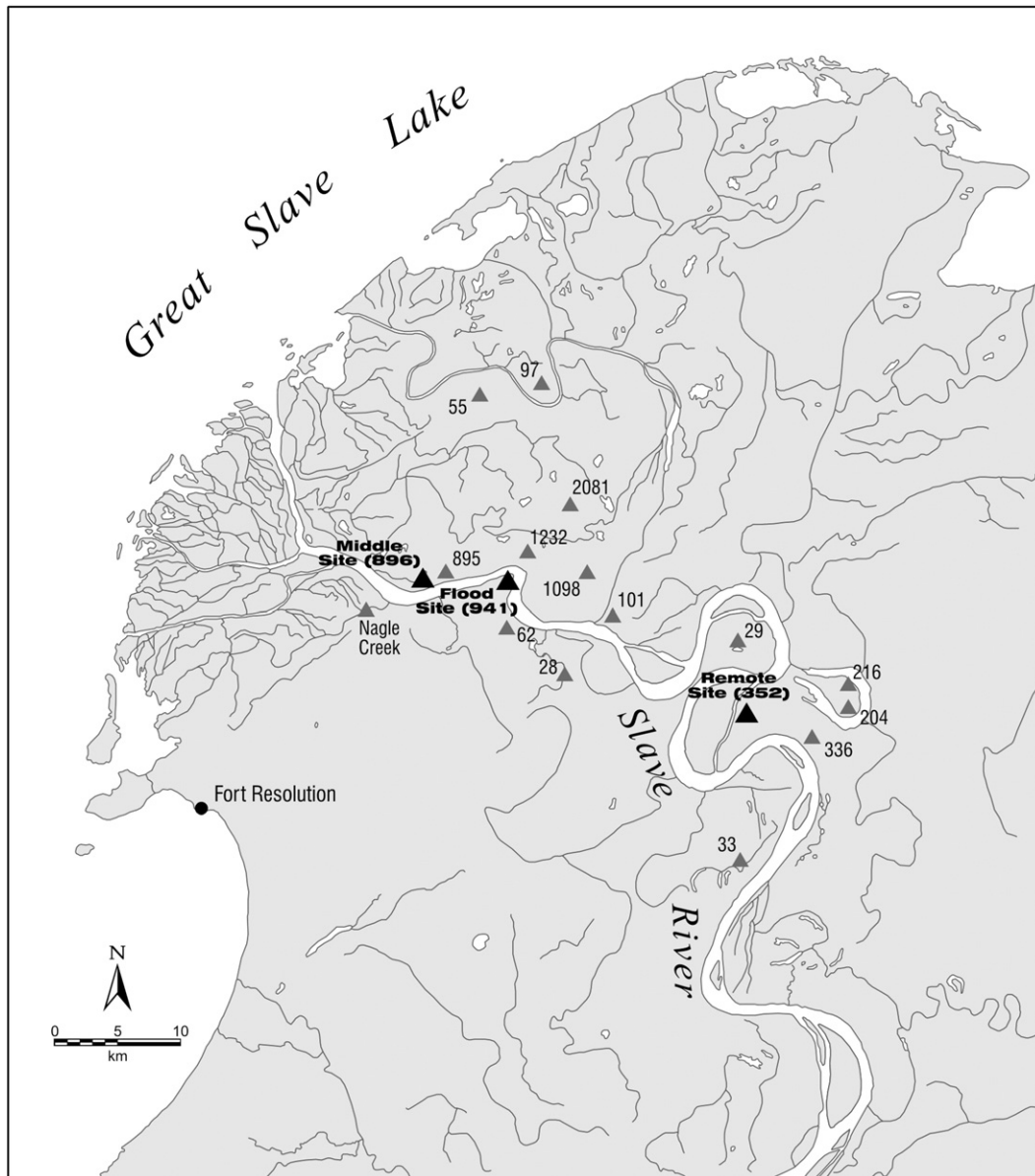
Fig. 2. The 18 Slave River Delta sites where white spruce (*Picea glauca*) trees were sampled. Sites 352 (remote), 896 (middle) and 941 (flood) are highlighted.

ambient atmosphere (Farquhar et al., 1982). Variations in stomatal conductance and photosynthetic rates have direct links to environmental parameters such as temperature, vapour pressure and precipitation (Robertson et al., 1997a,b; Anderson et al., 1998, Hemming et al., 1998; Jedrysek et al., 1998; Saurer et al., 1998; Schleser et al., 1999; Edwards et al., 2000; McCarroll and Pawellek, 2001; Treydte et al., 2001; Leavitt, 2002). In this study it is expected that temporal variations in moisture and temperature-related stresses imposed on the trees will emerge as variations in the carbon isotope time series from each Slave River Delta site. As indicated by the previous studies listed above, these carbon isotope variations primarily relate to plant responses to environmental changes. To avoid desiccation during periods of reduced water availability, plants decrease their transpiration rates by closing a proportion of their leaf stomata. For trees and other plants, this is usually in response to

inadequate precipitation replenishment of their substrate and/or elevated evapotranspiration rates related to higher growing season temperatures. With a greater proportion of its stomata closed, a plant has a reduced ability to replenish internal leaf CO_2 with atmospheric CO_2 and forces the plant to use ^{13}C-enriched CO_2 to maintain adequate photosynthetic rates. Therefore, enriched tree-ring $\delta^{13}C_{cellulose}$ values usually relate to some environmental moisture stress, while depleted values are usually indicative of non-stressful growing conditions (Ehleringer et al., 1993; Saurer et al., 1995). Recent evidence has revealed that increased levels of precipitation can also result in reduced stomatal conductance and/or increased assimilation rates in trees, resulting in relative carbon isotope enrichment (Ewe and Sternberg, 2002, 2003). Anderson et al. (2005) found a positive correlation between precipitation amounts and carbon isotope values in the rings of trees from wetland sites, which
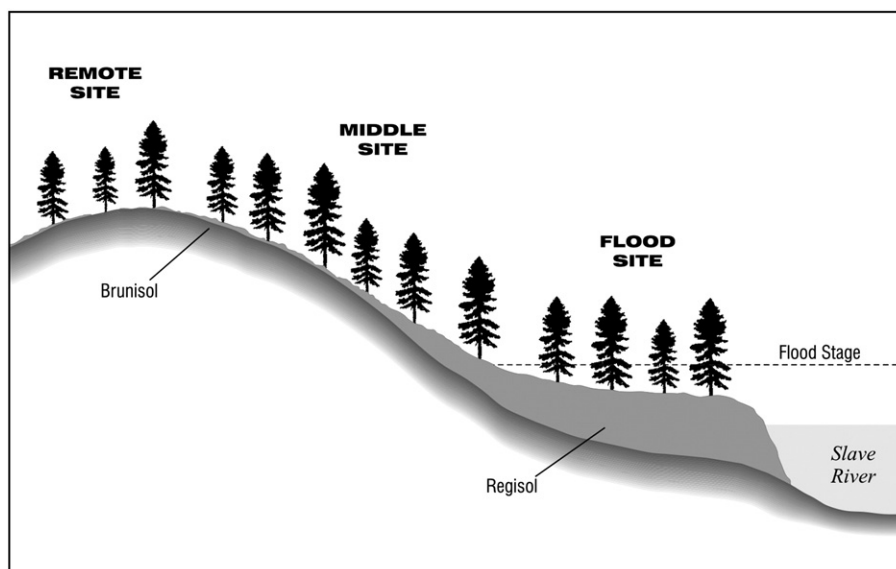
Fig. 3. A schematic diagram that shows the remote, middle and flood site relationships with the Slave River (not to scale). The horizontal dashed line indicates that the flood site is influenced by frequent Slave River flooding events while the remote and middle sites are not. Evidence of frequent inundation at the flood site is bolstered by the presence of a Regisol with multiple silt laminations that are not present in the juvenile forest Brunisols underlying the remote and middle sites.

they attributed to water stress (Anderson et al., 2005). This study suggests that excess soil moisture stress can also result in ^{13}C-enriched $\delta^{13}C_{cellulose}$ values in tree rings.

3. Methods

3.1. Sampling and rationale

The field component of this study was carried out during July 2003, 2004 and 2005 (Jarvis, 2004; Reynolds, 2005; Timsic, 2007). At 18 sites within the Slave River Delta apex sub-region, live and dead trees were sampled from white spruce trees within a 100 m^2 area (Fig. 2). Two increment borer cores were removed from 15 to 20 live trees at each site; cores were extracted at "breast height" perpendicular to each other using a 5.1 mm diameter 16″ Haglof® increment borer. Tree-ring cross-sections from dead or fallen trees were taken using a chainsaw. The intention was to obtain a mix of living and dead tree-ring chronologies that would facilitate the use of cross-dating to produce the longest possible chronologies.

At three of the 18 Slave River Delta sites (352, 896, and 941) (Fig. 2) two white spruce trees were selected for isotope analysis (two cores from each tree). The site selections were primarily based on the chronological extent of the records available from the trees, in addition to their proximity to the Slave River and elevation from the main channel. Differences in river proximity and site elevation were factored into the selection process to take advantage of potential differences in isotope climate and hydrology signals (Fig. 3). Clear-cut logging within 50 to 100 m of the active channel of the Slave River coupled with very low elevation gradients at the individual white spruce sites (Fig. 2) necessitated the investigation of isotope effects related to tree river proximity and elevation from multiple, not individual, sites.

At a distance of 200 m from the Slave River and an elevation of 160 m above sea level (masl), site 352 (N61° 16.110′; W113° 31.091′) was deemed to be remotely located with respect to Slave River flooding events, and thus more apt to provide true climate-related isotope signals (from this point onward this site is referred to as the remote site). An underlying juvenile forest Brunisol soil type (with no river silt lamellae) at the remote site is evidence of little exposure to flooding (Petrash, 2006). Site 896 (N61° 15.754′, W113° 24.343′) is closer to the Slave River (50 m) than the remote site, is at the same elevation (160 masl) and is also underlain by a silt free Brunisol. Site 896 (from this point onward referred to as the middle site) was also selected as a site likely to be relatively unaffected by Slave River flooding. Site 941 (N61° 12.051, W113° 11.534) is directly adjacent to the Slave River and at 156 masl is only a few meters above water level; it was selected because of its exposure to river flooding. Site 941 (from this point onward referred to as the flood site) is underlain by an undeveloped Regisol with multiple silt lamellae, suggesting regular occurrences of river alluvium deposition (Petrash, 2006). It was hypothesized that relatively frequent flooding would produce trees at this site with isotope-climate signals that differ from those recorded in the white spruce trees at the remote and middle sites.

3.2. α-cellulose and carbon isotopes

The purification of α-cellulose from wood required three main steps: a solvent extraction step to remove lipids, a bleaching step to remove lignins and an alkaline hydrolysis step to remove hemicelluloses and humic substances (Green, 1963; Loader et al., 1997). Carbon isotopic analyses of the purified and dried α-cellulose samples were accomplished by continuous flow ion ratio mass spectrometry (CF-IRMS) using a GV-Instruments® IsoPrime attached to a peripheral temperature
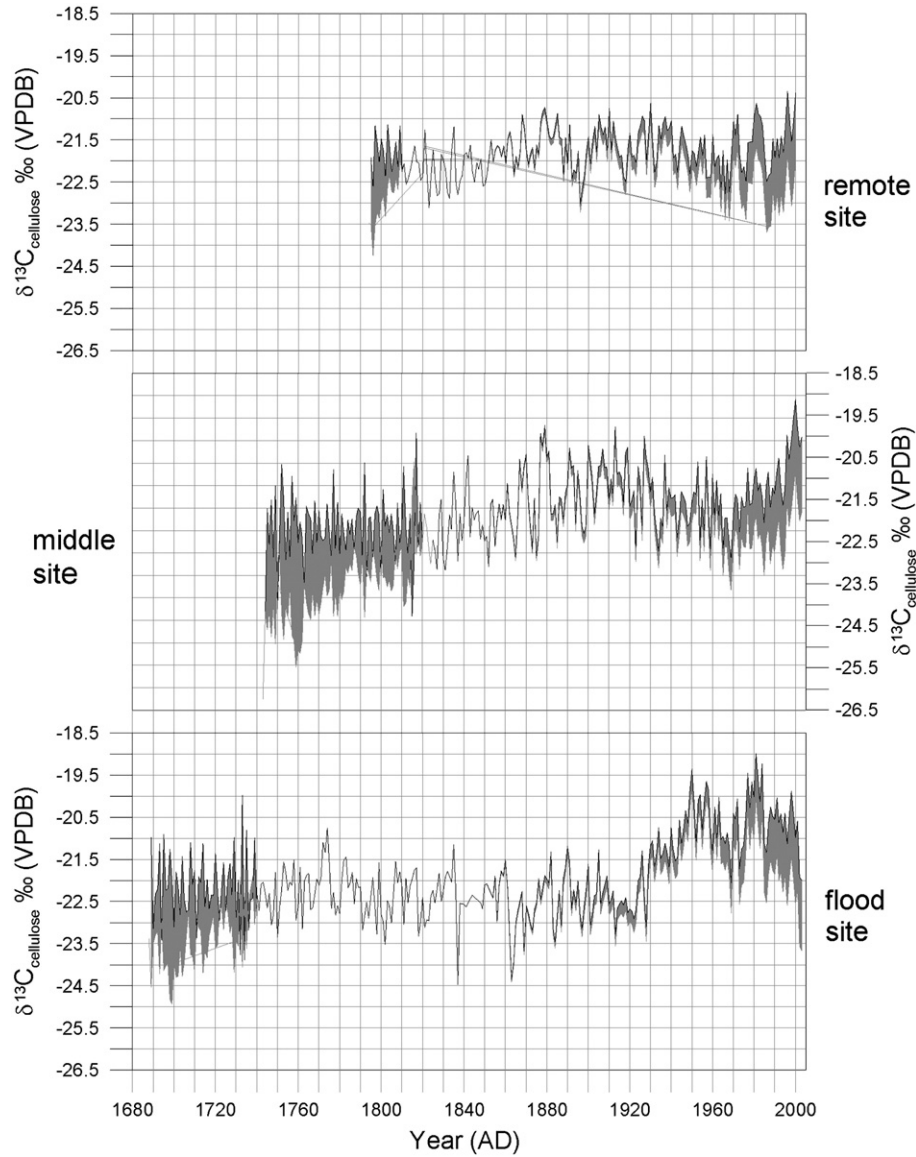
Fig. 4. The $\delta^{13}C_{cellulose}$ series for the remote, middle and flood sites. The upper black lines are the corrected values, adjusted for the juvenile (early in the series) and Suess (later in the series) effects. The uncorrected values are at the bottom of the shaded areas.

controlled EuroVector® elemental analyzer (EA) (University of Winnipeg Isotope Laboratory). Microgram samples of prepared α-cellulose were loaded into tin capsules and placed in the EA auto-sampler along with internally calibrated α-cellulose standards (Sigma α-cellulose: $\delta^{13}C = -23.5$‰ VPDB (see below); Casein: $\delta^{13}C = -26.98$‰ VPDB). A sample-to-standard ratio of 3:1 was employed. Carbon isotope results are expressed using a standard delta (δ.) notation in units of *per mil* (‰). The delta values of carbon ($\delta^{13}C_{cellulose}$) represent deviations from a standard, such that $\delta_{sample} = [(R_{sample}/R_{standard}) - 1]*10^3$, where R is the $^{13}C/^{12}C$ ratio in the sample and the standards (Sigma and Casein) calibrated to Vienna Pee Dee Belemnite (VPDB). Accuracy was maximized by calibration of laboratory standards (Sigma and Casein) and the reproducibility of natural samples. The $\delta^{13}C_{cellulose}$ values have analytical uncertainties of ±0.12‰.

3.3. Statistical analysis

Annual (combined early and latewood) tree-ring carbon isotope chronologies from six trees were developed. Two cores were taken from each tree; each of the three sites in the Slave River Delta is represented by two trees.

The carbon isotope data from the two cores taken from each tree were averaged to ensure that isotopic variations associated with tree physiology and laboratory procedures were minimized. In the end, carbon isotope time series were developed for the years 1796–2000 (remote site, tree 19), 1794–2002 (remote site, tree 23), 1743–1995 (middle site, tree 3), 1757–2003 (middle site, tree 4), 1732–2001 (flood site, tree 1), and 1688–2003 (flood site, tree 2). The resulting chronologies for each Slave River Delta site are 1794–2002, 1743–2003, and 1688–2003, for the remote, middle and flood sites, respectively.

Accounting and correcting for the juvenile and Suess effects in each of the six trees used in this study required data de-trending (McCarroll and Loader, 2004). The juvenile effect refers to depletion of carbon isotope values in the earliest years (rings) of a tree's growth that may be the result of the young tree's exposure to ^{13}C-depleted CO_2 respired from the soil of the forest floor (Dudziak and Halas, 1996). The Suess effect refers to the tree's incorporation of an atmospheric carbon isotope signal related to the input of ^{13}C-depleted CO_2 from anthropogenic fossil fuel emissions since the onset of the industrial revolution (ca. ~ 1850). The carbon isotope data was de-trended using a first difference filter and then direct comparison with the original, non-de-trended carbon isotope data. The observed intersection of the de-trended and non-de-trended carbon isotope data for each tree was interpreted as the termination of the juvenile effect for the tree (Gagen et al., 2006). To account for the Suess effect between 1850 and 1961, the progressive depletion in atmospheric δ^{13}C values during this period is accounted for by progressively adding 0.0044‰ per annum, and tree-ring series after 1961 are corrected by adding 0.0281‰ per annum, the latter to account for the escalation of anthropogenic CO_2 inputs into the atmosphere (Saurer et al., 1997). The de-trended data was then used in place of the original, juvenile- and Suess-affected carbon isotope series (Fig. 4).

For each of the three sites, the Pearson correlation (r) between the carbon isotope data series of the paired trees was calculated to assess the degree of correspondence in the isotopic series within trees exposed to similar environmental factors. The r-values for the two trees at the remote, middle and flood sites are 0.80, 0.86, and 0.74 ($p=0.001$ for all), respectively, resulting in calculated expressed population signal (EPS) values equal to and greater than 0.85 (EPS for site 352=0.89; EPS for site 896=0.92; EPS for site 941=0.85), suggesting that the δ^{13}C$_{cellulose}$ values for each tree are representative of the mean site environmental conditions (Wigley et al., 1984; McCarroll and Loader, 2004; Gagen et al., 2006). Between-site correlations were also assessed, using site-averaged time series. The r-values for the averaged series (2 trees from each site) are 0.59 (remote versus middle), 0.31 (remote versus flood) and 0.29 (middle versus flood) ($p=0.001$ for all); the corresponding EPS values of 0.74, 0.48 and 0.45 are each below the critical threshold of 0.85. Therefore, hydroclimatic influences on the δ^{13}C$_{cellulose}$ values from each site will be assessed individually rather than collectively for the Slave River Delta.

Since the Slave River Delta is situated in a remote part of northwestern Canada, instrumental climate data for the region is very limited. Therefore, the Slave River Delta δ^{13}C$_{cellulose}$ values were correlated with nearest-point interpolated temperature and precipitation data from the 1901–2000 10 km resolution Historical Monthly Climate Grid (HMCG) produced by McKenney et al. (2006). Annual average temperature and precipitation amounts from the HMCG were compared to average annual temperature and precipitation amounts from the Fort Resolution weather station 20 km southwest of the Slave River Delta, and it was found that there is a good correlation between Fort Resolution's annual precipitation totals (42 years)

Table 1
Shown are the Pearson correlations (r) with Historical Monthly Climate Grid model monthly temperature and precipitation amounts for the Slave River Delta and remote, middle and flood site δ^{13}C$_{cellulose}$ values

Period of influence	Correlation	Significance	Season of influence
	r	p	
Remote site precipitation			
y-1 Oct.–Nov.	−0.25	<0.01	Non-growing
y-1 5-year Oct.–Nov.	−0.35	<0.01	Non-growing
Dec., Jan., Feb.	−0.23	0.01	Non-growing
Dec., Jan., Feb. 5-year	−0.26	0.01	Non-growing
Apr.–May	−0.23	0.01	Early-growing
Apr.–May 5-year	−0.24	0.01	Early-growing
Apr.–May 10-year	0.53	<0.01	Early-growing
Remote site temperature			
Jun. Jul. 3-year	0.27	<0.01	Growing
Aug.	−0.43	<0.01	Late-growing
Sept.	−0.23	0.01	Late-growing
Middle site precipitation			
Nov.	−0.33	<0.01	Non-growing
Nov. 10-year	−0.81	<0.01	Non-growing
Jun.	0.23	0.01	Growing
Jun. 10-year	0.62	0.01	Growing
Middle site temperature			
Oct.	−0.13	0.1	Non-growing
Oct. 10-year	−0.57	<0.01	Non-growing
Flood site precipitation			
Oct.–Nov.	0.37	<0.01	Non-growing
Dec., Jan., Feb.	0.25	0.01	Non-growing
Oct. 5-year	0.71	<0.01	Non-growing
Oct. 10-year	0.82	<0.01	Non-growing
Nov. 5-year	0.59	<0.01	Non-growing
Nov. 10-year	0.69	<0.01	Non-growing
Mar., Apr., May	−0.21	<0.05	Start-growing
Jun., Jul., Aug.	−0.21	<0.05	Growing
Flood site temperature			
Oct.–Nov.	0.34	<0.01	Non-growing
Dec., Jan., Feb.	0.26	<0.01	Non-growing
Feb.–Mar.	0.29	<0.01	Non-growing
Aug.–Sept.	0.31	<0.01	Late-growing

Correlations are for the current non-growing (the period immediately prior to the growing season) and growing seasons unless otherwise portrayed. Previous year correlations are designated by y-1 and the 3-, 5- and 10-year running average correlations are designated as 3-year, 5-year and 10-year, respectively.

and the nearest HMCG point precipitation data ($r=0.825$, $p<0.001$). The stations nearest to the Slave River Delta with instrumental temperature data (not available for Fort Resolution) are Hay River (135 km west of the Slave River Delta; 100 years) and Fort Smith (170 km south of the Slave River Delta; 88 years); correlations with the nearest HMCG point temperatures were found to be good ($r=0.92$, $p<0.001$, and $r=0.95$, $p<0.001$, respectively).

To ensure that climate-isotope effects from the fall and winter seasons preceding the growing season would be included in the evaluation, each year was represented by a 12-month period starting in October of the 1st year and ending in September of the current year. Correlations between annual

$\delta^{13}C_{cellulose}$ values and climate data were performed on monthly, bi-monthly, seasonal (growing and regular), and annual bases, not only for the current year but also the previous year. Furthermore, 2, 3, 5, and 10-year running averages of the climate and carbon data were calculated for correlation analyses.

4. Results and discussion

Overall, the $\delta^{13}C_{cellulose}$ values for the trees from each site are somewhat better correlated with precipitation than temperature (Table 1). This is consistent with the findings of Jarvis (2004) and Reynolds (2005), who determined that tree-ring widths from 18 sites within the Slave River Delta (Fig. 2) are primarily sensitive to growing season (August) precipitation. It is also evident that the use of running averages for both the climatic parameters and $\delta^{13}C_{cellulose}$ values tend to improve the corresponding correlations and significance levels (Table 1). This is because the noise associated with year-to-year variations becomes less prominent with coarser time resolutions, thereby highlighting the more general trends. More specifically, as the temporal resolution decreases, $\delta^{13}C_{cellulose}$ values appear to capture more generalized variations or trends in climate, masking the influence of monthly or seasonal climate variations. The 5- and 10-year running averages tend to show the best correlations between climate and $\delta^{13}C_{cellulose}$.

4.1. The remote and middle sites

The remote and middle sites are located 200 and 50 m from the Slave River (SR), respectively (see Figs. 2 and 3). At an elevation of 160 masl, it is likely that trees at both sites prospered in the absence of considerable SR flooding and high water influences (Fig. 3). This assertion is reinforced by the presence of moderately mature forest Brunisols at these sites without any evidence of silt lamellae (Petrash, 2006). It is therefore anticipated that fluctuations in the amount of precipitation and their influence on soil and ground moisture, or the local levels of moisture-deficit-stress (MDS), will be revealed as the main determinant of carbon isotope variations for the trees at these sites.

For both sites, the most influential times of the current year in terms of the effect of precipitation totals on $\delta^{13}C_{cellulose}$ are the non-growing and early-growing months in the previous-year fall, winter and early spring, as demonstrated by the significant correlations in Table 1. For the remote site only, these periods in the previous year are also important (Table 1). The middle site trees also correlate positively and well with current-year June precipitation amounts. Negative correlations between $\delta^{13}C_{cellulose}$ and precipitation during non-growing season periods (fall, winter and spring) suggest that rejuvenation of soil moisture through slow penetration of accumulated snow during the spring thaw results in relatively non-stressful growing seasons for the remote and middle site trees. The consequent reduction in growing season MDS then facilitates relatively depleted $\delta^{13}C_{cellulose}$ values. Equivalently, these negative correlations could be interpreted to mean that carbon isotope

enrichment (stress) is associated with reduced levels of non-growing season precipitation. In any case, it seems clear that precipitation amounts in the non-growing season do have an effect on growing season stress. It is interesting that the $\delta^{13}C_{cellulose}$ values at the remote site correlate positively with 10-year running average April–May precipitation but negatively with the April–May 5-year averages and other non-growing season precipitation totals (see Table 1). For this site, the positive correlation with spring (April–May) precipitation using the 10-year averages could be interpreted to mean that, over the long term, if the majority of the non-growing season precipitation is delivered in the spring the trees are stressed during the subsequent growing season, resulting in enriched $\delta^{13}C_{cellulose}$ values. It may be that when the majority of this important non-growing season precipitation is delivered immediately prior to the start of the growing season, the end result is enhanced runoff and a reduction in soil moisture recharge. Historical climate records for Fort Resolution suggest that as much as half of the precipitation falling within the Slave River Delta during the months of April and May can be delivered as rain rather than snow (Adjusted Historical Canadian Climate Data). However, at this time of year, the soil would still be frozen and therefore unable to store the moisture. In contrast, moisture delivered as snow during the fall and winter seasons is stored on the forest surface and allowed to gradually penetrate and replenish local soil moisture conditions during gradual spring thaws. The negative (and weaker) correlation with the 5-year averages of April–May precipitation at the remote site may be indicative of especially large amounts of interannual variability in spring precipitation and its retention within the soil (as determined by concurrent temperatures and the speed of the spring thaw).

The positive correlation between $\delta^{13}C_{cellulose}$ values and June precipitation amounts at the middle site could, as with the positive correlations between 10-year averaged $\delta^{13}C_{cellulose}$ values and April and May precipitation amounts at the remote site, relate to the delivery of the precipitation too early for the trees to use it efficiently due to partially or completely frozen soil. Subsequent soil moisture deficits during the remainder of the growing season (May–September) would then result in MDS and enriched $\delta^{13}C_{cellulose}$ values.

Correlations between temperature and carbon isotope values at the remote and middle sites are generally weaker than those associated with precipitation (Table 1). At the remote site, June–July temperatures averaged over 3 years are positively correlated with the isotopes, and August and September current-year temperatures are each negatively correlated with the isotopes. At the middle site, the $\delta^{13}C_{cellulose}$ values are negatively correlated with current-year October temperatures, most strongly ($r = -0.53$) with the 10-year averaged data.

A positive correlation with growing season (June–July) temperature is indicative of ^{13}C enrichment induced by high temperature stress. Negative correlations with temperatures in the last half of the growing season (August and September) suggest that enrichment is being induced by low temperatures (or depletion by warmer than normal temperatures). With respect to cold temperatures, a rapid conclusion of the growth period could result in an overall assimilation of a lower than
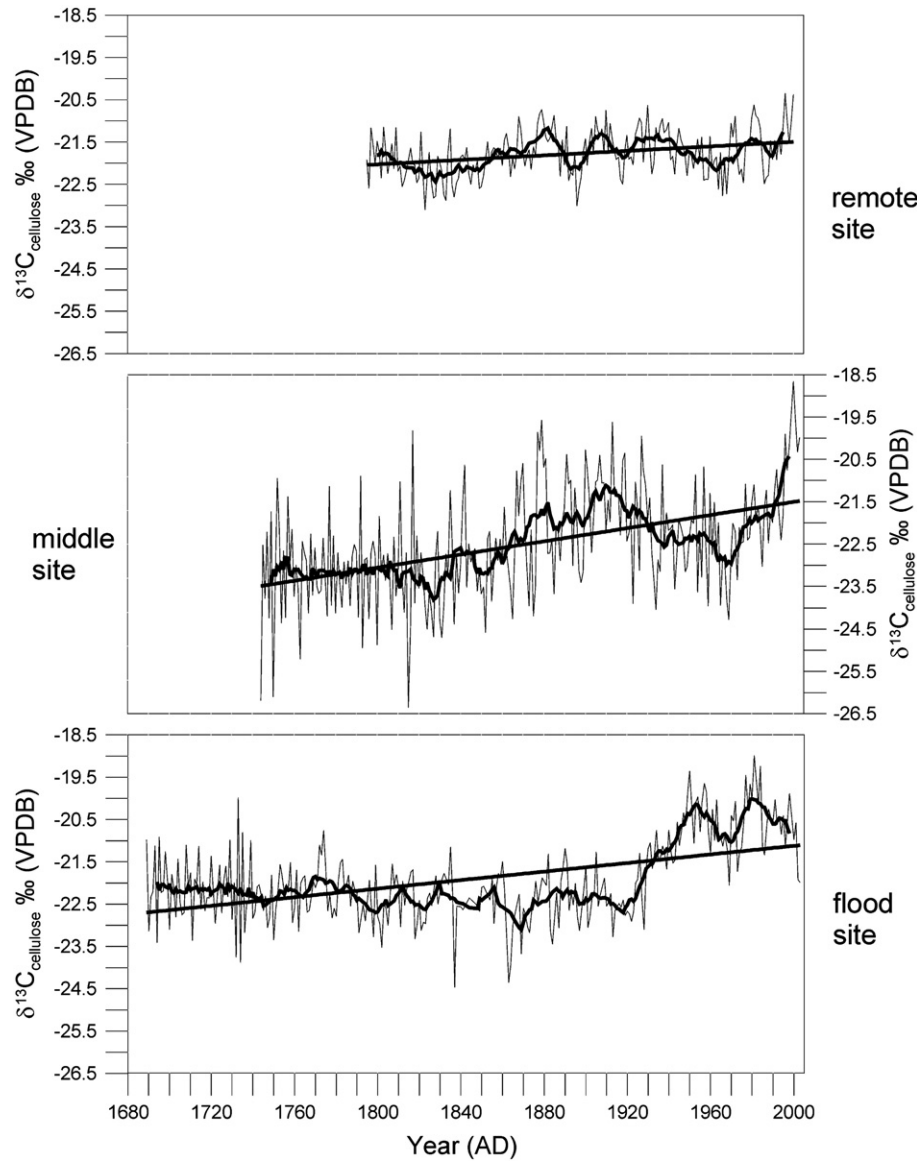
Fig. 5. The corrected $\delta^{13}C_{cellulose}$ annual time series and the 10-year running average and linear trends for the remote, middle and flood sites.

average volume of latewood relative to the generally more ^{13}C-enriched earlywood stored and remobilized from the previous year (Helle and Schleser, 2004). For the middle site, the negative correlation with October (non-growing season) temperature may indicate that warmer fall seasons may delay soil freeze-up and allow for soil moisture rejuvenation before the subsequent spring. Consequently, the middle site trees would start the following growing seasons with an abundance of water, and less chance of enriched tree-ring $\delta^{13}C_{cellulose}$ values induced by MDS. Equivalently, the correlation may also indicate that early freezing in cold autumns inhibits moisture recharge, setting up MDS-induced enrichment in the following growing season.

Trees at the two higher elevation sites are sensitive to non-growing season precipitation conditions and growing season temperatures. This suggests that moisture stress events occurring at these sites are, to some degree, related to inadequate water replenishment prior to the growing season

and anomalously high temperatures that enhance evapotranspiration during the growing season. In support of these assertions, Fig. 5 reveals that the remote and middle sites each had $\delta^{13}C_{cellulose}$ enrichment peaks in the years 1880, 1910 and 1995, taken to represent MDS years. The remote site also has enriched $\delta^{13}C_{cellulose}$ values in 1980 and during the period 1860–1920. The middle site has additional distinct enrichment during the periods of 1870–90, 1900–10 and 1925–40, and an enrichment peak in the year 1845. The HMCG data (1901–2000) show that the Slave River Delta received anomalously low pre-growing season precipitation amounts during the years of 1910 and 1980. Low pre-growing season precipitation amounts were also delivered to the Slave River Delta during the periods 1920–1930, 1935–45 and 1975–83. These periods overlap with some of the distinctly enriched $\delta^{13}C_{cellulose}$ periods for the remote (1860–1920) and middle (1870–90, 1900–10 and 1925–40) sites, again suggesting that low non-growing season precipitation amounts can emerge as growing season
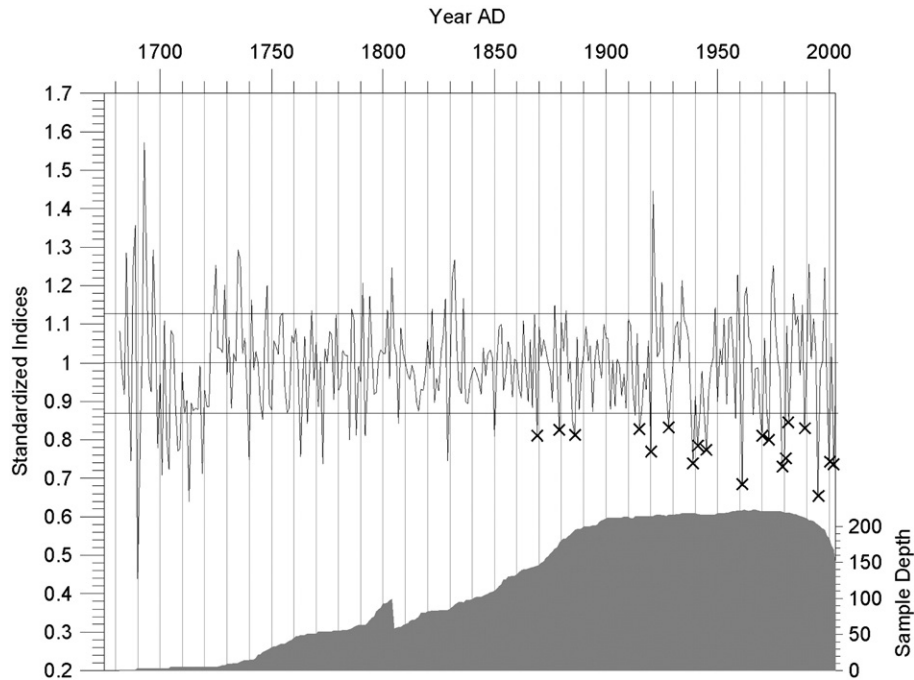
Fig. 6. The Slave River Delta master tree-ring chronology (standardized indices average 1.0; Std. Dev. 1.3) from Jarvis (2004) and Reynolds (2005). The X symbols indicate anomalously narrow tree-ring widths. The sample depth is indicated by the grey-shaded area.

MDS carbon isotope enrichments in the trees at these sites (Fig. 5).

Furthermore, the master tree-ring chronology for the entire Slave River Delta (Fig. 6) depicts very narrow tree-ring widths (pointer years) for the years 1869, 1879, 1880, 1885, 1886, 1915, 1920, 1928, 1939, 1941, 1945, 1961, 1969, 1972, 1979, 1980, 1982, 1995, 1998 and 1999; Jarvis (2004) and Reynolds (2005) each concluded that the tree-ring widths are primarily a function of August precipitation amounts. The majority of the late 19th and early 20th Century narrow rings fall within the periods of distinct $\delta^{13}C_{cellulose}$ enrichment indicated by the remote and middle site trees. Eight of the 15 narrowest 20th Century tree rings occur within the previously-noted anomalously low precipitation periods in the HMCG data series, further supporting the case that enrichment is enhanced by MDS related to low precipitation amounts in the pre-growing season.

4.2. Flood site

The lower elevation flood site (156 masl) is regularly influenced by Slave River floods (Fig. 3). Due to its close proximity to the river, it is plausible that this site is rarely if ever moisture stressed, in contrast to the remote and middle sites (perhaps only after 1968, as discussed below). In fact, the major stress imposed on the trees found at this site may not be related to moisture-deficit-stress (MDS) associated with insufficient non-growing season precipitation and higher-than-normal growing season temperatures, but instead moisture-excess-stress (MES) brought on by floods.

Among the three sites used in this study, the flood site has the strongest correlations between $\delta^{13}C_{cellulose}$ and climate (particularly precipitation) (Table 1). The correlations between

$\delta^{13}C_{cellulose}$ and precipitation are particularly strong, and positive, for the individual and paired months of October and November, and to a lesser degree for the three-month period of December through February. The positive correlations between $\delta^{13}C_{cellulose}$ and fall and winter precipitation amounts suggest that MES-induced enrichment is produced by anomalously high precipitation that contributes to high water levels in the Slave River during the growing season (Fig. 3). The resulting MES may have a variety of effects on the flood site trees. Flood water saturating the soil can displace soil-pore oxygen, thereby inhibiting root development and damaging root function, restricting respiration and stalling the mineralization and absorption of essential plant nutrients (Davies and Flore, 1986; Else et al., 2001; Anderson et al., 2005). Furthermore, flooding of seedlings for periods longer than 30 days has been linked to nitrogen reduction (denitrification) in the soils, which may result in tree growth limited by poor soil nutrition (Kreibich and Kern, 2003; Alaoui-Sossé et al., 2005). Prolonged flooding of sites may also result in the deposition of metabolic toxins (Jackson and Drew, 1984; Kozlowski, 1997). The ensuing soil and root alterations arising from any or all of these effects related to high water could in turn result in MES-related enrichment of cellulose carbon isotope signatures related to decreased stomatal conductance (Ewe and Sternberg, 2002, 2003).

Worbes (2002) suggests that cambial dormancy and the termination of ring cell divisions may occur as a result of flood stress on trees. If cambial dormancy caused by flooding occurred primarily during the growing season, the earlywood in that year may be dominated by ^{13}C-enrichment associated with the remobilization of starches stored from the previous growing season (Helle and Schleser, 2004). This could explain

some of the MES-related $\delta^{13}C_{cellulose}$ enrichment at the flood site. The converse of this explanation is that low levels of precipitation result in reduced or shortened flood events, less flood-induced MES, and more depleted (less enriched) isotope signatures.

Spring and summer precipitation is negatively correlated with $\delta^{13}C_{cellulose}$ at the flood site (Table 1). High spring and summer precipitation levels do not generally result in Slave River floods, thus it is not surprising that they do not result in the flood-related isotopic signatures. Indeed, the negative correlations suggest that abundant spring and summer precipitation promotes non-stressful growth conditions for the flood site trees and relatively depleted $\delta^{13}C_{cellulose}$ values (and MDS-enriched values when the precipitation is low).

Temperatures during the fall (October–November) of the previous year, and the winter (December–January and February–March) of the preceding growing season are positively correlated with $\delta^{13}C_{cellulose}$ values at the flood site. Warm non-growing seasons may promote more snow melt runoff, possibly leading to high water levels in the Slave River that result in MES for the flood site trees which, as discussed previously, could lead to more enriched $\delta^{13}C_{cellulose}$ values.

4.3. General $\delta^{13}C_{cellulose}$ trends from the remote, middle and flood sites

Fig. 5, depicting the cellulose carbon isotope record from the flood site, shows fairly minor variations of enrichment and depletion up until the year 1925, after which there is a dramatic shift toward substantially more enriched values. This enrichment coincides with the initiation of logging activities in this area in the early 1920s (pers. comm. Gabriel and Eddie Laferty, lifetime residents of Fort Resolution). Logging along the Slave River probably had a considerable impact on the regional hydrology of the area, as the removal of trees would allow for faster runoff of snow melt and more frequent high water levels (Goodwin et al., 1997; LaMarche and Lettenmaier, 2001). The primary effect of more frequent and perhaps longer flooding events on the trees of the flood site, as discussed previously, is to promote MES leading to more enriched $\delta^{13}C_{cellulose}$ values. Indeed, Fig. 5 suggests that the new hydrological dynamics of the Slave River resulted in a new and more enriched carbon isotope baseline (by 2‰) for the flood site trees, until 1955. The figure also suggests that the logging-related baseline enrichment of the $\delta^{13}C_{cellulose}$ values may have diminished slightly after 1955, perhaps as a result of forest re-growth leading to a reduction of flooding magnitudes and more depleted $\delta^{13}C_{cellulose}$ values.

In Fig. 5 it appears that the remote and middle sites underwent enrichment through the late 19th to early 20th Centuries; this is not evident at the flood site. This enrichment could indicate a trend toward drier conditions at the remote and middle sites, while the flood site remained resistant to drier conditions as a result of more frequent exposure to Slave River flooding (Fig. 3).

At all three sites, an abrupt period of enrichment is observed in the late 1960s (Fig. 5). The enrichment coincides with the

construction of B.C. Hydro's Bennett Dam. The Bennett Dam, one of the world's largest earthfill structures, located at the head of the Peace River Canyon, was completed in 1967 and put into operation in the following year. Although it is more than 1500 km downstream of the Bennett Dam, the Slave River Delta is thought to have been affected by the construction and operation of the dam. Specifically, these effects include lower peak flows within the Slave River Delta (and the Peace Athabasca Delta), a decrease in the amount of sediment load transported to the Slave River Delta, a reduction in the frequency of ice-jam and open-water flooding, and a prolonged period of drying in the Slave River and Peace Athabasca Deltas (Wolfe et al., 2005). The lower water levels depress the underground water tables (soil saturation zones) and, therefore, trees at sites located further from the Slave River would be more susceptible to MDS (Fig. 3). As shown in Fig. 5, the Bennett Dam-related drying of the Slave River Delta may be so severe as to not only explain the $\delta^{13}C_{cellulose}$ enrichment in the tree-ring records from the remote and middle sites but also at the flood site, which is generally much less susceptible to MDS.

5. Conclusions

Tree-ring carbon isotope analysis has now been used widely to reconstruct past climatic and environmental changes associated with temperature, precipitation, and ground moisture status. In the present study, carbon isotope dendrochronologies from three sites within the Slave River Delta, Northwest Territories, Canada, were correlated with Historical Monthly Climate Grid precipitation and temperature data for the time period 1901 to 2000.

While all three tree-ring site chronologies show a distinct trend towards more enriched $\delta^{13}C_{cellulose}$ values, possibly stemming from an overall drying of the Slave River Delta, some distinct differences in $\delta^{13}C_{cellulose}$ trends between the three sites may be attributed to their unique physical settings and local moisture conditions.

Trees at all three sites display carbon isotope sensitivity to the implementation of an upstream dam which may have acted to accentuate the general drying of the Slave River Delta. Only the low-lying site adjacent to the Slave River shows carbon isotope sensitivity to the commencement of logging activity in the delta during the 1920–1930s, supporting the suggestion that low-lying sites are susceptible to moisture-excess-stress brought on by high water levels.

Importantly, Slave River Delta trees at remote and higher elevation sites, relative to the river (the middle and remote sites) appear to have carbon isotopic and ring-width sensitivities to non-growing season precipitation conditions as well as growing season temperatures. Carbon isotope correlations with Historical Monthly Climate Grid precipitation and temperature data suggest that most of the moisture-deficit-stress events occurring at the elevated and remote sites are related to inadequate water replenishments prior to the growing season and enhanced evapotranspiration related to higher-than-normal growing season temperatures. Furthermore, carbon isotope values from trees sampled from a site close to the river (the flood site)

suggest that some of the inadequate water replenishments occurring during non-growing season periods for the elevated and remote sites may result in flooding. Evidence suggests that significant water inundations that result in soil and tree symptoms related to moisture-excess-stress may provide similarly enriched carbon isotope signatures for trees at low-lying sites, albeit from different hydroclimatic forcings.

Overall, the results discussed here further emphasize the need for diligent evaluation of the physical settings of trees used in riparian zone isotope tree-ring studies.

Acknowledgments

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