# Effect of interannual climate variations on radial growth of jack pine provenances in Petawawa, Ontario

**Y. Savva, Y. Bergeron, B. Denneler, A. Koubaa, and F. Tremblay**

**Abstract:** Effect of interannual climate variations on radial growth was compared among jack pine (*Pinus banksiana* Lamb.) of diverse geographical origins in a 41-year-old common-garden experiment in Petawawa, Ontario. Provenance experiments established from seeds transferred from different parts of a species range (from the northern United States to northern Canada) to the same environment might be considered as a simulation model of climate change and a shift of climate zones. The following questions are addressed: Did the response of growth to interannual climate variations differ among the provenances transferred within the experimental site? What climatic factors affect interannual growth variations of jack pine provenances? Tree-ring chronologies for 16 populations were developed for the period 1970–2004. The best climate predictors of radial growth were precipitation of June and March of the current year and precipitation of December of the previous year. Although, climatic factors affecting growth were similar between the provenances, absolute radial growth was proportional to the growth potential of the provenances. We conclude that variability due to seeds origins is not a significant source of variation for dendroclimatic studies of jack pine. Increased frequency of summer droughts might result in a growth decrease of jack pine.

**Résumé :** Nous avons étudié les relations entre le climat et la croissance radiale annuelle de provenance de pin gris (*Pinus banksiana* Lamb.) établis depuis 41 ans dans un jardin commun à Petawawa en Ontario. Des tests de descendance établis dans des conditions similaires à partir de graines provenant de différentes parties de l'aire de distribution de l'espèce (depuis le Nord des Etats-unis jusqu'au nord du Canada) simulent des changements climatiques et des transitions entre différentes zones bioclimatiques. Nous avons tentés de répondre aux questions suivantes : Est-ce que la relation entre la croissance radiale interannuelle et le climat varie en fonction des provenances? Quelles sont les facteurs climatiques qui contrôlent la croissance radiale des différentes provenances. Des chronologies de la croissance radiale couvrant la période 1970–2004 ont été développées pour 16 provenances. Les facteurs climatiques les plus corrélés avec la croissance radiale sont les précipitations pour juin et mars de l'année en cours et les précipitations de décembre pour l'année précédente. Bien que les facteurs climatiques contrôlant la croissance sont les mêmes pour toutes les provenances, la croissance absolue variait en fonction du potentiel de croissance de chaque provenance. Nous concluons que la variabilité due à la provenance des graines ne constitue pas une source importante de variation dans la réponse dendroclimatique chez le pin gris. Une augmentation de la fréquence des sécheresses durant la période estivale pourrait entraîner une diminution de la croissance du pin gris.

## Introduction

Jack pine (*Pinus banksiana* Lamb.) is widely distributed over Canada and the northern United States (Rudolph and Laidly 1990). It is a source of pulpwood and lumber, which is an important contributor to the Canadian economy. Natural regeneration of this serotinous species occurs following periodic stand-replacing wild fires. It is one of the least shade-tolerant species and usually grows on sandy soils.

There were several reports on climate change over the last decades (International Panel of Climate Change (IPCC) 2007). Some studies showed that mean temperatures during the last three decades were likely the warmest of the last millennium (Jones et al. 2001). While predicted climate change can have tremendous effect on forest biomes, species composition, and distribution (Saxe et al. 2001), estimations of the potential effect are currently unknown. If climate change occurs, forest species might appear in other climatic and biological zones. Some studies have shown potential

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**Y. Savva,[1,2] Y. Bergeron, B. Denneler,[3] and F. Tremblay.** Chaire Industrielle CRSNG-UQAT-UQAM en Aménagement Forestier Durable, Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université, Rouyn-Noranda, QC J9X 5E4, Canada.
**A. Koubaa.** Chaire de Recherche du Canada en Valorisation, Caractérisation et Transformation du Bois, Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université, Rouyn-Noranda, QC J9X 5E4, Canada.

[1]Corresponding author (e-mail: julia.savva@uqat.ca).
[2]Present address: Université du Québec à Montréal, Département des sciences biologiques, CP 8888 Succ Centre Ville, Montréal, QC H3C 3P8, Canada.
[3]Deceased.

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**Table 1.** Site origin descriptions and descriptive statistics of ring-width chronologies of jack pine (*Pinus banksiana*) populations in a common garden in Petawawa, Ontario (45°58′N, 77°25′W, at 183 m a.s.l.) calculated for the period 1970–2004.

| Provenance No. | Provenance origin | Sample size (no. of trees) | Latitude and longitude | Elevation (m a.s.l.) | Mean annual temp. (°C) | Mean max. daily temp. (°C) | Total annual precipitation (mm) | Standard deviation of standard chronology | Autocorrelation of first order of standard chronology | RBAR of tree-ring series | Sensitivity of standard chronology |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Toulnoustook River, Quebec | 15 | 49°7′N, 68°4′W | 76 | 1.5 | 6.3 | 1014 | 0.24 | 0.07 | 0.442 | 0.22 |
| 30 | Port Alfred, Quebec | 17 | 48°3′N, 70°9′W | 251 | 2.3 | 7.9 | 951 | 0.25 | –0.05 | 0.386 | 0.20 |
| 37 | Lac Des Loutres, Quebec | 20 | 49°6′N, 72°2′W | 229 | –0.9 | 4.6 | 954 | 0.20 | 0.30 | 0.461 | 0.17 |
| 45 | York River, Ontario | 26 | 45°2′N, 77°7′W | 320 | 4.0 | 10.5 | 843 | 0.22 | 0.32 | 0.498 | 0.17 |
| 47 | Harry Lake, Quebec | 21 | 46°4′N, 76°2′W | 183 | 3.7 | 9.9 | 909 | 0.24 | 0.37 | 0.415 | 0.20 |
| 48 | Baskatong Lake, Quebec | 18 | 46°8′N, 76°1′W | 244 | 3.3 | 9.2 | 1015 | 0.25 | 0.44 | 0.538 | 0.17 |
| 49 | Capitachouare River, Quebec | 21 | 47°8′N, 76°7′W | 457 | 2.8 | 7.9 | 950 | 0.20 | 0.40 | 0.419 | 0.17 |
| 55 | Clark Point, Ontario | 18 | 44°1′N, 81°8′W | 180 | 6.7 | 11.8 | 1121 | 0.27 | 0.45 | 0.489 | 0.20 |
| 57 | Miller Lake, Ontario | 13 | 45°1′N, 81°5′W | 198 | 6.6 | 10.8 | 830 | 0.21 | 0.39 | 0.379 | 0.15 |
| 61 | Benny, Ontario | 13 | 46°8′N, 81°6′W | 396 | 3.7 | 8.8 | 899 | 0.20 | 0.28 | 0.471 | 0.17 |
| 62 | Cowganda Lake, Ontario | 18 | 47°7′N, 80°7′W | 335 | 2.2 | 8.2 | 785 | 0.23 | 0.38 | 0.494 | 0.19 |
| 63 | Nellie Lake, Ontario | 22 | 48°8′N, 80°8′W | 305 | 0.9 | 7.4 | 776 | 0.22 | 0.36 | 0.434 | 0.17 |
| 70 | Nokomis, Wisconsin | 20 | 45°6′N, 89°8′W | 472 | 6.4 | 12 | 847 | 0.18 | 0.46 | 0.421 | 0.13 |
| 79 | Cloquet, Minnesota | 22 | 46°7′N, 92°6′W | 390 | 4.6 | 11.2 | 807 | 0.18 | 0.31 | 0.402 | 0.13 |
| 81 | Fort Frances, Ontario | 17 | 48°8′N, 93°5′W | 338 | 2.9 | 8.8 | 721 | 0.19 | 0.25 | 0.460 | 0.12 |
| 86 | Red Lake, Ontario | 15 | 51°0′N, 94°1′W | 354 | 0.9 | 6.4 | 640 | 0.20 | 0.56 | 0.415 | 0.18 |

shifts for tree species (Iverson and Prasad 1998), dramatic change in the sensitivity of tree growth to temperature forcing (Briffa et al. 1998*a*, 1998*b*), and changes and shifts in the main climatic factors controlling tree growth for the last several decades (Solberg et al. 2002; Wilson and Elling 2004; Buntgen et al. 2006).

Provenance experiments established from seeds transferred from different parts of a species range to the same environment might be considered as a simulation model of climate change and a shift of climate zones (Matyas 1999; Rehfeldt et al. 1999). Recently, there were several studies using provenance material for analysis of the effect of climate change on growth of jack pine and its adaptation to climate change (Matyas and Yeatman 1992; Parker et al. 2006; Savva et al. 2007). Parker et al. (2006) analyzed height, diameter, and survival data of jack pine populations from 16 of the provenance tests in Canada and concluded that northern seed sources were currently growing at temperatures below the optimum and would benefit from transfer to warmer environments and from increased global temperatures in the future. Central sources were currently growing at optimum or close to optimum and would be negatively affected by increased temperatures in the future. Southern seed sources might currently benefit from transfer to cooler environments and might be negatively affected by global warming. Matyas and Yeatman (1992) analyzed height growth of jack pine provenances planted at eight sites in Ontario and showed that height growth of jack pine populations was shaped by thermo- and photo-periodic effects and that the southern seed sources might benefit from a moderate transfer up north. Savva et al. (2007) studied ring width of jack pine provenances of the same provenance experiment in southern Ontario and also showed that the southern seed sources might benefit from a moderate transfer of seeds up north.

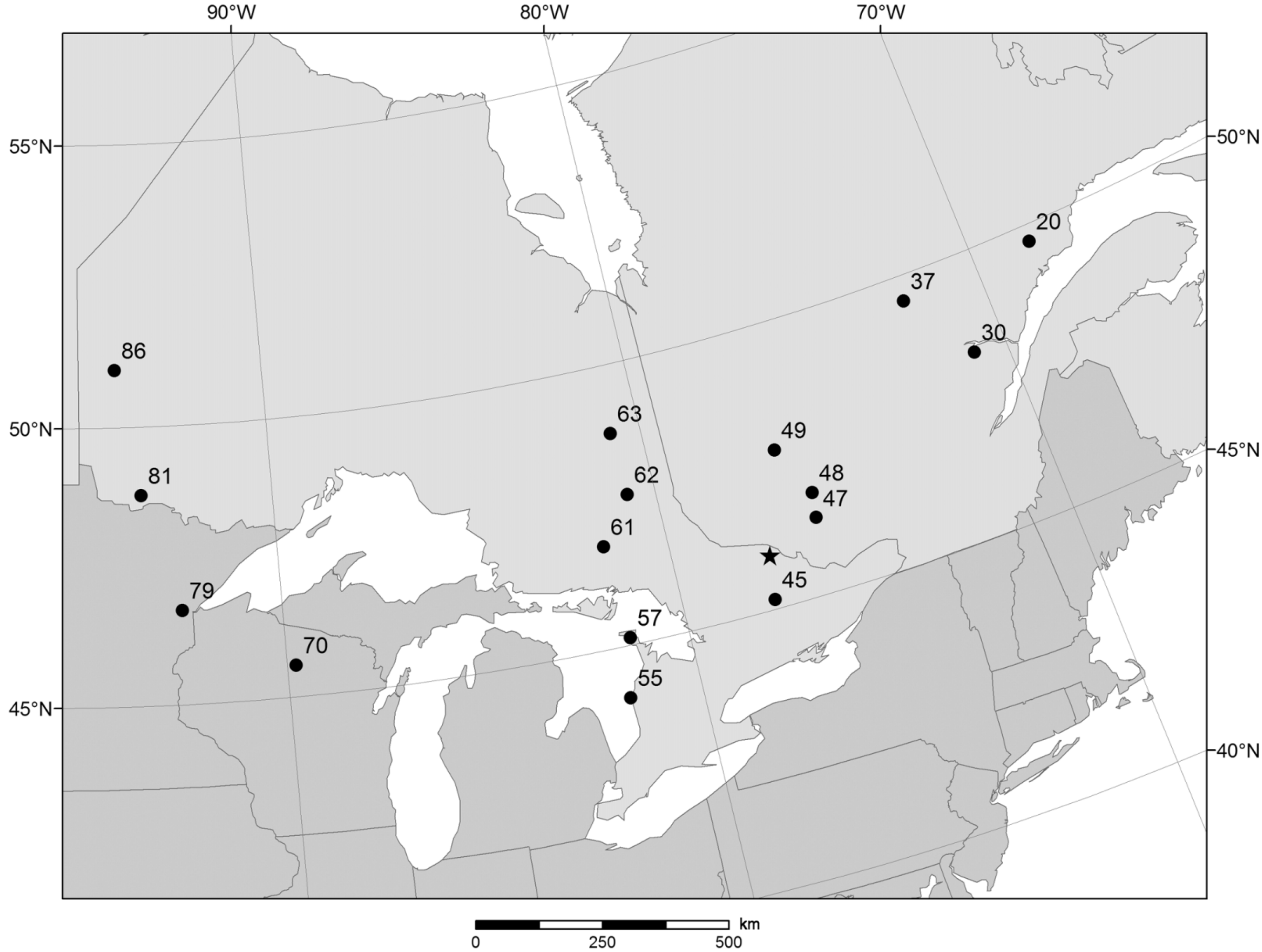
Recently, there have been discussions about responses of trees to climate that are not uniform (from the International Tree-ring Data Bank forum). The possible reasons might include genetic differences, genotype by environment interactions, varying climate, forest disturbances, and pollutant depositions. Provenance material might be used to test this hypothesis if trees of diverse geographical origins do not respond to climate uniformly, and seed-source origins should be taken into account in climate reconstructions and predictive growth models.

Despite the long interest in tree response to climate variability, relatively few studies exploring interannual radial growth variations and their environmental correlates using common-garden experiments have been conducted (Oleksyn et al. 1993, 1998; Savva et al. 2002, 2003). Tree rings integrate information on tree genetics and environmental variability (Fritts 1976; Schweingruber 1996), and application of the methods of dendroclimatology to provenance material could enable comparison of the responses of diverse populations planted in the same environment to climatic factors and predict a potential effect of climate change on their growth.

We addressed the following questions:

(1) Did response of growth to interannual climate variations differ among the diverse provenances transferred into the same experimental site?

**Fig. 1.** Map of the geographical locations of jack pine (*Pinus banksiana*) populations studied in a common garden in Petawawa, Ontario. The study site is indicated with a star and the studied provenances (16) are indicated with circles. See Table 1 for the details regarding the numbers of the provenances.




(2) What climatic factors affect interannual growth variations of diverse jack pine provenances?

These questions are discussed in the context of the potential effect of future climate change on the growth of jack pine.

## Material and methods

### Study material

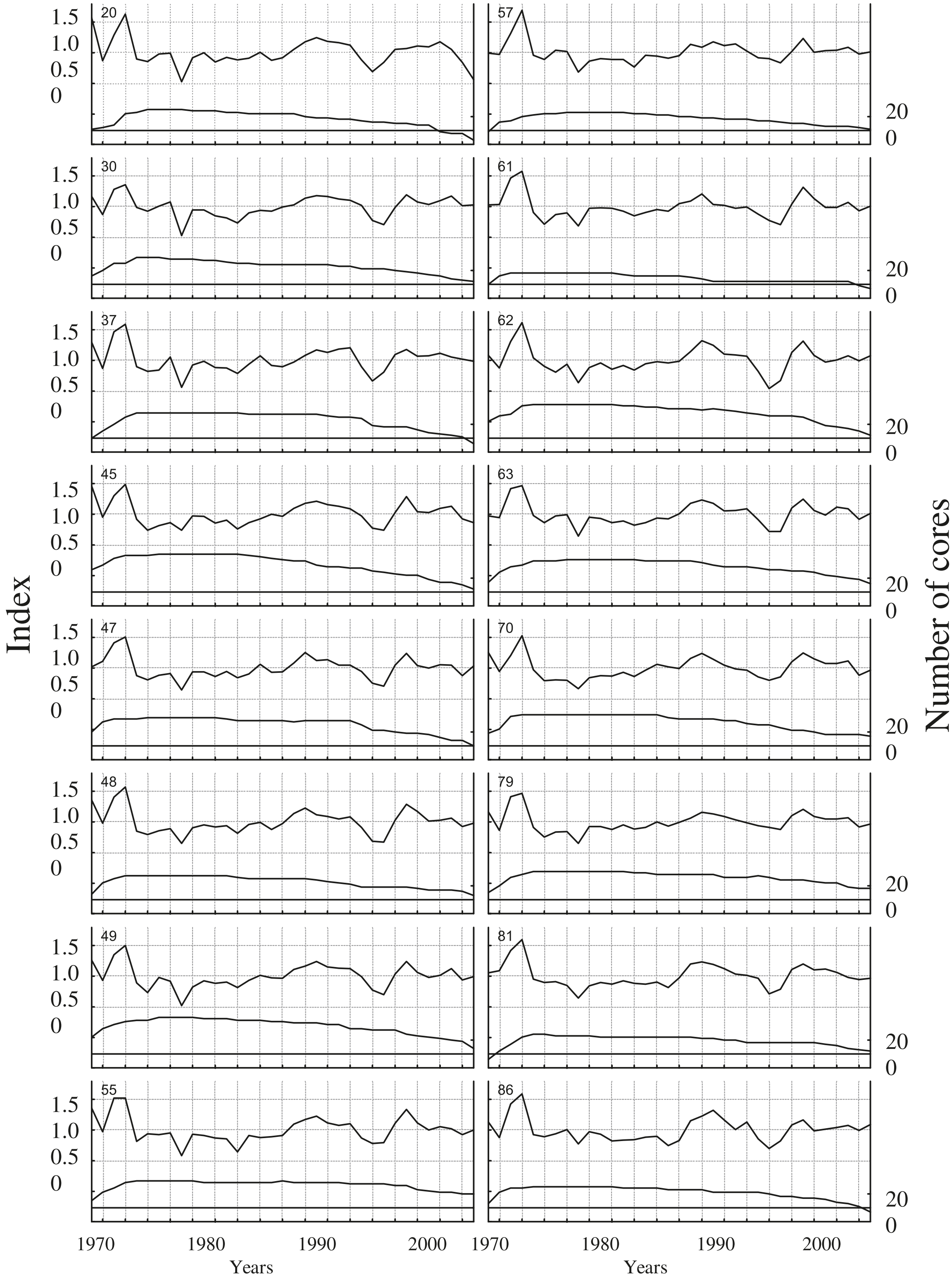
We studied a common-garden plantation of jack pine in the Petawawa Research Forest, southern Ontario (45°58′N, 77°25′W), that is part of a rangewide provenance experiment established in 1966. Seed sources from 99 geographical origins were collected from native stands throughout the geographic range of the species and planted at several sites in Canada and the United States (Holst 1967). For this test all seeds were sown in nurseries in Petawawa in 1964 and transferred to the planting sites 2 years later. The experimental design of the common-garden plantation in Petawawa is a triple lattice square. The experimental plantation consisted of 10 blocks (replications) and one demonstration block near the edge of the plantation. Every block included one plot per provenance whose position within the block was randomly assigned. Every plot was initially represented by 10 trees of the same provenance in a single row and planted at an 1.8 m × 1.8 m spacing. The mineral soil of the planting site is an acidic, light-textured sandy loam on granite sand with stony till sediments (Wilde 1946; Hills and Pierpoint 1960).

There was a history of thinning of this trial in the fall of 1987. Every third tree of the 10-tree row plots was removed regardless of previous mortality in adjacent trees. At least one side of every remaining tree would have been exposed to thinning. This thinning was part of the original plan for the test to prevent growth stagnation (personal communication with W.H. Parker, Lakehead University, Thunder Bay, Ontario).

### Ring-width chronologies statistics

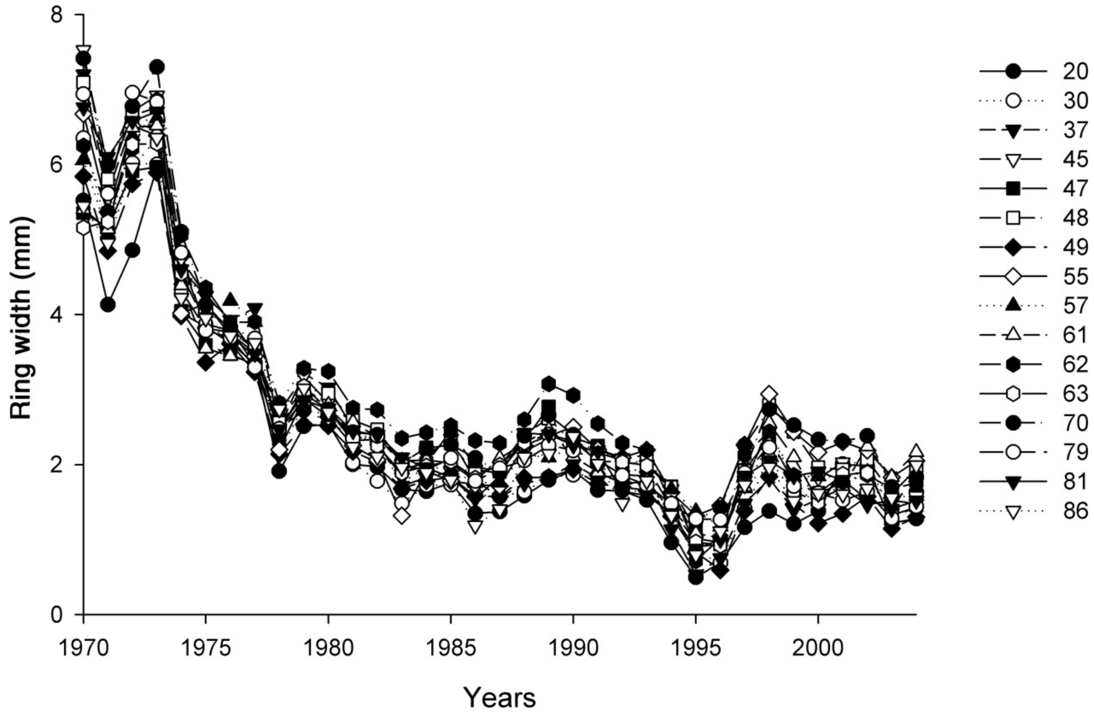
For this study we used tree-ring cores of 16 *Pinus banksiana* Lamb. provenances that were collected within the Petawawa common-garden plantation in the fall of 2006 (Table 1 and Fig. 1). We selected the provenances to ensure

**Fig. 2.** Ring-width chronologies of jack pine (*Pinus banksiana*) populations in a common garden in Petawawa, Ontario. The numbers of the populations are shown for each tree-ring chronology (see Table 1 for details). The upper plots show the annual tree-ring indices. The lower plots show the sample size for each year. The horizontal lines indicate a level at 10 numbers of cores. All chronologies are truncated at a sample size less than five series.




a wide range of origins in latitudinal and longitudinal directions so that they were located along several latitudinal and longitudinal transects that might be of interest for other studies in the future. We excluded four northeastern and two southern provenances that originate near the Great Lakes prior to the analysis because they did not pass statisti-

**Fig. 3.** Mean raw ring-width chronologies of jack pine (*Pinus banksiana*) populations in a common garden in Petawawa, Ontario. The numbers of the populations are shown for each tree-ring chronology (see Table 1 for details).




cal tests for this study (low sample size, the average correlation among all series (RBAR) or expressed population signal (EPS)) and, therefore, were not able to show a strong climatic signal for the analysis of the relationships of growth with climate, which might be related to the increased mortality of trees of these populations at some period of time.

For each tree, we collected one core, which included two radii. We collected about 20 cores for each provenance. Cores were taken at approximately 50 cm above ground to ensure a maximum number of tree rings. This height above the base represented a loss of about 3–6 years growth in relation to the total tree age.

The total number of ring widths was measured with the QTRS-01X tree-ting scanner (QMC, Knoxville, Tennessee). The QTRS-01X utilizes X-ray technology to receive density profiles and measures annual ring-width and density characteristics of tree-ring samples. We used a 0.04 mm linear resolution step size for measurements. The measured tree-ring series for every tree were cross-dated and quality-checked with COFECHA software (Holmes 1983). Correlation coefficients between single tree-ring series of the populations were high and varied from 0.81 to 0.99 at $p < 0.01$. Correlation analysis and output of the COFECHA software showed that the tree-ring series were correctly cross-dated.

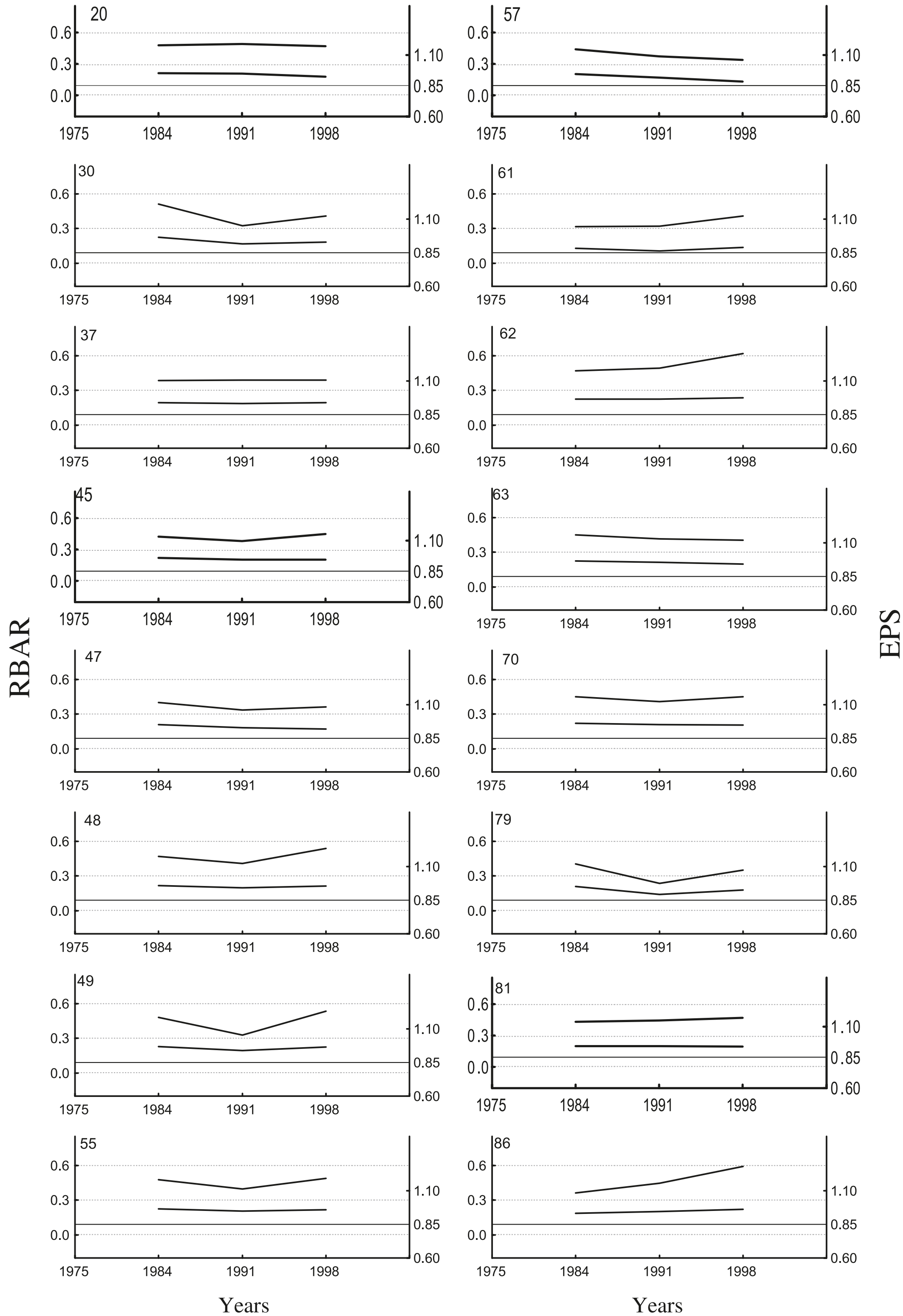
Ring-width chronologies were developed with ARSTAN software (Cook 1985) for every provenance using individual tree-ring series of the provenances. To minimize a post-thinning effect and emphasize interannual high-frequency variations, a spline function with a 50% frequency response of 30 years was fitted to the individual tree-ring series and indices were calculated as the differences between the observed and the expected values for every provenance. Flexible cubic spline curves are efficient at removing a long-term trend and the effect of localized disturbance events, such as the long-term afterthinning effect, but at the risk of removing possible low-frequency climatic information (Cook et al. 1990). Given the stand-thinning history and that the length of the tree-ring chronologies of jack pine populations is not long enough to study low-frequency variations, we considered using spline curves for detrending. This detrending technique preserved interannual growth variations related to high-frequency climate variations. Obtained tree-ring chronologies were referred to as standard chronologies.

The sample size decreased for the developed chronologies at the ends (Fig. 2). It was related to accidental breaks of some samples, especially for the two to three last rings of the increment cores during the sawing and extraction procedure that we used for the future work with wood density. Including these small pieces in the analysis might have increased the chance of incorrect cross-dating of the material.

To ensure the quality of the developed chronologies they were truncated at a sample size less than five. It resulted in a loss of the last year (2005) for some provenances. The first date of the chronologies varied from 1967 to 1970 among the provenances. The first few rings (1967–1970) had a shape that could be well described as a hump of the Hugershoff function and contained an increased nonclimatic signal that might not be always correctly separated from climate-related variations in tree rings. Therefore, we studied the growth of the provenances for the common growth period 1970–2004.

Chronology statistics, such as mean sensitivity (a measure of the annual variability in tree rings), EPS, RBAR, and a first-order autocorrelation of standard chronologies (a measure of the association between growth in the previous year and that in the current year), were calculated to show the

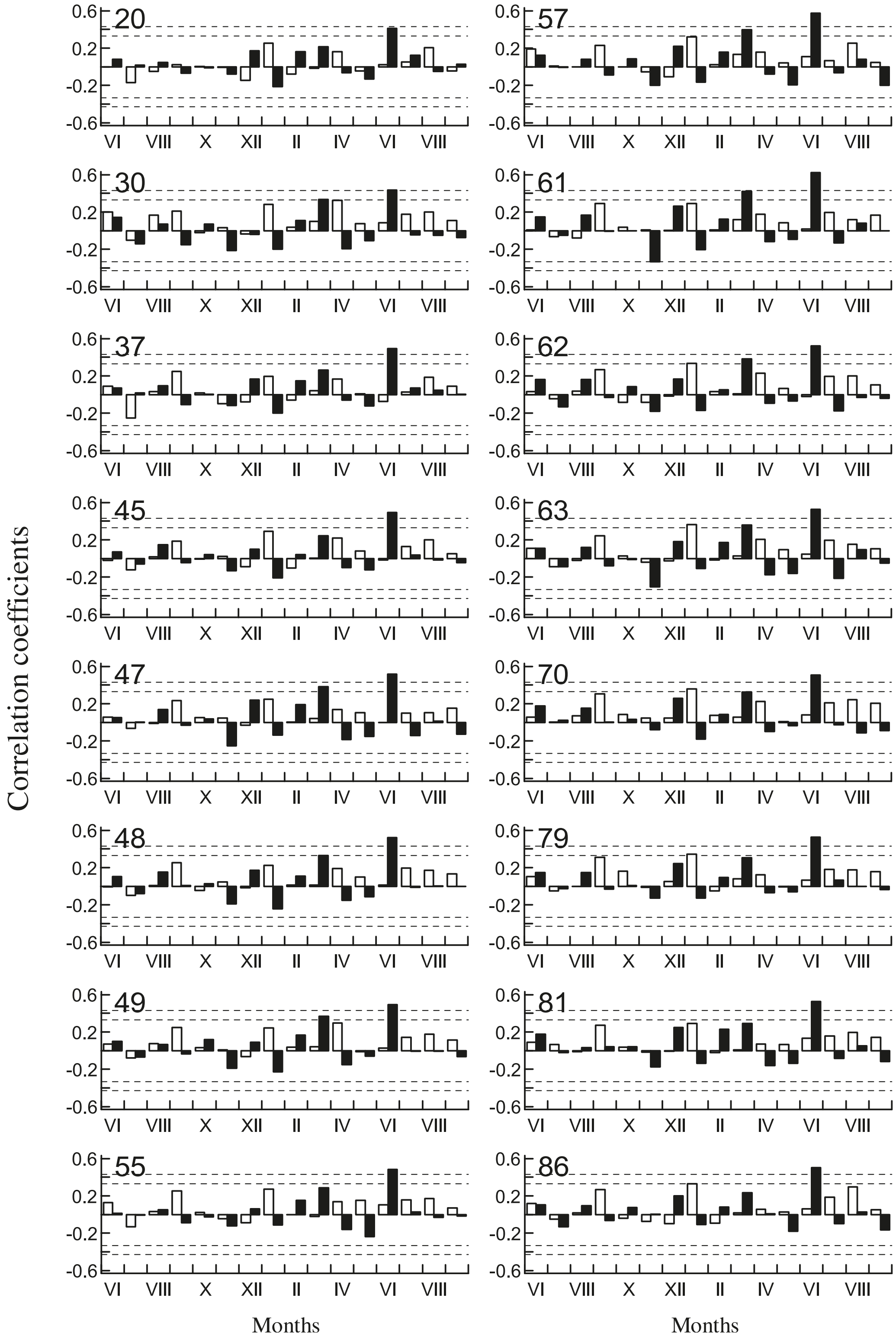
**Fig. 4.** Running average correlation between all series (RBAR, upper plots) and expressed population signals (EPS, lower plots) of the tree-ring chronologies of jack pine (*Pinus banksiana*) populations based on a 14 year window with 7 year overlaps. The rough cutoff point for accepting EPS is 0.85. The numbers of the populations are shown for each tree-ring chronology (see Table 1 for details).




statistical characteristics of the tree-ring chronologies (Table 1).

RBAR is a measure of common variance between single series, independent of the number of measured series (Wigley et al. 1984). EPS measures how well the finite-sample chronology compares with the theoretical population chronology based on an infinite number of trees (Wigley et al. 1984). It varies from 0.0 to 1.0. The rough cutoff point for

**Fig. 5.** Correlation coefficients relating mean monthly temperature and precipitation to the tree-ring chronologies of jack pine (*Pinus banksiana*) populations for the period 1970–2004. The horizontal lines indicate significance levels ($p < 0.05$ and $p < 0.001$). The correlation coefficients were calculated for 16 months from June of the previous growth year to September of the current growth year. The numbers of the populations are shown for each tree-ring chronology (see Table 1 for details).

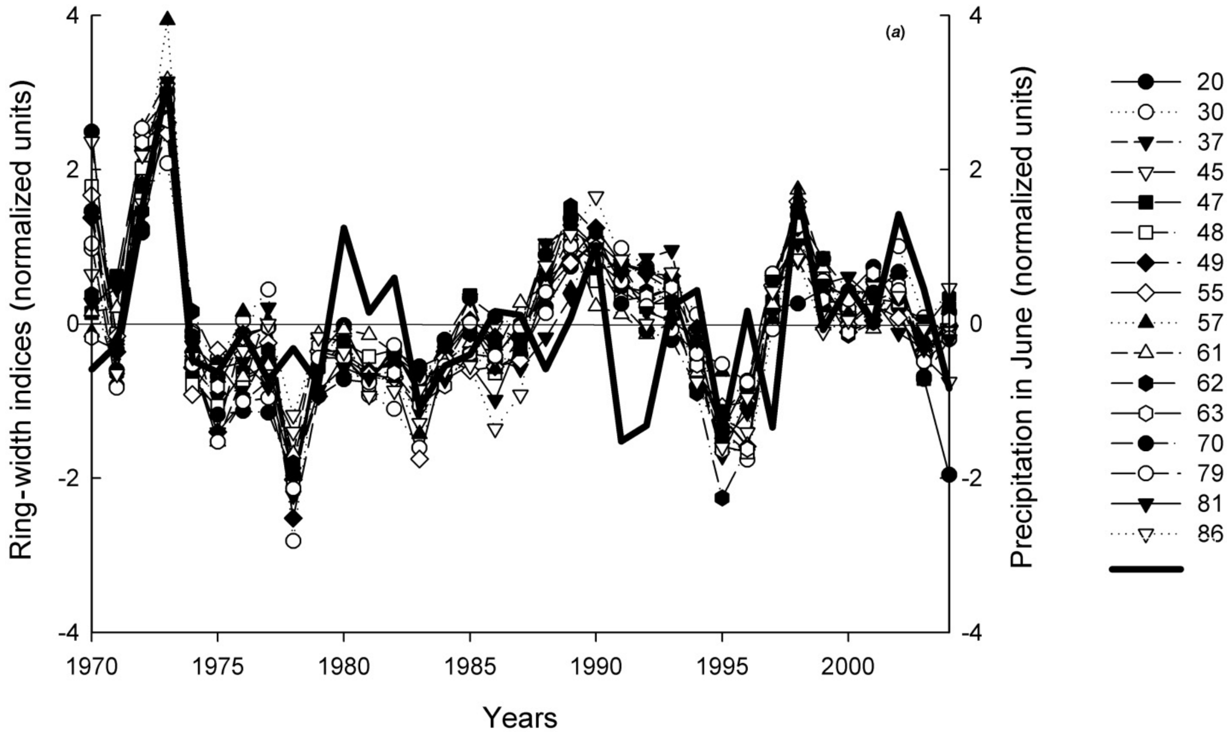


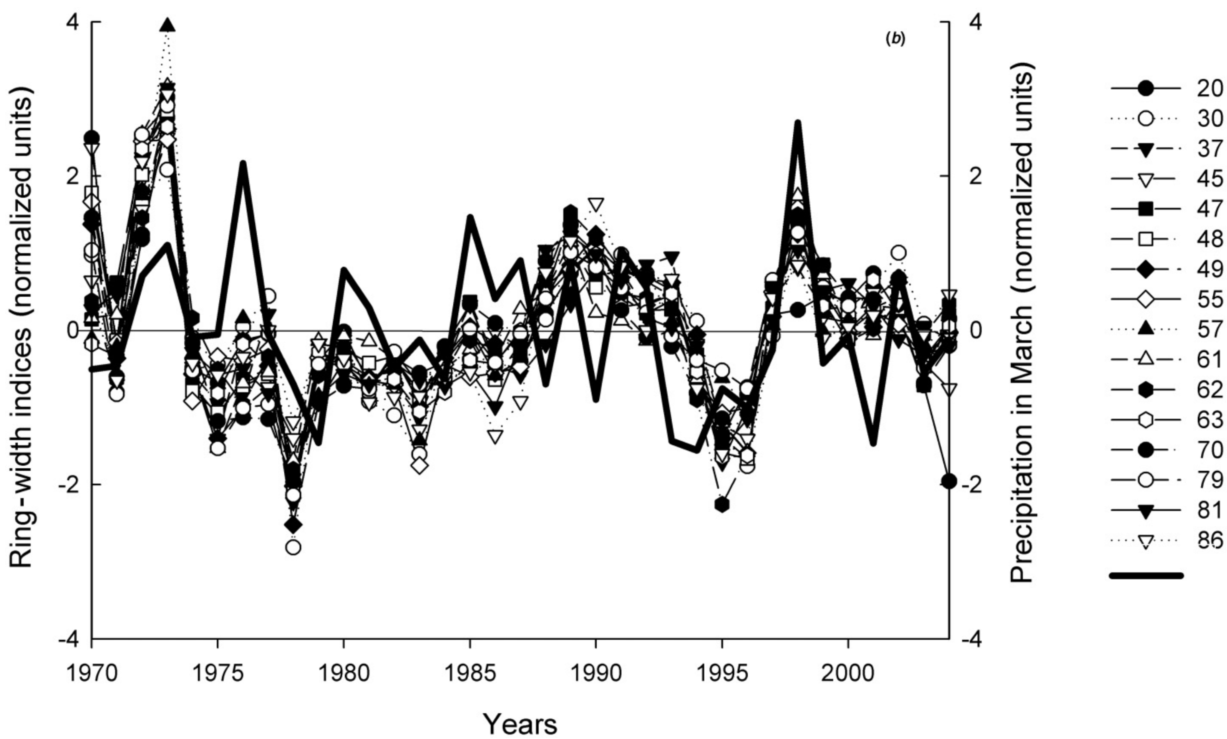

accepting EPS is considered by Wigley et al. (1984) to be 0.85. RBAR and EPS values were computed using a 14 year moving window with a 7 year overlap.

## Climate data

For the weather station closely located to the plantation site, mean monthly temperature and precipitation data were

**Fig. 6.** Interannual variations in tree-ring indices of jack pine (*Pinus banksiana*) populations and monthly precipitation in June and March for the period 1970–2004, scaled to zero mean with equal variances. The numbers of the populations are shown for each tree-ring chronology (see Table 1 for details). The bold lines indicate yearly changes in monthly precipitation.




downloaded for the period 1970–2004 from the Environment Canada web site (Environment Canada 2007).

## Climate–growth relationships

Climate–growth relationships for the provenances were analyzed by calculating correlation coefficients between the standard tree-ring chronologies and mean monthly temperature and precipitation data in Petawawa for the period 1970–2004. We chose mean monthly temperature and precipitation data over a 16 month period from June of the previous year to September of the current year as predictor variables for current-year tree-ring indices.

**Table 2.** General linear model relating tree-ring indices calculated for the period 1970–2004 for 16 jack pine (*Pinus banksiana*) provenances to climate, thinning, and provenance effects in Petawawa, Ontario.

| Source of variation | SS | df | MS | *F* | *p* |
|---|---|---|---|---|---|
| Precipitation in March | 1.01 | 1 | 1.01 | 45.9 | 0.001 |
| Precipitation in June | 3.47 | 1 | 3.47 | 157.5 | 0.001 |
| Precipitation in December of previous year | 1.27 | 1 | 1.27 | 57.8 | 0.001 |
| Thinning[a] | 2.02 | 1 | 2.02 | 91.6 | 0.001 |
| Provenance | 0.01 | 15 | 0.01 | 0.1 | 1.000 |
| Thinning[a] by provenance | 0.05 | 15 | 0.01 | 0.2 | 1.000 |
| Error | 11.60 | 526 | 0.02 | | |

**Note:** SS, the sum of squares between the means for a given effect; df, degrees of freedom for a given effect; MS, mean square defined as the sum of squares between the means for a given effect divided by its df; and *F* is calculated as a ratio of MS and MS error.

[a]Thinning: term included in the model as a dummy variable and assigned as 0 for the period before thinning (1970–1987) and 1 for the period after thinning (1988–2004).

We also used a general linear model (GLM) to develop relationships between ring-width indices and climate effect, afterthinning effect (indicated further as thinning in the text and tables), and provenance effect. Calculated tree-ring indices of the provenances for the period 1970–2004 were used as dependent variables. The variable responsible for thinning effect was represented as a dichotomous variable and was assigned a value of 0 for the period before thinning (1970–1987) and 1 for the period after thinning (1988–2004). Provenance effect was a categorical predictor, and mean monthly temperature and precipitation data over a 16 month period from June of the previous year to September of the current year for the period 1970–2004 served as continuous variables. All continuous dependent and independent variables such as ring width and climate data were centered around zero.

We tested several linear models with different combinations of the predictors using statistical software Statistica 6.0 (available from www.Statsoft.com). Adjusted $R^2$, Mallow's $C_p$ statistics, and the significance of the model's coefficients served as criteria for the selection of the best subset model among the tested models.

## Results

### Statistical characteristics of tree-ring chronologies

The age trend of ring-width chronologies was similar among the studied populations showing a precipitous growth decrease followed by a leveling off (Fig. 3). Tree-ring chronologies of the provenances were also highly correlated and showed a high similarity in interannual ring-width variations (Fig. 2). Descriptive statistics for the developed tree-ring chronologies showed that the used ring-width series and sample sizes of the provenances were representative for developing tree-ring chronologies and contained a common climatic signal for a given provenance (Table 1, Fig. 2, and Fig. 4). Mean RBARs ranged from 0.38 to 0.54 and showed relatively strong common signals between individual tree-ring series of every provenance. EPS values were high for the studied period for all provenances and exceeded the rough cutoff value of 0.85, indicating that a given subsample of a population is in a high agreement with the theoretical population chronology for every studied provenance.

The values of mean sensitivity varied from 0.12 to 0.22 showing that interannual ring-width variability of the provenances was relatively low. The values of the first-order autocorrelation varied from –0.05 to 0.56 for the provenances and showed the correlation of growth of the previous year with growth of the current year.

### Climate–growth relationships

Correlation coefficients between developed tree-ring chronologies and climate data showed that, for almost all provenances, precipitation in March ($p < 0.05$) and June ($p < 0.001$ for provenances 57 and 61, originated in Miller Lake and Benny, Ontario, and $p < 0.01$ for all other provenances) were positively correlated with ring-width indices of the provenances (Figs. 5 and 6). Several provenances showed a positive effect of temperature on interannual growth variations in January.

We used a GLM to account for climate and thinning effects. The best subset of the GLM had the following significant terms: March precipitation ($p < 0.001$) and June precipitation ($p < 0.001$) of the current growth year, December precipitation of the previous year ($p < 0.001$), and a thinning effect ($p < 0.001$) (Table 2). Including provenance-related terms in the model, such as provenance effect and thinning by provenance interaction effect, did not improve the model and were not significant.

Standardized regression coefficients showed that the most significant effect was the positive effect of June precipitation, followed by thinning effect, variations in the December precipitation of the previous year, and March precipitation (Table 3).

The multiple $R^2$ values showed that the model explained 38% of the total variation in ring-width indices of the jack pine provenances in Petawawa. Including a thinning term in the model improved the multiple $R^2$ values by 7% alone.

## Discussion

This study is among only a handful that have considered the relationship between interannual growth variations of diverse populations and environmental variability. In spite of the significant differences in annual radial growth between the provenances that we found earlier for the same provenance experiment (Savva et al. 2007), age trends and interannual variations of ring width did not differ much among

**Table 3.** Estimated parameters of the general linear model relating tree-ring indices calculated for the period 1970–2004 for 16 jack pine (*Pinus banksiana*) populations in a common garden in Petawawa, Ontario, to climate variables and a thinning effect.

| Effect | Parameter (±SE) | *t* | *p* | –95.00% Cnf. Lmt. | +95.00% Cnf. Lmt. | $\beta$ (±SE) | –95.00% Cnf. Lmt. | +95.00% Cnf. Lmt. |
|---|---|---|---|---|---|---|---|---|
| Thinning[a] | 0.0784 (0.0096) | 8.1 | 0.001 | 0.0595 | 0.0974 | 0.29 (0.04) | 0.22 | 0.36 |
| Precipitation in March | 0.0016 (0.0003) | 5.5 | 0.001 | 0.0010 | 0.0022 | 0.19 (0.04) | 0.12 | 0.26 |
| Precipitation in June | 0.0024 (0.0002) | 13.3 | 0.001 | 0.0020 | 0.0027 | 0.47 (0.04) | 0.40 | 0.53 |
| Precipitation in December of previous year | 0.0020 (0.0003) | 6.7 | 0.001 | 0.0014 | 0.0026 | 0.24 (0.04) | 0.17 | 0.31 |

**Note:** Cnf. Lmt., 95% confidence interval limit; and $\beta$, standardized regression coefficients (the magnitude of these coefficients allows comparison of the relative contribution of each independent variable in the prediction of the dependent variable).

[a]Thinning: dummy variable showing before and after thinning effect. It equals 1 for the period after thinning (1988–2004), otherwise 0 (1970–1987).

the studied populations in response to climate variations. Our analysis showed that the interannual ring-width variations of the provenances were mainly controlled by environmental variability. Climate variations and thinning practice in 1987 mainly affected interannual growth of the provenances, whereas the provenance effect related to seed-source origins was not significant in predicting relative interannual growth variations. Climate factors affecting growth were similar between the provenances, and absolute radial growth of the provenances was proportional to the growth potential of the provenances (Savva et al. 2007).

Precipitation in June and March of the growth year and precipitation in December of the previous year mainly affected radial growth variations of the provenances over the last 34 years. This can be explained by the fact that the jack pine mainly grows on sandy soils, which have a low water-storage capacity. Trees were likely to experience drought stress mainly in summer because of this season's high temperatures. Therefore, increased amounts of summer precipitation could positively affect growth of jack pine populations. A positive effect of precipitation on growth of jack pine was also found earlier by Larsen and MacDonald (1995), who studied jack pine and white spruce (*Picea glauca* (Moench) Voss) in northern Alberta and showed that one of the standard and residual chronologies was positively correlated with precipitation in June. Brooks et al. (1998) also showed that radial growth of jack pine in south-central Canada positively responded to spring precipitation. Hofgaard et al. (1999) demonstrated that a moist summer in the prior year and an early start of the current growing season favoured the growth of jack pine in western Quebec.

It is challenging to minimize the effect of thinning to maximize interannual climate variations in tree rings of the provenances owing to a lack of data and studies of precommercial thinning effect on growth dynamics of jack pine trees after thinning (Smith et al. 1986; Barbour et al. 1994; Tong and Zhang 2005). There are a number of factors that could affect temporal growth dynamics of trees after thinning including site index and intensity of thinning treatment. While stand management diagrams (SDMD) were developed for dynamic relationships among stand density, tree size, and wood volume at various stages of stand development for jack pine (Sharma and Zhang 2007), they are usually applied to untreated stands, which is not the case in our study of the diverse populations.

Results based on correlation coefficients between climate factors and radial growth indices were similar to the developed regression model, which included a thinning treatment effect, showing the robustness of our analysis and the conclusions about positive spring and summer precipitation effects on growth of the jack pine populations.

This study contributes to our knowledge concerning the effect of climate change on the growth of jack pine in the area of Petawawa, Ontario. It also has implications for dendrochronologists who are searching for answers to the question of whether trees of different geographical origins record the same information about environmental variability, which is of interest in light of current debates about possible explanations for the lack of uniformity in the response of trees to climate change.

## Conclusions

Based on this study of jack pine populations for the 34 year period the following conclusions can be drawn:

(1) Although interannual growth variations were mainly controlled by environmental variations and did not differ significantly between the jack pine provenances, absolute radial growth differed between the provenances and was determined by a growth potential of the provenances. For dendroclimatological purposes, growth variability of jack pine induced by differences in seed-source origins should not be considered as a significant cause of the lack of uniformity in the response of trees to climate change. However, variations of the seed-source origin of jack pine should be taken into account for the development of predictive growth models.

(2) Precipitation in summer and spring were significantly correlated with radial growth of the jack pine populations. We suggest that, if climate warming resulted in increased frequency of summer droughts, it might negatively affect growth of jack pine in this area. For forest management purposes, other characteristics should be also taken into account such as absolute growth and other traits, mortality, and adaptation to environmental variability.

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