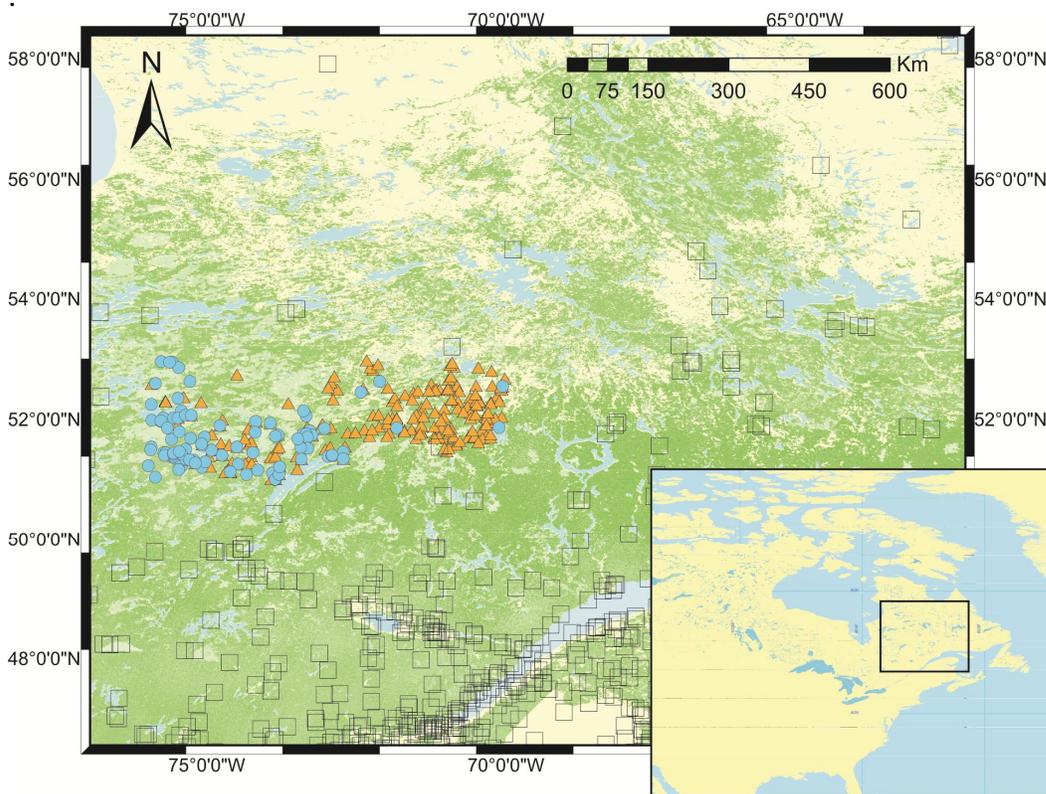


## Supplemental material

### Appendix 1 Distribution of tree-ring sampling sites

The black spruce and jack pine forests under study encompass 76°W to 70°W and 51°N and 53°N (Fig. S1). Data on forest composition, stand age (oldest trees approximated by tree-ring count), soil texture, aspect and slope were obtained from a database of 400 m<sup>2</sup> circular sample plots established by the ministère des Ressources naturelles et de la Faune du Québec in 2005 and 2006 (Program d'inventaire écoforestier nordique: Létourneau et al., 2008). A total of 284 sample plots were preselected for our work; only those plots that had all the available information necessary for modeling experiments were used.



**Fig. S1.** Distribution of tree-ring sampling sites used in this study. Triangles and circles denote black spruce and jack pine dominated stands, respectively. The distribution of available weather stations across the territory is shown by squares. The background colours indicate the stand age distribution as of 2008 (data from Chen et al. 2003), with darker tones referring to mature and overmature stands.

## Appendix 2 Computation of the tree growth index (TGI) time series

All ring-width measurement series were rescaled using a power transformation method and detrended using negative exponential modeling in order to eliminate noise caused by site- and biological-related effects such as resulting from competition, self-thinning and aging.

The method used for computation of the plot-level TGI time series was derived from methods described by Cook and Peters (1997):

- 1) the first 10 years of each measurement series was removed to avoid biases induced by the abrupt phase of post-fire growth acceleration at the juvenile stage;
- 2) the power for each individual tree ring series was estimated and applied using the power transformation method;
- 3) each individual transformed series was fitted with three growth trend models, that is, linear (*L*), negative exponential (*NE*) and generalized negative exponential (*GNE*):

$$L : Gt = a + bt$$

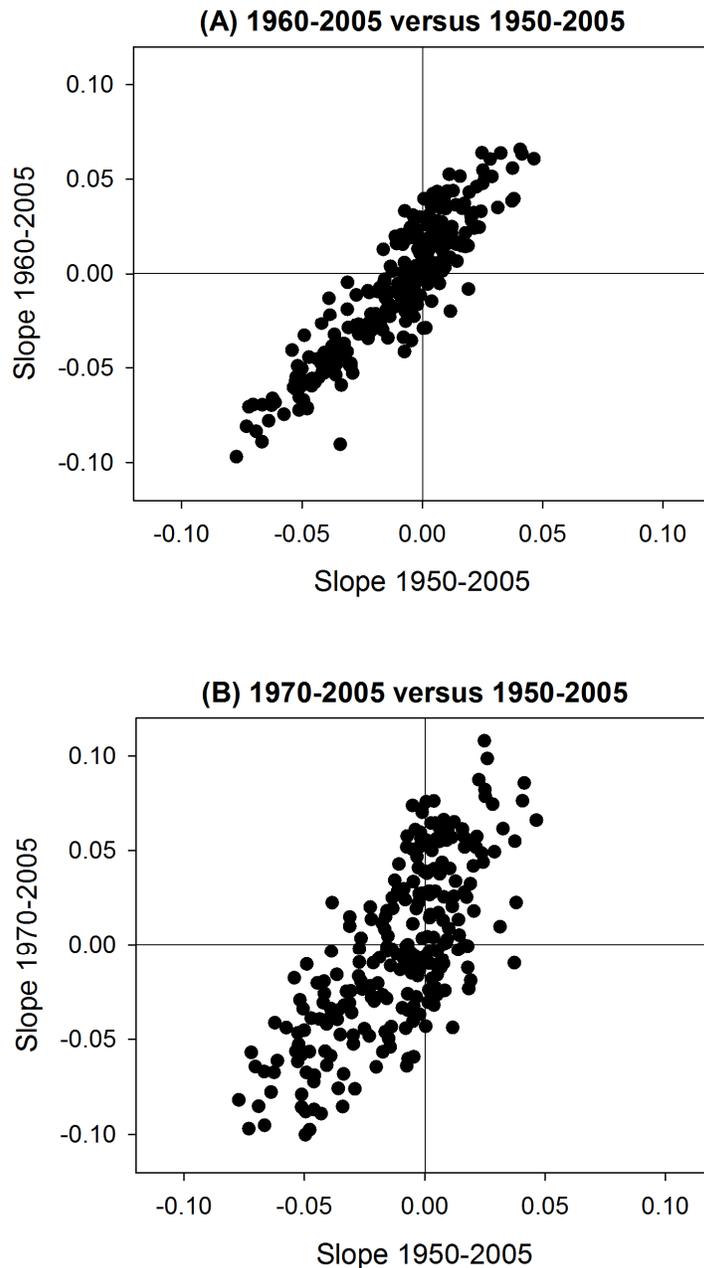
$$NE : Gt = a * \exp(bt)$$

$$GNE : Gt = a * \exp(bt) * t^c$$

where t represents year;

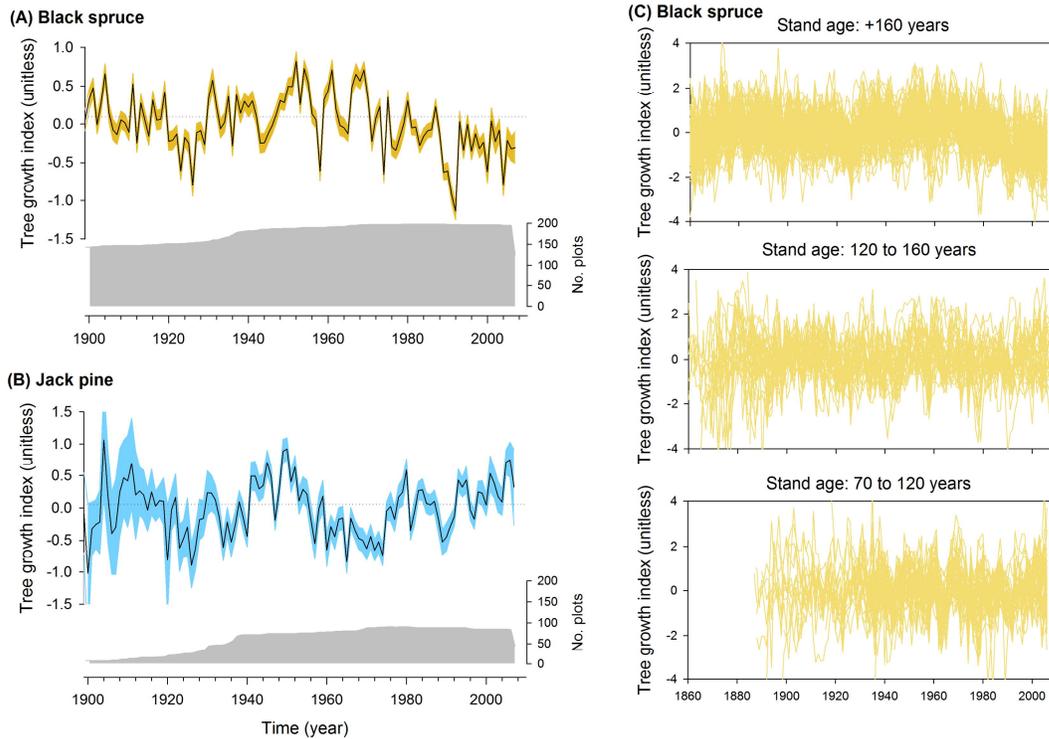
- 4) the model was selected by comparing the  $R^2$  of the candidate models. The one with higher  $R^2$  between *L* and *NE* was selected; *GNE* was selected if its  $R^2$  was over 5% more than the one selected from above;
- 5) the TGI time series were calculated using biweight robust means of the differences between the transformed ring series and the selected growth trend model.

Analyses were conducted using SAS software.

**Appendix 3 Sensitivity analysis of linear fits to the detection period**

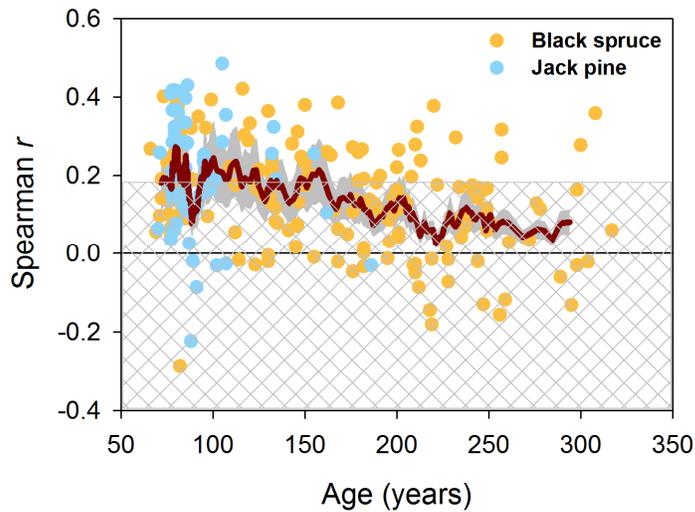
**Fig. S2.** Sensitivity analysis of linear fits to the 252 plot-level tree growth indices (TGI) of jack pine and black spruce. The two biplots show the slopes (standardized units) of the linear trends over 1950–2005 against those of a) 1960–2005 and b) 1970–2005.

## Appendix 4 Species-specific TGI time series averaged across all plots

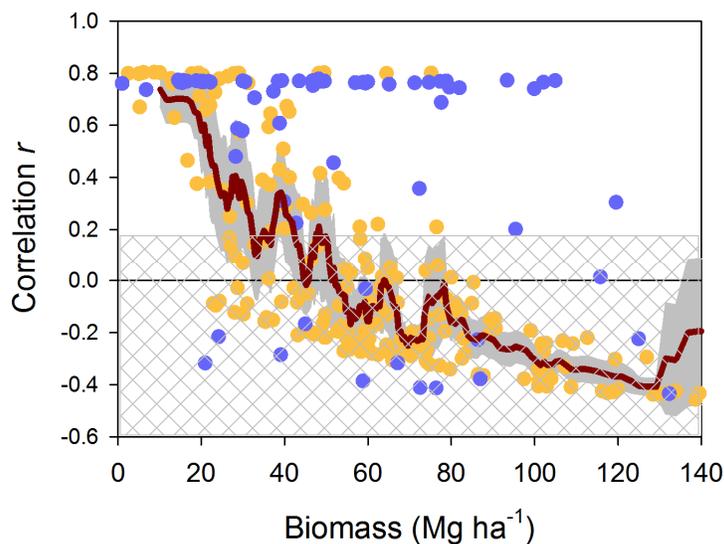


**Fig. S3.** (a-b) Species-specific TGI time series averaged across all plots with 95% confidence intervals. Also shown is the number of sample plots used across time. c) Individual black spruce plot-level TGI time series; three stand age groups are shown.

## Appendix 5 Correlation between plot-level TGI and April-May temperatures



**Fig. S4.** Spearman correlation coefficients computed between the 252 plot-level tree growth index (TGI) time series and mean April-May daily temperatures. The period of analysis is 1950–2005. The cross-hatched area marks the critical limit at which the null hypothesis of ‘no significant correlation’ is rejected ( $P < 0.10$ ; one-sided test). The thick-solid line shows the mean correlation within a moving window of 11 observations; the shaded area shows 95% confidence interval. Autocorrelation in the TGI data was removed prior to analysis using autoregressive modeling.

**Appendix 6 Correlation between plot-level NPP and April-May temperatures**

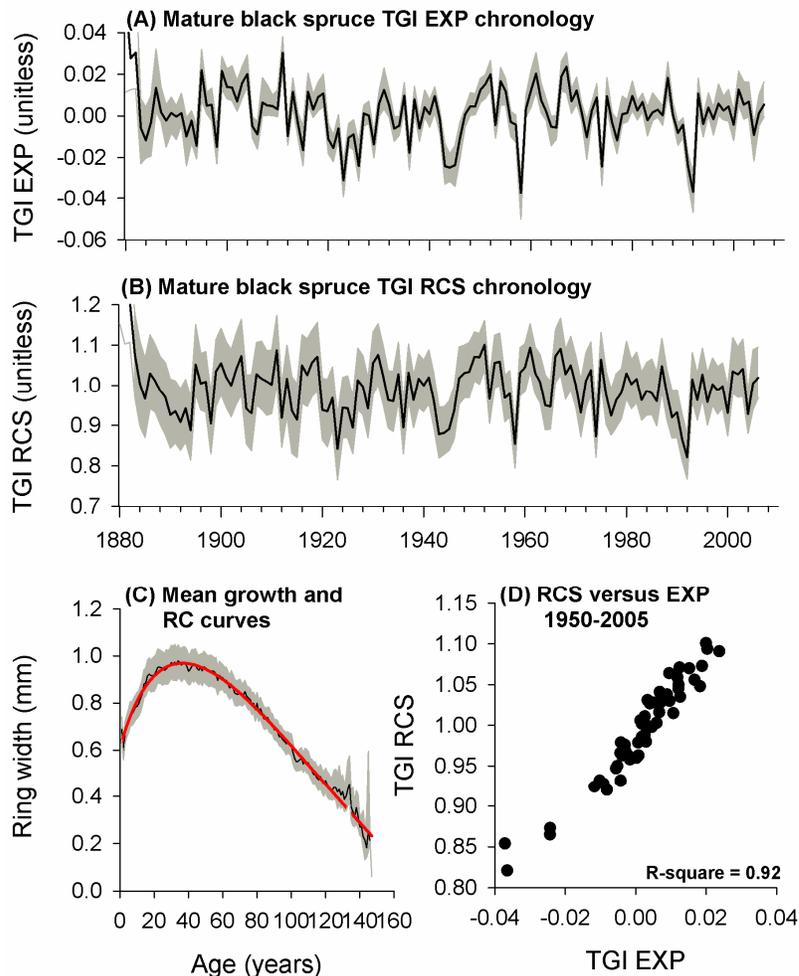
**Fig. S5.** Pearson correlation coefficients computed between the 284 plot-level simulations of NPP and mean April-May daily temperatures. The period of analysis is 1950–2005. The cross-hatched area marks the critical limit at which the null hypothesis of ‘no significant correlation’ is rejected ( $P < 0.10$ ; one-sided test). The thick-solid line shows the mean correlation in black spruce within a moving window of 11 observations; the shaded area shows 95% confidence interval.

## Appendix 7 Sensitivity analysis to the detrending method

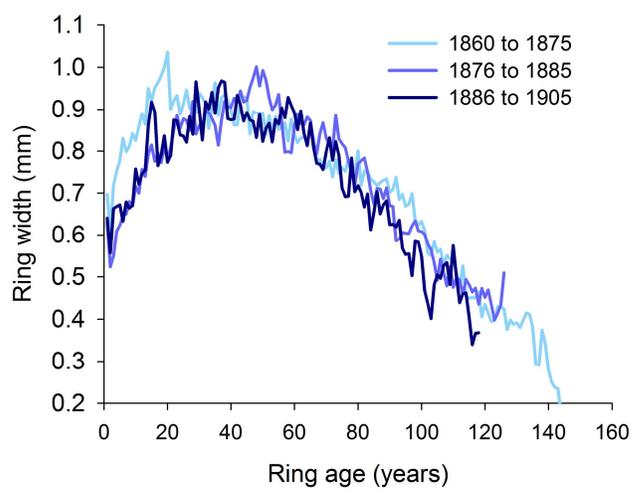
Plot-level time series under study for mature forests range in length from about 80 years and over, and it can be expected that long-term signals in such series will not be recovered. This could cause an absence of a long-term trend in growth as seen in mature jack pine and black spruce forests. This point was addressed in a comment posted on 14 March 2012 that can be found at <http://www.biogeosciences-discuss.net/9/C292/2012/bgd-9-C292-2012.pdf>. Therein a sensitivity analysis consisted on the application of the regional curve standardization (RCS) technique to the jack pine tree-ring width measurement series, and comparing the final results to those presented in the original manuscript. The RCS approach has the potential to preserve the evidence of long-time scale forcing of tree growth. The two standardization methods yielded very similar changes in mean jack pine growth for the post-1920 period.

Sensitivity tests were also made on mature and overmature black spruce trees established between 1860 and 1905 on silty-sand, loamy-sand, and sand, with depth of the organic layer ranging from 5 to 25 cm. Overmature trees established prior to 1860 were excluded of this analysis as they did not satisfy the assumption of homogeneity in level and slope of growth curves. The 294 available black spruce measurement series were aligned by cambial age, scaled using the power-transformation method, and the arithmetic mean of ring width for each ring age was calculated. A regional curve (RC) was then created by applying a flexible smoothing (Hugershoff) to the age series of arithmetic means (Fig. S6). Next, each one of the original ring-width measurement series was divided by the RC value for the appropriate ring age to create standardized series. Finally, the standardized series were realigned by calendar year and averaged using a bi-weight robust mean to create the mature black spruce tree growth index (TGI). As shown by Fig. S6, changes in growth of mature black spruce obtained through the application of the RCS technique were similar to those obtained using the exponential detrending approach. The multi-decadal environmental signal thus appears to be adequately recovered. In addition, in these sites the age-related growth trend of overmature trees originating from 1860 to 1877 (n=104 trees) was similar in level and slope to a curve obtained from mature trees originating from 1887 to 1905 (n=106 trees) (Fig. S7).

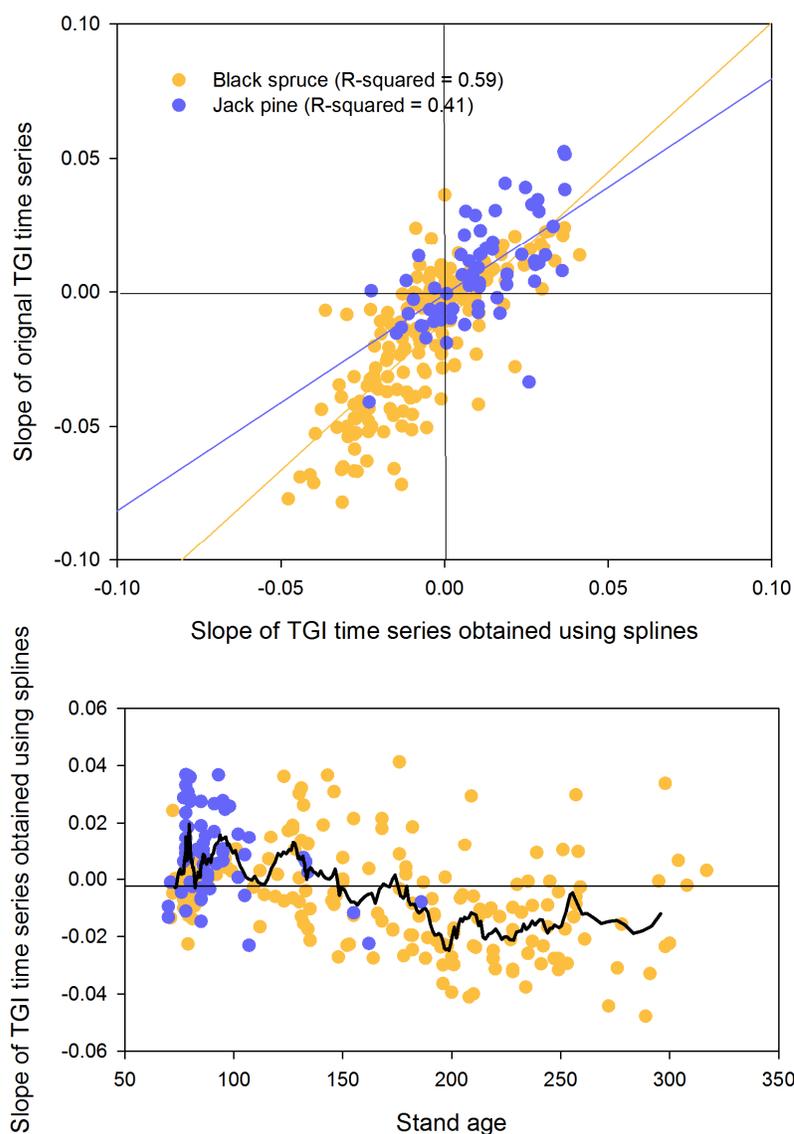
Application of a more flexible detrending procedure, i.e. cubic smoothing spline functions of wavelength equal to 67% of the ring-width series length with 50% frequency response and calculation of TGI time series as ratios of ring width to predicted growth, yielded trend results (Fig. S8) similar to those obtained after detrending using exponential modelling. Additionally, we found that demographic and species differences in direction and levels of trends persist after the application of a flexible detrending technique to the ring-width measurements (i.e. 80-year smoothing splines; Supplemental material Fig. S9). The higher frequency variability (interannual to multidecadal) that characterizes the period under study remains largely unaffected by the application of detrending.



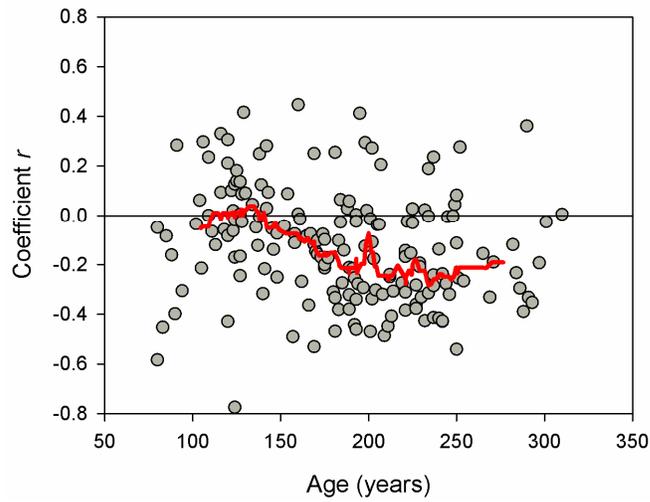
**Fig. S6.** Mature black spruce tree growth index (TGI) and 95% confidence interval obtained after the application of two different standardization techniques. A) TGI record obtained after the application of an exponential fitting (TGI EXP) to measurement series as described in the manuscript. B) TGI record obtained through the application of the Regional Curve Standardization technique (TGI RCS). C) Mean growth curves for trees established between 1860 and 1905. Gray shaded area shows 95% confidence intervals associated with the mean growth of trees for each ring age. The red line is the regional curve obtained after application of a smoothing to the mean growth of trees. (D) Scatter-plot of TGI EXP and TGI RCS, 1950-2005.



**Fig. S7.** Growth curves for overmature and mature black trees established between 1860 and 1875, 1876 and 1885, and 1886 and 1905. Sample sizes are  $n=104$ ,  $n=104$  and  $n=84$  trees, respectively.



**Fig. S8.** Top: Comparison of linear fits to the 252 plot-level tree growth indices (TGI) of jack pine and black spruce derived from the application of two different statistical methods of tree-ring measurement detrending, i.e. the generalized negative exponential modeling described in Appendix 2 (original TGI) versus the smoothing spline functions of wavelengths equal 67% of the ring-width series length with 50% frequency response. Bottom: Trends in TGI obtained from spline functions versus stand age. Results are in agreement with those presented in Fig. 1e.



**Fig. S9.** Distribution of linear fits for detection of trends applied to spline-detrended plot-level tree growth indices of black spruce as a function of stand age. The period of analysis for trend detection is 1960-2005. The thick line is a 20-year moving median across observations. In this analysis, 80-year splines were applied to each measurement series to remove the age/size related trend (Cook and Peters, 1981). This flexible smoothing allows constraining the measurement series to a similar frequency spectrum. As seen here, the decline with age in black spruce trees persists after application of non-conservative detrending procedure.

## Appendix 8

**Table A1.** Parameters and allometric coefficients used in the bioclimatic model StandLEAP.

| Description  | Black spruce | Jack pine |
|--|--------------|-----------|
| <b>Plot-level partition model parameters</b>   |              |           |
| Allometric coefficient $a$ relating foliage biomass to crown biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass           | 0.667        | 0.825     |
| Allometric coefficient $b$ relating foliage biomass to crown biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass           | 0.978        | 0.931     |
| Allometric coefficient $a$ relating stem biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass        | 0.359        | 0.600     |
| Allometric coefficient $b$ relating stem biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass        | 1.065        | 1.030     |
| Allometric coefficient $a$ relating coarse root biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass | 1.263        | 1.401     |
| Allometric coefficient $b$ relating coarse root biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass | 0.983        | 0.791     |
| Allometric coefficient $a$ relating crown biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass       | 2.111        | 2.007     |
| Allometric coefficient $b$ relating crown biomass to aboveground biomass; these are the parameters of the equation $y = ax^b$ , where $x$ is the crown biomass       | 0.811        | 0.762     |
| <b>Tree-level partition model parameters</b>   |              |           |
| Allometric coefficient $a$ relating aboveground biomass and DBH; these are the parameters of the equation $y = ax^b$ , where $x$ is the average DBH                  | 0.144        | 0.068     |
| Allometric coefficient $b$ relating aboveground biomass and DBH; these are the parameters of the equation $y = ax^b$ , where $x$ is the average DBH                  | 2.260        | 2.488     |
| Allometric coefficient $a$ relating stem sapwood biomass and DBH; these are the parameters of the equation $y = ax^b$ , where $x$ is the average DBH                 | 0.029        | 0.012     |
| Allometric coefficient $b$ relating stem sapwood biomass and DBH; these are the parameters of the equation $y = ax^b$ , where $x$ is the average DBH                 | 2.584        | 2.686     |
| Fine root foliage ratio  | 0.750        | 1.473     |
| <b>Epsilon and water use efficiency model parameters</b>   |              |           |
| Parameter $\beta_l$ for the epsilon temperature modifier <sup>(1)</sup>  | 0.456        | 0.359     |
| Parameter $\beta_q$ for the epsilon temperature modifier <sup>(1)</sup>  | -0.250       | -0.194    |
| Parameter $\bar{x}$ for the epsilon temperature modifier <sup>(1)</sup>  | 13.336       | 13.332    |
| Parameter $\beta_l$ for the epsilon VPD modifier <sup>(1)</sup>  | 0            | 0         |
| Parameter $\beta_q$ for the epsilon VPD modifier <sup>(1)</sup>  | 0            | 0         |
| Parameter $\bar{x}$ for the epsilon VPD modifier <sup>(1)</sup>  | 0.653        | 0.653     |
| Average quantum efficiency (mol C (mol photon) <sup>-1</sup> )   | 0.011        | 0.015     |
| Parameter $\beta_l$ for the epsilon leaf area index modifier <sup>(1)</sup>  | 0.204        | 0.347     |
| Parameter $\beta_q$ for the epsilon leaf area index modifier <sup>(1)</sup>  | -0.271       | -0.166    |
| Parameter $\bar{x}$ for the epsilon leaf area index modifier <sup>(1)</sup>  | 5            | 5         |
| Parameter $\beta_l$ for the epsilon PAR modifier <sup>(1)</sup>  | 0            | 0         |
| Parameter $\beta_q$ for the epsilon PAR modifier <sup>(1)</sup>  | 0            | 0         |
| Parameter $\bar{x}$ for the epsilon PAR modifier <sup>(1)</sup>  | 1047.307     | 1036.687  |
| Parameter $\beta_l$ for the water use efficiency - leaf area index modifier <sup>(1)</sup>   | -0.463       | 0         |

|  |         |         |
|--|---------|---------|
| Parameter $\beta_q$ for the water use efficiency - leaf area index modifier <sup>(1)</sup>   | 0.048   | 0       |
| Parameter $\beta_l$ for the water use efficiency – VPD modifier <sup>(1)</sup>   | 0.952   | 0.782   |
| Parameter $\beta_q$ for the water use efficiency – VPD modifier <sup>(1)</sup>   | -0.087  | 0       |
| Average water use efficiency (mol CO <sub>2</sub> /mol H <sub>2</sub> O/kPa)   | 0.0036  | 0.0040  |
| Parameter $\beta_l$ for mortality model climate modifier <sup>(1)</sup>  | 0.805   | 1.268   |
| Parameter $\beta_q$ for mortality model climate modifier <sup>(1)</sup>  | -0.895  | 0       |
| Parameter $\bar{x}$ for mortality model climate modifier <sup>(1)</sup>  | 0.534   | 0.717   |
| Parameter $\beta_l$ for mean ratio of aboveground mass increment over aboveground mass   | -4.897  | 0       |
| Parameter $\beta_q$ for mean ratio of aboveground mass increment over aboveground mass   | 2.681   | 0       |
| <b>Ingrowth model parameters</b>   |         |         |
| Parameter of the relationship between the extinction coefficient and leaf area index   | 0.851   | 0.748   |
| Parameter of the relationship between the extinction coefficient and leaf area index   | -0.152  | -0.252  |
| Degree days (0°C) to bud break   | 300.000 | 116.000 |
| Degree days to end of leaf expansion   | 800.000 | 766.664 |
| Lower base temperature for growing degree days sum   | 0       | 2.900   |
| Mean foliage retention time (number of growing seasons)  | 8.621   | 4.180   |
| Julian day when leaf fall is allowed to start (day)  | 270.00  | 270.000 |
| Proportion of GPP partitioned to growth respiration  | 0.200   | 0.200   |
| R <sub>m10</sub> for respiration rate at 10°C  | 0.0106  | 0.011   |
| Nitrogen concentration of foliage (gN / gC)  | 0.007   | 0.009   |
| Nitrogen concentration of fine roots (gN / gC)   | 0.009   | 0.003   |
| Nitrogen concentration of wood (gN / gC)   | 3.2E-4  | 4.0E-4  |
| Nitrogen of structural roots (gN / gC)   | 3.2E-4  | 4.0E-4  |
| Q <sub>10Rm</sub> for temperature sensitivity of R <sub>m</sub> , defined as the relative increase in respiration for a 10°C increase in temperature | 2.000   | 2.000   |
| R <sub>10</sub> for relative increase in heterotrophic respiration for a 10°C increase in temperature ( <i>Lloyd and Taylor, 1994</i> )              | 0.800   | 0.800   |
| Heterotrophic respiration $y_0$ parameter; these are the parameters of the equation $R_h = y_0 + ae^{bT}$ , where $T$ is monthly mean temperature    | -5.252  | -5.252  |
| Heterotrophic respiration $a$ parameter; these are the parameters of the equation $R_h = y_0 + ae^{bT}$ , where $T$ is monthly mean temperature      | 18.302  | 18.302  |
| Heterotrophic respiration $b$ parameter; these are the parameters of the equation $R_h = y_0 + ae^{bT}$ , where $T$ is monthly mean temperature      | 0.075   | 0.075   |

1. Expressed using the quadratic function  $f_x = 1 + \beta_{lx} \left( \frac{x - \bar{x}}{\bar{x}} \right) + \beta_{qx} \left( \frac{x - \bar{x}}{\bar{x}} \right)^2$