

Comparative dendroclimatological analysis of two black ash and two white cedar populations from contrasting sites in the Lake Duparquet region, northwestern Quebec

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Abstract: The relationship between radial growth and climate was analyzed in two black ash (*Fraxinus nigra* Marsh.) and two white cedar populations (*Thuja occidentalis* L.) growing in contrasting sites in the Abitibi region of Quebec. An indexed mean chronology of radial growth was developed in each case. Black ash from flooded sites did not cross-date with those from unflooded sites and responded differently to climate. On the floodplain sites, black ash radial growth is directly correlated with the previous year's August precipitation ($i - 1$) and with the current year's June precipitation (i). High water levels at the beginning of the growing season also had a negative impact on the following year's growth, whereas a high drought index during June of the preceding year ($i - 1$) had a positive one. Radial growth of unflooded black ash is mainly related to temperature. For those black ash not exposed to flooding, the preceding year's August temperature ($i - 1$), as opposed to August precipitation, had a negative impact on the current year's growth. A high drought index in June (i) also had a negative impact on the current year's growth. Compared with black ash, white cedar from both xeric and mesic sites showed good between-site cross dating and had similar relationships to climate. In both cases, abundant summer precipitation, associated with cool temperature, produced maximum growth. Temperature during August of the preceding year ($i - 1$) was also negatively correlated with radial growth. White cedar from xeric sites also responded more intensely to drought, as revealed by the negative relationship to the June–July (i) drought index. In conclusion, growth-ring analyses show the specificity of the climatic response of these two species and the filtering effect caused by different environments.

Résumé : L'effet du climat sur la croissance radiale de deux populations de frêne noir (*Fraxinus nigra* Marsh.) et de deux populations de cèdre blanc (*Thuja occidentalis* L.) a été étudiée dans des sites aux caractéristiques écologiques distinctes situés dans la région de l'Abitibi au Québec. Une chronologie moyenne indicée de l'accroissement radial a été développée pour chacune des situations. Les frênes noirs sur les sites inondés n'interdatent pas avec ceux des sites non inondés et montrent des réponses climatiques différentes. En plaine de débordement, la croissance radiale du frêne noir est positivement corrélée aux précipitations du mois d'août de l'année précédente ($i - 1$) et du mois de juin de l'année courante (i). En début de saison de croissance, les crues ont aussi un impact négatif sur l'accroissement de l'année suivante. Les conditions de sécheresse du mois de juin ($i - 1$), au contraire, favorisent l'accroissement radial de l'année suivante. La croissance radiale des frênes noirs non exposés aux crues est surtout reliée aux températures. Les températures du mois d'août ($i - 1$), contrairement aux précipitations, ont un impact négatif sur la croissance de l'année courante. Un indice de sécheresse élevé en juin (i) engendre aussi un impact négatif sur la croissance de l'année courante. Les populations de cèdre blanc des sites xérique et mesique, contrairement à celles du frêne noir, interdatent bien entre elles et ont une réponse climatique similaire. Une forte pluviosité estivale couplée à des températures fraîches semble engendrer une croissance maximale. Les températures du mois d'août ($i - 1$) sont aussi négativement corrélées à la croissance. Les cèdres blancs des sites xériques répondent, cependant, avec plus d'intensité au stress hydrique comme l'indique la relation négative avec l'indice de sécheresse des mois de juin–juillet (i). En conclusion, l'analyse des cernes de croissance a permis de mettre en évidence l'unicité de la réponse climatique des deux espèces et l'effet filtre opéré par les conditions abiotiques propre à chaque environnement.

Introduction

In dendroclimatology, site selection is an important element, as it constitutes an extension of the limiting factors principle (Fritts 1976; Lamarche 1982; Schweingruber et al. 1990). Proper site selection allows one to maximize the response of a

tree species to the factor of interest; it enables a selected climatic signal to be revealed in the rings of trees (Fritts 1976; Schweingruber et al. 1990). For example, one who wishes to reconstruct past precipitation will preferably select trees that grow in the driest sites; that is, where moisture will probably be the limiting factor (Schweingruber et al. 1990).

For the ecologist, however, the variability seen in the growth pattern or in the climatic response of trees growing in contrasting environments may be of greater interest. Many tree-ring characteristics are known to vary according to environmental stresses (Fritts et al. 1965; Phipps 1982; Fritts and Swetnam 1989). Trees from both hydric and xeric sites, for example, tend to have higher ring to ring variability and common

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variance compared with trees found on mesic sites (Fritts et al. 1965; Phipps 1982). On both xeric and hydric sites, radial growth may also be most sensitive to those weather conditions that lead, respectively, to extremely dry or wet situations (Phipps 1982). Changing tree responses to variations in ecological conditions can be used to determine the role that different environmental factors have in controlling tree growth (Fritts et al. 1965). Within the same species, different responses to climate using the same meteorological data can be explained by differences in habitat (Fritts 1976). Tree-ring analyses can, therefore, strengthen our understanding of the ecology of tree species by comparing their climatic responses in different habitats (Serre-Bachet and Tessier 1990). A better knowledge of the biological processes in trees from different habitats may also help in the quest for more reliable reconstructions of climatic variables (Shiyatov 1992).

In this study the radial growth behaviour of two species, black ash (*Fraxinus nigra* Marsh.) and white cedar (*Thuja occidentalis* L.), from Quebec's southwestern boreal forest limit was analyzed. For each species, two tree-ring chronologies were developed from trees growing in contrasting environments. The black ash chronologies were developed from floodplain trees that are flooded annually in the spring and from higher elevation trees not exposed to flooding. Comparison of the climatic responses of both these black ash populations should allow us to better understand the role of spring floods and water availability in controlling its radial growth. The importance of both water availability and temperature on radial growth is also evaluated by an analysis of two white cedar populations growing on xeric and on mesic sites. For white cedar, the growth form, or the architecture, may also be of interest, since trees growing on xeric sites (wind-exposed sites) are stunted with high cambial mortality and strong unilateral growth (Archambault and Bergeron 1992a, 1992b). Trees from mesic sites are, in contrast, well developed with well-defined crowns and concentric growth.

Study area

The study area is located about 900 km north of Montréal, in the Abitibi region of northwestern Quebec (48°28'N, 79°17'W). This region is part of the Northern Clay Belt of Quebec and Ontario, which resulted from the maximum extension of the postglacial Lakes Barlow and Ojibway (Vincent and Hardy 1977). The closest meteorological station to our study area is at La Sarre, about 42 km to the north. The climate is cold temperate with a mean 1961–1990 annual temperature of 0.8°C and a mean total annual precipitation of 856.8 mm (Environment Canada 1993). Snow represents 25% of the yearly total precipitation. Most liquid precipitation falls during the growing season, but high levels of evaporation in June and July may limit plant growth (Dermine 1965). The mean frost-free period is 64 days, but freezing can occur at any time (Environment Canada 1982). In the spring, generally from early May to early June, flooding occurs on rivers and lakes, in part as a result of snow melting and spring precipitation.

The Abitibi region is located at the southern limit of the Boreal Forest (Rowe 1972), where an association of *Abies balsamea* (L.) Mill., *Picea mariana* (Mill.) BSP, and *Betula papyrifera* Marsh. dominates with *Picea glauca* (Moench) Voss and *Populus tremuloides* Michx. In this area, black ash mainly colonizes hydric sites with high water fluctuation (alluvial levees and floodplains), although the species also occurs infrequently in intermittent higher elevation creeks (Bergeron et al. 1983). White cedar is typical of old-growth forests (Bergeron and Dubuc 1989). A more complete description of

the vegetation in this area can be found in Bergeron and Dubuc (1989) and De Grandpré et al. (1993).

Materials and methods

Data collection

The first black ash chronology was built from trees growing in pure stands found on Lake Duparquet's floodplains (elevation: ca. 260 m above sea level) and annually exposed to high water levels during spring floods (Tardif and Bergeron 1992). In these lowland sites, flooding may extend well into the black ash growing season. In 1989, for example, flooding lasted until the end of June, whereas in 1991 and 1992, water withdrawal was completed by the end of May (field observation). In these sites, water table depth is closely associated with Lake Duparquet water levels. The sampling was conducted from 1989 to 1992 with more than 300 black ash trees being sampled from many floodplain sites surrounding Lake Duparquet.

The second black ash chronology was built from a small population (about 20 trees) located in a small higher elevation drainage near Roquemaure. This site, about 10 km north of Lake Duparquet, has an elevation of about 300 m above sea level. In this stand, black ash is associated with *B. papyrifera* and *A. balsamea* and is found growing on partially reworked and eroded morainic deposits enriched by superficial alluvial deposits (Bergeron et al. 1983). On this site black ash are not affected by flooding, but seepage is an important soil process. Cores were not collected from stump sprouts of larger trees, although black ash trees that have been cut are reported to produce root suckers (Sims et al. 1990). To our knowledge, however, black ash root sucker production has never been quantified. The large distance between trees suggests, however, that this population is not clonal. Furthermore, trees from this small population also cross-date with four scattered black ash trees found in the nearby hills (COFECHA (Holmes 1983), mean correlation with master chronology: $r = 0.53$) and these were therefore included in the chronology. At the Roquemaure site, black ash trees survived a forest fire in 1944, as revealed by both fire scar dates and from growth release patterns.

White cedar were sampled from both xeric and mesic sites located along the margin of Lake Duparquet (see Archambault 1989). White cedar (trees and snags) from the xeric environment were found growing on elevated rocky outcrops located on the shore and on islands. These sites are characterized by a sparse soil cover and very rapid drainage (Archambault and Bergeron 1992a). On these sites, white cedar trees are exposed to dominant winds from the west and their roots are not in contact with water from Lake Duparquet (Archambault 1989). These trees are characterized by their small stature, gnarled appearance, loss of apical dominance, and cambial dieback, which leads to strong asymmetric growth (Archambault and Bergeron 1992a, 1992b).

In contrast, the 28 white cedar trees sampled on the mesic sites are characterized by their large size and symmetric growth. These trees were found growing on rocky banks and sandy beaches bordering the lake (Archambault 1989). On these low sites, the vegetation is more developed and trees may be flooded for a short period in the spring. In a study of fuel characteristics on both xeric and mesic sites distributed around Lake Duparquet, Hébert (1995) demonstrated that the water content of both litter and humus was significantly higher on the mesic sites. No white cedar were sampled in bogs or swampy sites.

Chronology development and dendrochronological analyses

All samples were processed using standard dendrochronological procedures (Stokes and Smiley 1968; Fritts 1976). Two cores were generally collected for black ash trees, whereas for white cedar, frequently only one core was collected because of strong unilateral growth (xeric sites) or heart rot (mesic sites). After mounting and sanding, all cores were cross-dated and ring width was measured to the nearest 0.01 mm. For each species-habitat combination,

Table 1. Characteristics of the meteorological stations used to compute regional climate for the Lake Duparquet region.

Station	Location	Elevation (m) ^a	Period of records	Missing data (%)	Mean temp. (°C)	Mean precipitation (mm)
Abitibi Post	48°43'N 79°22'W	259	1896–1936	7.9	—	—
Amos	48°34'N 78°07'W	305	1913–1992	6.2	1.5	806.7
Cochrane	49°04'N 81°02'W	275	1910–1992	8.4	0.9	771.4
Duparquet	48°31'N 79°16'W	290	1981–1992	9.7	1.5	856.0
Iroquois Falls	48°45'N 80°40'W	259	1913–1992	1.8	1.1	653.2
La Sarre	48°48'N 79°12'W	274	1951–1977	5.6	0.8	856.8
Kinojevis	48°13'N 78°52'W	290	1974–1992	11.8	2.0	746.5
Val St-Gilles	48°59'N 79°07'W	290	1974–1991	13.4	0.2	723.1
Harricana	48°34'N 78°07'W	3680 ^b	1915–1933	0	—	—
	48°36'N 78°06'W	3680 ^b	1933–1992	0	—	—

Note: Both annual mean temperature and total precipitation for the reference period 1981–1990 are presented. The Harricana River hydrological station is also indicated.

^aAbove sea level.

^bWatershed area (km²).

cross-dating quality was validated using the program COFECHA. Series showing portions of abnormal growth or low correlation with the reference chronology were either truncated or disregarded to minimize the effect of atypical tree-ring series on the final chronology. For example, all series showing strong growth release effects (some of the Roquemaure cores) were split and separately detrended (Blasing et al. 1983).

All black ash series were detrended using cubic smoothing splines (with a 50% frequency response cutoff of 53 years), which were found to be satisfactory for trees growing in a closed-canopy forest (Cook and Peters 1981). To be consistent, the same detrending was applied to white cedar. Autoregressive modelling was performed on each detrended ring-width series, and each residual chronology (two black ash and two white cedar) was computed using a biweight robust mean. The program ARSTAN was used to develop the four residual chronologies (Cook 1985), and the common interval analysis was calculated using a common reference period for all four chronologies.

The climatic signal contained in the two residual chronologies per species was evaluated using Pearson's correlation (Blasing et al. 1984) and bootstrapped response functions (Fritts 1976; Guiot et al. 1982; Briffa and Cook 1990; Guiot 1990). The bootstrap procedure provides an alternative approach to test the significance and stability of the regression coefficients within a specific time period (Guiot 1993). All climatic analyses were computed with the program PRECON (version 4.03) (Fritts et al. 1991). Climatic data from eight weather stations distributed within ca. 100 km of Lake Duparquet were used to compute both regional monthly mean temperature and total precipitation (Table 1). Only data not affected by station relocation through time were used. The program MET from the Dendrochronology Program Library was used to estimate missing data and to construct the regional climatic series (Holmes 1992).

In addition, untransformed mean monthly discharge from the Harricana River (ca. 100 km to the east) for the period 1916–1990 was also used (Table 1). A good agreement between the daily Harricana River discharge and Lake Duparquet water levels during the late spring and summer of 1989 to 1991 (unpublished data) allowed us to interpret water levels directly from the discharge data. Finally, the Drought Code from the *Canadian Forest Fire Behaviour System* (Turner 1972) was calculated using daily data from the Iroquois Falls meteorological station (100 km to the west). The daily drought indices from May to August were averaged to produce monthly drought indices.

Results

General statistics and chronologies

The descriptive statistics indicate that all four chronologies have a similar common variance in the first principal component, ranging from 35% to 38% (Table 2). The expressed population signal statistics show, however, that the strength of the unflooded black ash chronology is somewhat lower than that of the other chronologies. All chronologies have relatively low mean sensitivity and standard deviation, ranging, respectively, from 0.14 to 0.20 and from 0.12 to 0.19. No clear pattern in these statistics can be related to differences in habitat (Table 2).

Both species also show similar mean correlation between cores and between trees (Table 2). The mean correlation within trees is, however, slightly higher in both flooded ($r = 0.74$) and xeric site ($r = 0.62$) trees than in their counterparts. The mean

Table 2. Descriptive dendrochronological statistics for the two black ash and the two white cedar tree-ring residual chronologies.

	Black ash flooded	Black ash unflooded	White cedar xeric	White cedar mesic
Chronology length	1683–1990	1791–1990	1186–1987	1417–1987
Number of trees	141	24	38	28
Number of radii	253	40	55	43
Mean ring width (mm)	0.70	0.68 ^a	0.36	0.54
Mean sensitivity	0.20	0.19	0.16	0.14
Standard deviation	0.19	0.17	0.14	0.12
Autocorrelation order 1 ^b	0.25	0.46	0.35	0.32
Variance due to autoregression (%)	6.30	19.80	10.30	13.01
ARMA model (AR) ^c	1	1	1	3
Common interval analysis (1860–1940)				
Number of trees	48	10	29	27
Number of radii	66	16	34	39
Signal to noise ratio ^d	24.75	4.51	13.92	14.32
Variance in the first principal component (%)	36.31	38.07	35.50	38.40
Expressed population signal ^e	0.96	0.82	0.93	0.94
Intercore correlation	0.34	0.33	0.33	0.36
Intertree correlation	0.34	0.31	0.32	0.36
Intratree correlation	0.74	0.61	0.62	0.56

^aOnly trees established before the 1944 fire were used in the calculation.

^bCalculated from the standard chronology.

^cAR, autoregressive.

^dSignal to noise ratio (SNR) is presented here only for illustration; this statistic is difficult to use for comparison, since it has no upper bound and varies nonlinearly with an increasing number of trees (Briffa and Jones 1990).

^eExpressed population signal is equivalent to $SNR/(1 + SNR)$ (see Wigley et al. 1984; Briffa and Jones 1990).

correlation between trees was comparable on all sites. Black ash trees in both flooded and unflooded sites also show, respectively, the lowest ($r = 0.25$) and the highest ($r = 0.46$) first-order autocorrelations, whereas autocorrelations were similar for the white cedar chronologies (Table 2). On xeric sites, however, white cedar registered a lower annual mean ring width ($0.36 \text{ mm}\cdot\text{year}^{-1}$) than on mesic sites ($0.54 \text{ mm}\cdot\text{year}^{-1}$). Black ash trees had, however, the highest radial growth rate (Table 2).

Figure 1 portrays the difference between the two black ash and the two white cedar standard chronologies. Both black ash chronologies present more year to year variability than the white cedar chronologies (Fig. 1). This is also emphasized by the higher mean sensitivity and standard deviation in both black ash chronologies (Table 2). The black ash chronologies also differ markedly and have a lower correlation ($r = 0.32$, $p = 0.0001$) than the two white cedar chronologies ($r = 0.84$, $p = 0.0001$). As well, black ash chronologies often present similar year to year direction in growth, although the variation in amplitude does not correspond (Fig. 1). Pearson's correlations between species chronologies for the 1850–1987 period were low (white cedar xeric – black ash flooded: $r = 0.26$, $p = 0.0018$; white cedar xeric – black ash unflooded: $r = 0.25$, $p = 0.0032$; white cedar mesic – black ash flooded: $r = 0.19$, $p = 0.0248$; white cedar mesic – black ash unflooded: $r = 0.17$, $p = 0.0501$).

Black ash response functions

The two black ash populations show different responses to

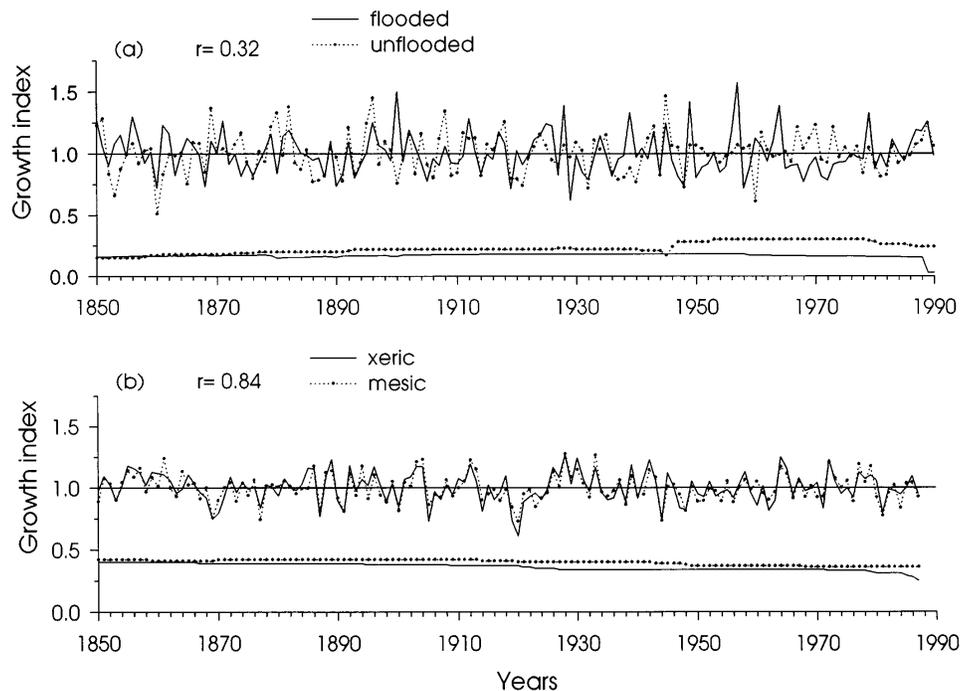
climate (Fig. 2). Response functions indicate that trees exposed to flooding respond more to precipitation (model $r^2 = 0.45$) than to any other climatic variable (Fig. 2). Heavy precipitation in August of the previous year ($i - 1$) and in both December and especially June of the current year (i) have a positive effect on radial growth. The effect of June precipitation is also demonstrated by a direct correlation with mean July discharge (Fig. 2). In the previous growing season, the negative effect of early growing season flooding on radial growth is shown by the inverse relationship to discharge and the positive one to the June drought index (Fig. 2).

Black ash from the Lake Duparquet floodplain showed no correlation with temperature, whereas on the Roquemaure site, trees responded more to temperature (model $r^2 = 0.31$) than to any other climatic variable (Fig. 2). On this site, radial growth shows an inverse relationship to August ($i - 1$) temperature and a direct one to August ($i - 1$) precipitation. In the early growing season, both warm May temperature (i) and a high June (i) drought index have a negative effect on radial growth. At Roquemaure, radial growth also shows a slight inverse relationship to winter (January–February) temperatures (Fig. 2).

White cedar response functions

Compared with the two black ash chronologies, white cedar trees from both xeric and mesic sites show a similar response to climate (Fig. 3). On xeric sites, however, response functions using either precipitation data or the drought index explain more variation in growth ($r^2 = 0.30$ and 0.25 , respectively) than

Fig. 1. Residual ring-width chronologies for black ash (a) and white cedar (b). The number of cores is indicated by the lines below each chronology and was divided by 100. For the black ash flooded chronology, the number of cores was divided by one thousand.



on mesic sites ($r^2 = 0.24$ and 0.17 , respectively). More specifically, white cedar radial growth, on xeric sites, responded negatively to August ($i - 1$) temperature and positively to both June ($i - 1$) precipitation and August ($i - 1$) discharge. In the current growing season, high June temperature also has a negative effect on radial growth as opposed to June precipitation. On xeric sites, a significant relationship to drought is also indicated by the negative correlation with the June–July (i) drought index (Fig. 3). In the current growing season, both high July discharge and low August temperature also favour radial growth.

On mesic sites, white cedar radial growth is negatively correlated with July and August ($i - 1$) temperature and positively correlated with August ($i - 1$) discharge (Fig. 3). In the current year, radial growth is also favoured by heavy May precipitation. In contrast with xeric sites, radial growth on mesic sites only shows a slight inverse correlation with the June (i) drought index and a positive one with May–June–July (i) river discharge (Fig. 3). Again temperature in August (i) has a negative effect on growth.

Discussion

The descriptive statistics for each of the four chronologies reported here are similar to those reported for other eastern North American tree species (Phipps 1982; Graumlich 1992). In contrast with radial growth in semiarid (Fritts et al. 1965) or wetland environments (Phipps 1982), trees from our sites showed no major changes in ring-width variability (mean sensitivity or standard deviation) with increasing environmental stress. The mean correlation within trees shows, however, an increase from mesic to xeric and from unflooded to flooded conditions. This may reflect the more extreme influence of external climatic conditions in both flooded and xeric sites, whereas trees in the other two habitats may be more strongly affected by

microsite factors and competition. On unflooded sites, black ash trees also showed higher autocorrelation, and this may reflect a smaller fluctuation in year to year environmental conditions.

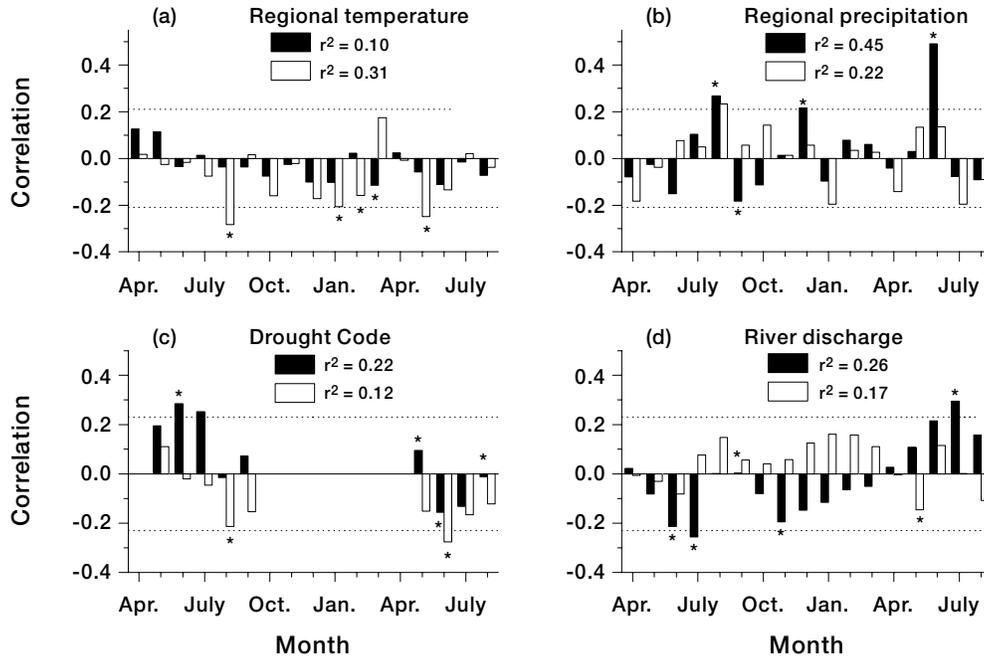
The statistics reported for white cedar are also comparable to those presented for this species on the Niagara Escarpment cliff faces (Kelly et al. 1994). In both studies, mean sensitivity, mean correlation between trees, and signal to noise ratio were comparable. No percentage of variation explained by the first principal component was, however, presented by Kelly et al. (1994). First-order autocorrelation was lower in our study, but this was largely due to the more flexible curves used in detrending.

The two black ash chronologies are not as well correlated as the two white cedar chronologies. For black ash, marker years differed in both habitats, and no significant correlations were found when trees from each habitat were compared using COFECHA (not presented). On flooded sites, visual cross dating depended mainly on wide rings, whereas on unflooded sites, visual cross dating was less effective. In this study, however, the sample size of the unflooded black ash chronology was small and inclusion of young trees may have strengthened the differences with the lake chronology, although we found that young black ash trees cross-dated well with mature trees in both habitats. Despite the fact that we did not evaluate the effect of possible root suckering in the Roquemaure site chronology, the cross-dating potential between Roquemaure's black ash and others found on similar sites (see methods) suggests that black ash trees growing on inland sites are affected by different conditions from those found on floodplain sites.

Comparison of black ash climatic response

The two black ash populations had different responses to climate. On flooded sites, radial growth and especially latewood growth (Tardif 1996) were primarily influenced by heavy June

Fig. 2. Pearson correlation between black ash residual chronologies and (a) mean monthly temperature for the period 1900–1990, (b) total monthly precipitation for the period 1900–1990, (c) the Canadian Drought Code for the period 1914–1990, and (d) the Harricana River discharge for the period 1916–1990. The dotted lines indicate a significant relationship at $p < 0.05$ (noncorrected significance level). The asterisks also indicate significant factors ($p < 0.05$) from the response function analyses testing each individual variable (temperature, precipitation, etc.) separately. Each model r^2 is indicated. Filled bars, flooded; empty bars, not flooded.



precipitation, as this is a time that coincides roughly with leaf expansion. The negative effect of prolonged flooding on the following year's radial growth reported here was also inferred by Tardif and Bergeron (1993) and attributed to the determinate nature of black ash growth, i.e., the winter buds produced in year i contain all the leaf primordia that will develop during the next growing season (Kramer and Kozlowski 1979). In this study, however, the negative effect of flooding on tree growth was demonstrated directly by the inverse relationship to mean discharge and the positive one to drought in the early growing season. According to Fritts (1976), a positive relationship to drought is less commonly encountered, and it suggests the existence of a relationship to other more limiting factors. It could, for example, reflect conditions where soil oxygen is being depleted and root growth impeded (Fritts 1976).

We hypothesize that in black ash, an increase in depth and duration of floods during the growing season may also result in conditions leading to a shorter growing season. For example, in mid-June 1989, flooded trees standing in >1 m of water had only started to leaf out, whereas, in both 1990 and 1991, leaf expansion was completed by that date (and probably since the end of May). In Ontario, near Chalk River ($46^{\circ}00'N$, $77^{\circ}26'W$), Fraser (1956) showed that black ash radial increment may start as early as May 6 and that it could last up to August 20. Similar results were also reported in northeastern Minnesota (Ahlgren 1957). On floodplain sites, a longer growing season resulting from a shorter flood period and coupled with heavy August precipitation may improve the following year's growth.

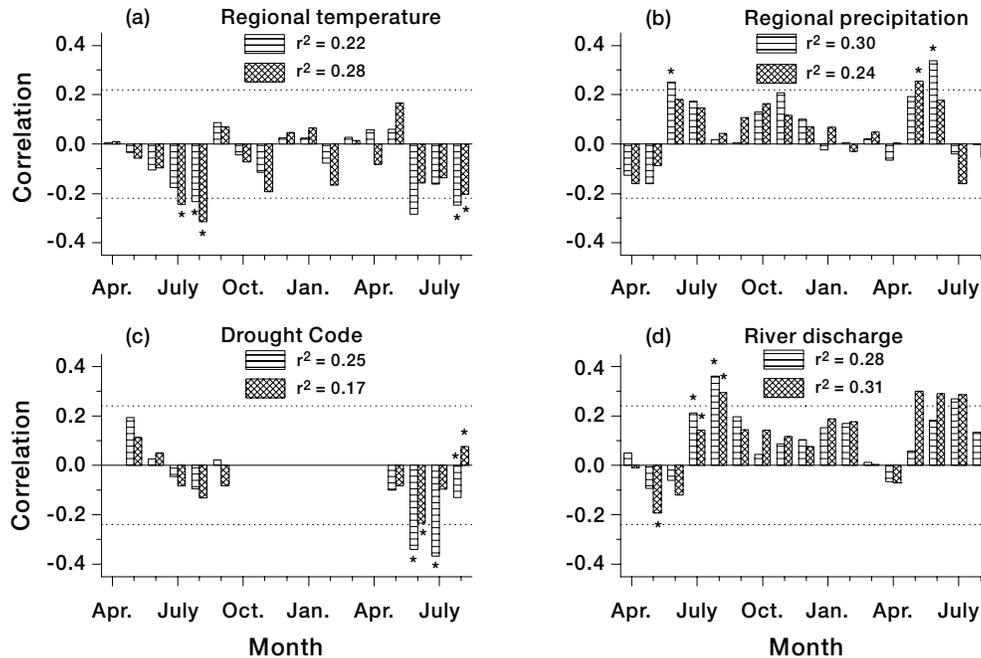
In contrast, radial growth in black ash trees from the Roquemaure watershed may be affected mainly by lower water availability. In the previous year's August, both flooded and unflooded

black ash responded positively to heavy precipitation, but only on the Roquemaure site was the temperature effect negative. This direct relationship to temperature may reflect an increase in water stress, as higher temperatures lead to greater evapotranspiration (Fritts 1976). Relationships to warmer May and higher June drought also suggest a higher susceptibility to water stress in the early growing season, at the time of shoot growth and leaf expansion. Strangely, black ash mean ring width on unflooded sites is similar to that of floodplain sites. Ronald (1972) reported that black ash, once established, is well adapted to "disjunct" drier sites. At the Roquemaure site, black ash trees are not exposed to prolonged flooding, and we hypothesize that they may benefit from an earlier growing season start that, if not impeded by severe drought, may allow for a growth rate similar to that of the floodplain sites. Soil water depletion in the early growing season could, however, reduce leaf development and photosynthate production.

Comparison of white cedar climatic response

Compared with black ash, radial growth in the two white cedar populations was very similar. In general, white cedar's radial growth was better in years with heavy precipitation and cool temperatures during the growing season. In northeastern Minnesota, Ahlgren (1957) observed that abrupt changes in white cedar stem diameter during the growing season were associated with sharp changes in temperature and that heavy rainfall (>2.2 mm) resulted in stem expansion. However, no attempt was made to determine whether stem expansion reflected an actual increase in radial growth or a temporary water swelling (Ahlgren 1957). Differences between the climatic response on

Fig. 3. Pearson correlation between white cedar residual chronologies and (a) mean monthly temperature for the period 1900–1990, (b) total monthly precipitation for the period 1900–1990, (c) the Canadian Drought Code for the period 1914–1990, and (d) the Harricana River discharge for the period 1916–1990. The dotted lines indicate a significant relationship at $p < 0.05$ (noncorrected significance level). The asterisks also indicate significant factors ($p < 0.05$) from the response function analyses testing each individual variable (temperature, precipitation, etc.) separately. Each model r^2 is indicated. Horizontally lined bars, xeric; crosshatched bars, mesic.



both the xeric and mesic sites were, however, observed, with white cedar growing in xeric sites being more affected by drought than trees from the more mesic sites.

Results presented in this study are in accord with those of Archambault and Bergeron (1992a), who found that a good water supply and low evaporation were the factors of importance on xeric sites. Similar results were also reported for *Juniperus virginiana* L., which was shown to have an inverse relationship to both temperature and precipitation during the growing season and a negative one to the Palmer drought index (McGuinness et al. 1983). Our results also agree with those of Kelly et al. (1994), who found that white cedar on the Niagara Escarpment cliff faces had a strong negative correlation with the previous growing season's July and August mean maximum temperature ($r = -0.43$ and -0.30 , respectively). In the Lake Duparquet area, this is especially true with respect to white cedar growing on mesic sites.

In the Abitibi region, white cedar on both mesic and xeric sites also responded to precipitation. No clear precipitation signal was reported by Kelly et al. (1994), who argued that this signal in Lake Duparquet was probably reflecting site-specific drought stress related to increased exposure to solar radiation on flat rocky islands and peninsula sites. Trees growing on mesic sites around Lake Duparquet also responded, however, to precipitation, and on these sites, the positive relationship to both May precipitation and the late spring Harricana River discharge suggests that white cedar radial growth may benefit somewhat from higher Lake Duparquet water levels.

In the Abitibi region, we hypothesize that white cedar response to precipitation may reflect regional conditions rather than being site specific. In addition to results presented here, Archambault and Bergeron (1992a) reported a highly signifi-

cant correlation between their chronology and a shorter one developed from xeric sites 14 km inland. Large and narrow rings were similar in both chronologies and stress the regional nature of white cedar's response to climate (Archambault 1989). In addition, Archambault and Bergeron's (1992a) chronology was also successfully used to date and cross-date old white cedar snags found on clay deposits with a moderate moisture regime in a stand on the shore of Lake Duparquet (Bergeron and Charron 1994). Furthermore, it was reported in Bergeron and Archambault (1993) that the growth pattern of white cedar located 600 km eastward corresponded to those from the Lake Duparquet area (H. Morin, personal communication). This suggests a general response by this species to climate throughout all of Quebec's southern boreal fringe.

The strong correlation between both the mesic and xeric white cedar chronologies for almost 400 years (not presented) also suggests that cambial dieback does not modify the climatic response of trees with different growth forms. Both stunted and normal trees reacted to the same general high frequency climatic signal. White cedar possesses a broad physiological tolerance to moisture availability, and its presence in contrasting habitats indicates site acclimation (Collier and Boyer 1989). It is not known, however, whether trees showing strong cambial dieback could be reacting to long-term climate change by forming wider (or smaller) tree rings, increased (or reduced) ring area, or both.

In conclusion, the results presented here demonstrate that both black ash and white cedar are affected in different ways by weather conditions during the active radial growth season and that environmental variation within a species' range can be important in filtering this climatic response. For black ash, flood conditions, because of their possible effect on the growing

season length, may have affected between-habitat cross dating and the species' response to climate. In this species, however, water availability at the time of shoot growth and leaf expansion as well as during the late growing season appears to be the dominant factor influencing radial growth. Unlike deciduous black ash, white cedar from both xeric and mesic sites reacted in a similar way to both the temperature and precipitation signals during the growing season. Sensitivity to drought was, however, observed and can be attributed to the more severe conditions encountered on the very dry rock outcrops.

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