Effect of tree-ring detrending method on apparent growth trends of black and white spruce in interior Alaska

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Effect of tree-ring detrending method on apparent growth trends of black and white spruce in interior Alaska

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Abstract

Boreal forests are critical sinks in the global carbon cycle. However, recent studies have revealed increasing frequency and extent of wildfires, decreasing landscape greenness, increasing tree mortality and declining growth of black and white spruce in boreal North America. We measured ring widths from a large set of increment cores collected across a vast area of interior Alaska and examined implications of data processing decisions for apparent trends in black and white spruce growth. We found that choice of detrending method had important implications for apparent long-term growth trends and the strength of climate-growth correlations. Trends varied from strong increases in growth since the Industrial Revolution, when ring widths were detrended using single-curve regional curve standardization (RCS), to strong decreases in growth, when ring widths were normalized by fitting a horizontal line to each ring width series. All methods revealed a pronounced growth peak for black and white spruce centered near 1940. Most detrending methods showed a decline from the peak, leaving recent growth of both species near the long-term mean. Climate-growth analyses revealed negative correlations with growing season temperature and positive correlations with August precipitation for both species. Multiple-curve RCS detrending produced the strongest and/or greatest number of significant climate-growth correlations. Results provide important historical context for recent growth of black and white spruce. Growth of both species might decline with future warming, if not mitigated by increasing precipitation. However, widespread drought-induced mortality is probably not imminent, given that recent growth was near the long-term mean.

Introduction

Boreal forests make up ~45% of the global net terrestrial carbon (C) sink (Pan *et al* 2011). However, considerable uncertainty exists regarding the future of the boreal C sink. Recent studies point to increasing frequency and extent of wildfire (Turetsky *et al* 2011), decreasing landscape greenness (Verbyla 2008, Ju and Masek 2016), increased tree mortality (Peng *et al* 2011), reduced biomass accrual (Ma *et al* 2012) and declining growth of black spruce (*Picea mariana*) (Beck *et al* 2011, Walker and Johnstone 2014) and white spruce (*Picea glauca*) (Barber *et al* 2000, McGuire *et al* 2010, Juday and Alix 2012, Juday *et al* 2015).

Declining growth and increased mortality of spruce in boreal North America have generally been attributed to drought stress, as evidenced by carbon isotope chronologies and correlations between growth or mortality and climate variables, such as temperature, precipitation and/or indices of moisture availability (Barber *et al* 2000, Lloyd and Fastie 2002, Beck *et al* 2011, Peng *et al* 2011, Juday and Alix 2012, Lloyd *et al* 2013, Walker and Johnstone 2014, Juday *et al* 2015, Walker *et al* 2015). Observations of declining spruce growth have led some investigators to suggest that boreal forests of interior Alaska may be in the early stages of a 'biome shift' from forests dominated by coniferous tree species to grasslands or temperate

forests (Beck *et al* 2011, Juday *et al* 2015). If widespread changes in forest composition are occurring, they would have profound implications for wildlife habitat, the forest products industry and exchanges of C, water, energy and nutrients.

Radial growth in the main stem is an indicator of tree health and an important C flux into forested ecosystems. To reveal climate-driven trends in tree growth, age-related trends must be removed from ring width series. There are two sources of age-related trends: (1) physiological and/or developmental effects on wood production and (2) geometric effects associated with increasing stem circumference. It is well known that tree growth tends to decline with age (e.g., Gower *et al* 1996). The causes of this age-related decline are an active area of research, with hypotheses that include hydraulic limitation, declining photosynthesis and/or changes in biomass allocation with age. In addition to these potential physiological effects, increment cores may also show an apparent growth decline, as new biomass is distributed around a progressively increasing circumference. The process of removing age-related trends in ring width series is known as 'detrending'. Historically, most studies have used detrending methods that fit curves or lines to individual tree-ring series, which represent either one increment core or one tree (e.g., Cook 1985). In the most 'conservative' approach, ring width series are fit with either a negative exponential or a negative linear model. This method tends to preserve high-frequency variation of shorter duration than the length of the individual series (inter-annual and inter-decadal variation), while removing longer-term low frequency trends. Accurately estimating low frequency variation in tree-ring chronologies is important, however, when testing for temporal trends in tree growth and attempting to place contemporary growth in a historical context.

Several new detrending methods have been developed with the goal of preserving both high and low frequency trends in tree-ring chronologies. Biondi and Qeadan (2008) proposed an alternative to the traditional negative exponential or negative linear method known as the C-method. Rather than fitting empirical detrending curves to the individual ring width series, the C-method uses a geometrically defined detrending curve to remove the expected ring width decline as a function of increasing stem circumference from each series. Another alternative is the regional curve standardization (RCS) method, which has a long history (Erlandsson 1936, Briffa *et al* 1992), but has received renewed interest in recent years (Esper *et al* 2003, Briffa and Melvin 2011). The RCS method involves aligning the ring width data by cambial age (the approximate age at the height of increment core collection) to define the age-related ring width decline. This empirical curve (the 'regional curve') is then removed from each tree-ring series, typically by calculating ratios of observed to expected ring width. A key

benefit of RCS is that aligning the ring width data by cambial age, rather than calendar year, should break the connection between ring widths and climate, thereby preserving low frequency climate-driven trends in tree growth. One of the most important recent improvements of RCS was the introduction of multiple-curve RCS (Briffa and Melvin 2011), in which individual tree-ring series are sorted by mean ring width into a number of classes and the age-related ring width decline is defined separately for each class. The benefit of this method is that it can more accurately simultaneously detrend ring width data from slow- and fast-growing trees, the latter of which exhibit a more rapid decline in ring width with age. There is one important difference in sampling design between traditional tree-ring studies and those that plan to detrend using RCS. While traditional studies generally focus on the oldest and largest trees, in order to construct the longest possible tree-ring chronology, studies that use RCS must sample trees across a wide age range to ensure that cambial age is not confounded with calendar year when defining the regional curve. A key benefit of the sampling requirements of RCS is that the resulting tree-ring chronology is likely to be more representative of the tree population, rather than just the oldest cohort of trees.

In this study, we used a large tree-ring dataset (213 black spruce cores, 339 white spruce cores) collected from randomly located plots throughout the 922 000 ha of forested land in the Tanana Valley State Forest and the Tetlin National Wildlife Refuge in interior Alaska. Previous studies of black and white spruce growth trends have used a variety of detrending methods and most have restricted their analyses to the 20th and 21st centuries. Our overall goals were to (1) improve the historical context of recent growth by extending our chronologies to the middle of the 19th century and (2) examine the effect of detrending method on apparent long-term growth trends. Specifically, we asked the following questions:

(1) Is there evidence of an age-related effect on ring widths of black and white spruce?

(2) Do low frequency trends in the black and white spruce tree-ring chronologies depend upon detrending method?

(3) Does choice of a detrending method have implications for the strength of climate-growth correlations?

Methods

Increment core collection
Increment cores (5 mm dia) were collected during 2013 and 2014 from United States Forest Service Forest Inventory and Analysis (FIA) and Alaska Integrated Resources Inventory System (AIRIS) plots
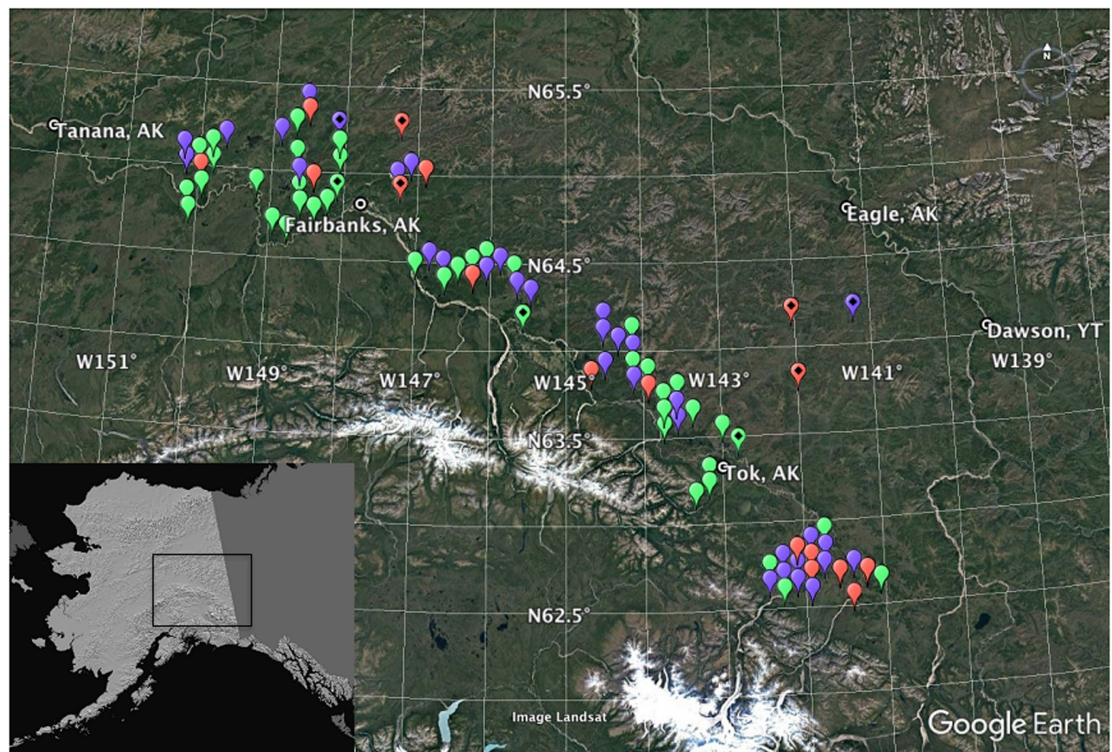
Figure 1. Approximate locations of the FIA and AIRIS plots where increment cores were collected in interior Alaska. FIA plots are shown with open symbols, while AIRIS plots are shown with closed symbols. Plots sampled for white spruce are indicated by green symbols, plots sampled for black spruce are indicated by purple symbols and plots sampled for both species are indicated by red symbols. Locations of Tanana, Fairbanks, Eagle and Tok, Alaska, along with Dawson, YT are shown for reference.

Table 1. Distribution of sampled black and white spruce trees across plots and plot types, along with mean interseries correlations and mean sensitivities.

Species	Plot type	Plots (#)	Trees sampled (#, 1 core/tree)	Trees per plot (mean)	RBAR	Sensitivity
P. glauca	FIA	52	266	5.1	0.400	0.214
P. glauca	AIRIS	7	73	10.4	0.401	0.206
P. glauca	Combined	59	339	5.7	0.388	0.212
P. mariana	FIA	45	158	3.5	0.371	0.206
P. mariana	AIRIS	6	55	9.2	0.307	0.206
P. mariana	Combined	51	213	4.2	0.349	0.206

in interior Alaska (figure 1). FIA plots ($n = 100$, 673 m^2/plot) were randomly located within tessellated hexagons of 2400 ha in size (Barrett and Gray 2011), while AIRIS plots ($n = 9$, 8 ha/plot) were located at randomly selected intersections of 40×40 km grid squares overlain on interior Alaska (Schreuder *et al* 1993). One core was collected per tree, with approximately 5 cores/species collected from each FIA plot and approximately 10 cores/species collected from each AIRIS plot, when the species was present in the plot (table 1). On FIA plots, cores were collected from apparently healthy trees that fell within the stand size class, which was defined following the standard FIA protocol (Bechtold and Patterson 2005). On AIRIS plots, cores were collected from a wider range of tree sizes and tree health conditions. Size cohorts were visually defined on the AIRIS plots and cores were collected from representative trees of each species (when present) within each size cohort, regardless of

apparent health. For instance, if the majority of white spruce with a diameter at breast height of 25–30 cm on a given plot had evidence of bark beetle infestation, then trees with evidence of bark beetle infestation were sampled. Because approximately 75% of our cores were collected from apparently healthy trees, our dataset contains a bias toward visibly healthy trees that is lessened by inclusion of cores collected on the AIRIS plots (Sullivan and Csank 2016).

Increment core processing

Increment cores were air-dried in paper straws prior to mounting and sanding to 600 grit. The cores were visually dated and measured to the nearest 0.001 mm using a sliding bench micrometer and digital encoder (Velmex Inc., Bloomfield, NY). Ring width data were analyzed in COFECHA by species and plot type (FIA or AIRIS) to identify and correct dating errors

(Holmes 1983). The pith was present in 90 of the white spruce and 85 of the black spruce cores. For cores that missed the pith, but the inner ring formed a complete arc, the geometric method was used to estimate the missing radius of the core (Duncan 1989). To estimate the number of rings within the missing radius, we divided the mean width of the first ten rings into the missing radius for each core. Incomplete cores that did not pass close enough to the pith for the innermost ring to form a complete arc were eliminated from the dataset. Fourteen of the FIA plots from which increment cores were collected are known to have burned between 1950 and present. For cores that were collected from plots with a known fire history, the post-fire ring width data were removed from the dataset, to limit the influence of disturbance on the tree-ring chronologies.

Detrending

The raw ring width data were detrended using six different methods in either CRUST (Melvin and Briffa 2014a) or dplR (Bunn 2008):

(1) Multiple-curve RCS, in which the tree-ring series are grouped by mean ring width (>40 series per group) and the age-related decline in ring width is defined for and removed from each group. To determine the optimum number of groups (curves), we detrended the data using 1, 2, 3, 4 and 5 curves, then identified the point at which adding more curves had a minor impact on the tree-ring chronology (CRUST).

(2) The C-method (Biondi and Qeadan 2008), in which the expected decline in ring width as a function of increasing circumference is removed from each tree-ring series (dplR).

(3) The negative exponential or negative linear method, which fits individual ring width series with either a horizontal line, a line with a negative slope or a negative exponential model, depending on the presence and form of the trend in the data (CRUST).

(4) The horizontal line method, which does not detrend the data, but instead normalizes each ring width series such that the mean is equal to 1.0 (CRUST).

(5) No detrending, in which the raw ring widths were averaged across trees (dplR).

(6) Basal area increment (BAI), which is the cross-sectional surface area of annual wood production (dplR, 'inside-out' method).
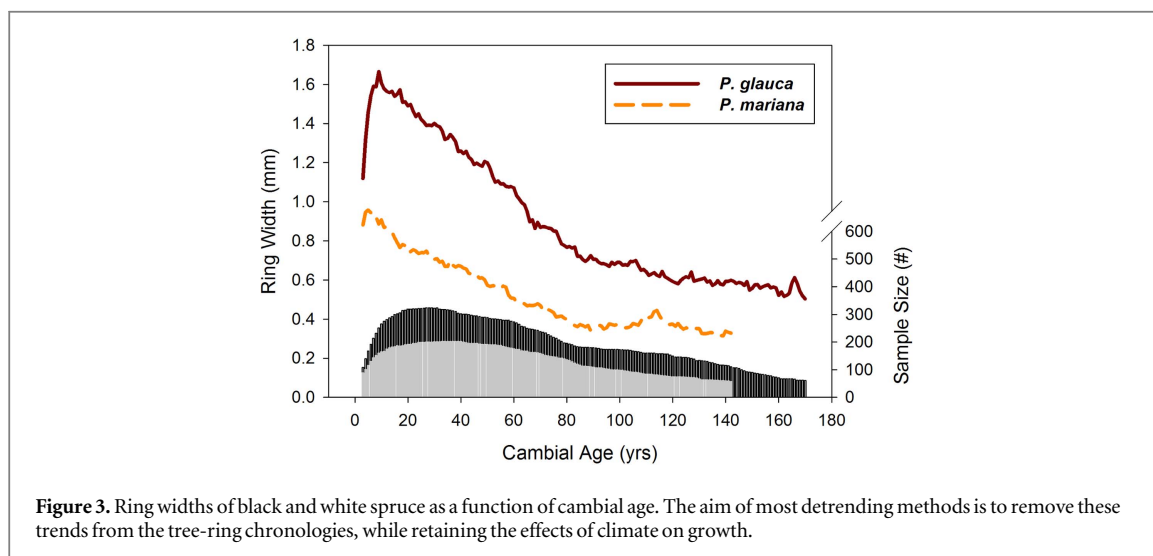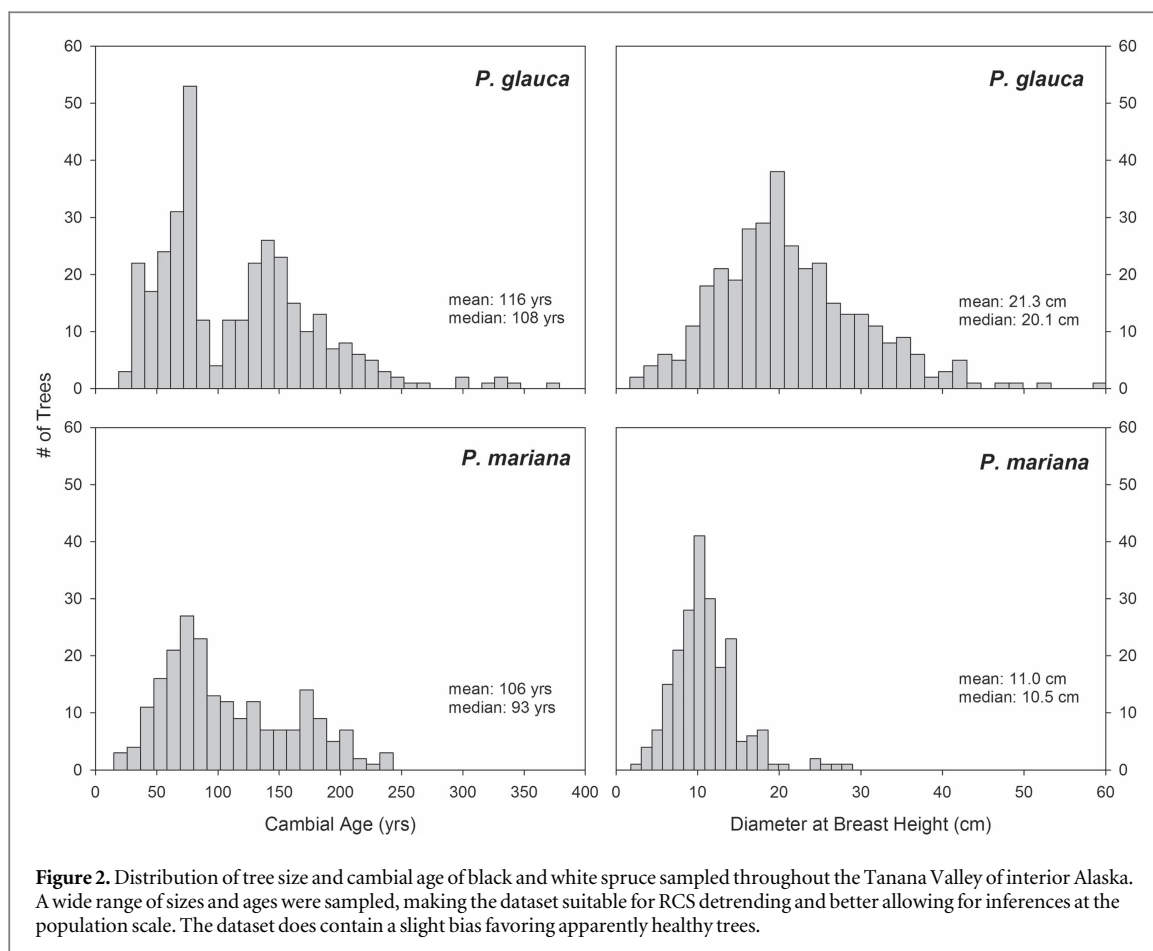
Ring width indices were calculated as ratios of observed to expected growth (methods 1–4) and tree-ring chronologies were calculated using Tukey's biweight robust mean (methods 1–5). Data were processed following Melvin and Briffa (2008) to produce 'signal-free' chronologies when detrending using methods 1, 3 and 4. The aim of the signal-free method is to correct for inadvertent removal of some of the climate signal during the detrending process. Producing signal-free chronologies involves repeatedly dividing the raw ring widths by the detrended chronology until the variance is minimized. No more than 10 iterations of this process were utilized. Chronologies were truncated when the sample size dropped below 50 trees.

To examine the effect of detrending method on climate-growth correlations, we used the package treeclim (Zang and Biondi 2015) in R 3.1.2 (R Core Team 2014). Measured climate data for Fairbanks, AK (1915–2013) were obtained from the Alaska Climate Research Center, while modeled (interpolated) climate data (1906–2013) were acquired for the grid point nearest to Fairbanks, AK (64.75, −147.75) from the CRU 3.23 time series (Harris *et al* 2014). Correlations between both climate data sources and the ring width indices were examined for detrending methods 1–3 and 5 using monthly mean air temperature and precipitation totals for May–August of the growth year and the previous year. We also included the sum of precipitation from October through April of the growth year. Winter precipitation was only included when using the CRU 3.23 data, because of gaps in the early part of the Fairbanks station record. Significance of the correlations was assessed using 'exact' bootstrap resampling.

Results

The sampled black and white spruce trees covered a wide range of diameters and cambial ages (figure 2), making the dataset well suited to detrending using RCS. Age-related ring width trends showed brief increases in ring width over time, followed by strong decreases, and limited evidence of asymptotes within the first ~150 years for both species (figure 3). These age-related trends highlight the need for detrending. Apparent long-term trends in black and white spruce growth depended strongly upon detrending method (figure 4). All methods revealed a distinct peak in growth centered near 1940, but the methods differed widely in their representation of growth prior to and after the peak. Single-curve RCS detrending produced the most positive trend overall, while the horizontal line method produced a strong overall declining trend. The C-method, the negative exponential or negative linear method and averaging the raw ring widths produced broadly similar chronologies, with important fine-scale differences (discussed below). Converting the ring width data to BAI yielded strong positive trends in both species (figure 5). However, age-aligning the BAI data revealed a strong positive effect of cambial age over the first ~50 years, followed by a general flattening of the BAI trend. Comparison of

Figure 2. Distribution of tree size and cambial age of black and white spruce sampled throughout the Tanana Valley of interior Alaska. A wide range of sizes and ages were sampled, making the dataset suitable for RCS detrending and better allowing for inferences at the population scale. The dataset does contain a slight bias favoring apparently healthy trees.

Figure 3. Ring widths of black and white spruce as a function of cambial age. The aim of most detrending methods is to remove these trends from the tree-ring chronologies, while retaining the effects of climate on growth.

chronologies produced using single-curve RCS with those produced using multiple-curve RCS revealed a bias in the single-curve RCS chronologies (figure 6). Adding additional curves reduced the strength of the overall positive trend and revealed a decline in growth of both species following the mid-20th century peak. Adding curves beyond three had increasingly minor effects on the resulting chronologies. More detailed comparison of four-curve RCS chronologies with the C-method, negative exponential or negative linear and the raw ring width chronologies revealed numerous

important differences, particularly near the beginnings and the ends of the chronologies (figure 7). The negative exponential or negative linear method, in particular, showed abrupt increases in growth of both species during the first decade of the 21st century that were not apparent when the data were detrended using the other methods.

The strength and number of significant climate-growth correlations depended strongly upon detrending method for both species (table 2). Four-curve RCS revealed the strongest and/or greatest number of
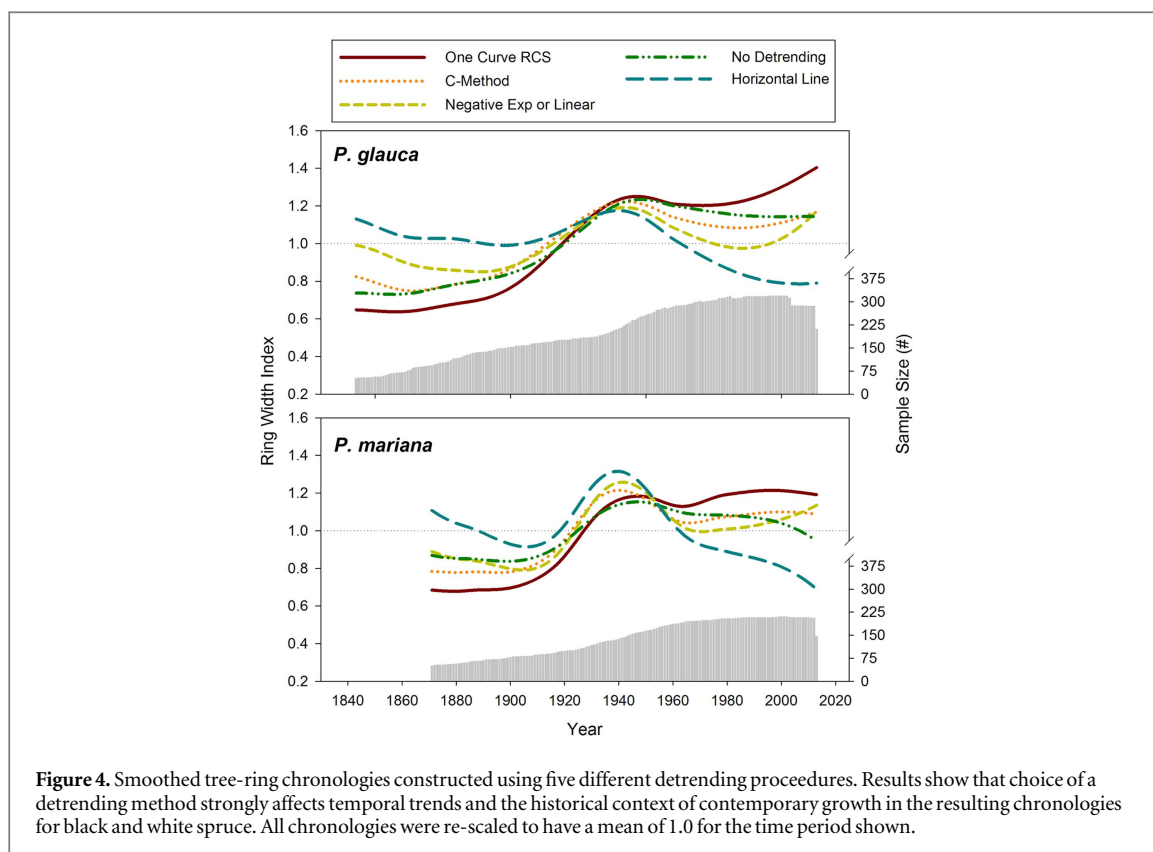
Figure 4. Smoothed tree-ring chronologies constructed using five different detrending proceedures. Results show that choice of a detrending method strongly affects temporal trends and the historical context of contemporary growth in the resulting chronologies for black and white spruce. All chronologies were re-scaled to have a mean of 1.0 for the time period shown.
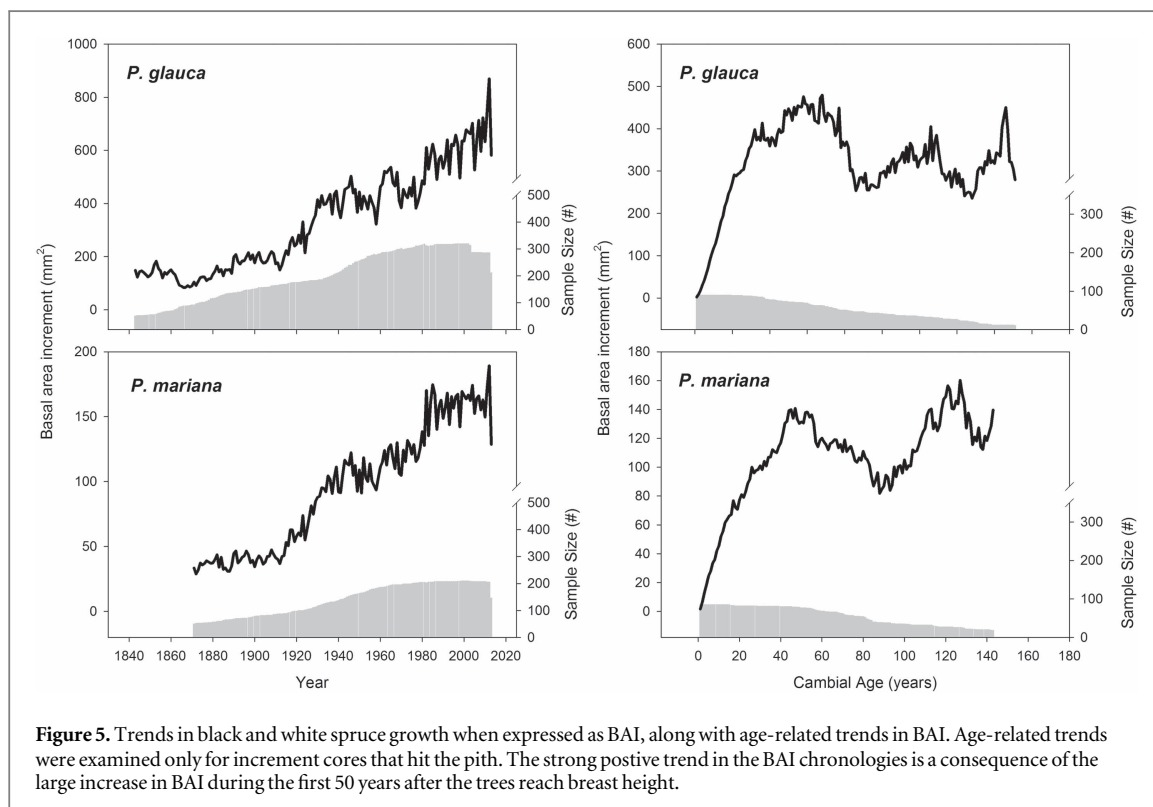

Figure 5. Trends in black and white spruce growth when expressed as BAI, along with age-related trends in BAI. Age-related trends were examined only for increment cores that hit the pith. The strong postive trend in the BAI chronologies is a consequence of the large increase in BAI during the first 50 years after the trees reach breast height.

significant correlations, while the raw ring width chronologies had the fewest significant and weakest correlations of the methods tested. However, the key climate variables identified and the sign of their correlation with growth, were remarkably consistent across detrending methods and species. The monthly mean air temperatures most closely correlated with growth of both species were those during July and August of the previous year and during May and August of the growth year. The monthly precipitation sums most closely correlated with growth were those of the previous August and August of the growth year.
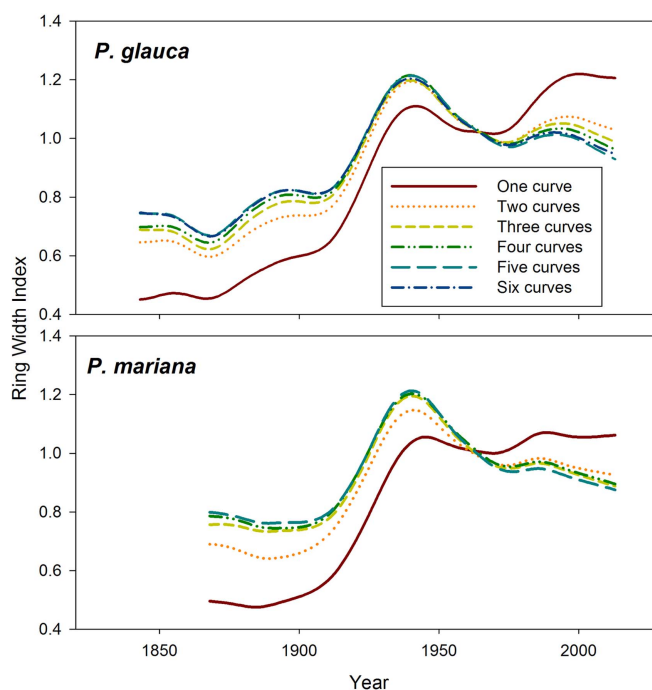
Figure 6. The effect of switching from single-curve RCS to multiple-curve RCS and subsequent addition of curves. The difference between single- and multiple-curve RCS highlights an important bias in the single-curve chronologies.
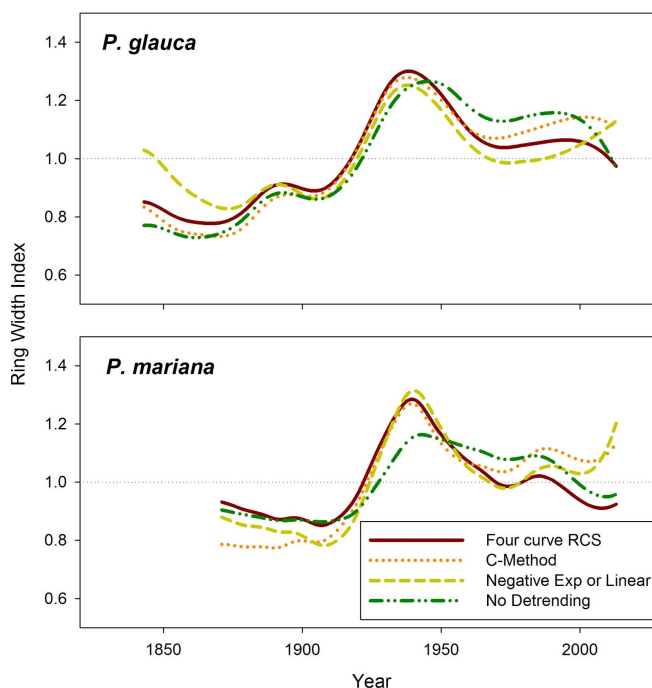

Figure 7. Comparison of smoothed four-curve RCS chronologies with three common detrending methods that produce broadly similar results, but also highlight important 'end-effects', particularly in the traditional negative exponential or negative linear method. All chronologies were re-scaled to have a mean of 1.0 for the time period shown.

Examination of the measured Fairbanks climate data and the modeled CRU TS 3.23 data revealed good agreement in growing season air temperature and August precipitation (figure 8). Both datasets show a strong increase in air temperature beginning near 1940 and no evidence of a long-term trend in August precipitation. The mid-20th century growth peaks of black and white spruce correspond with a period of relatively cool growing seasons prior to the initiation of the warming trend. The time period immediately preceding the growth peaks was also a period of greater than average August precipitation.

Table 2. Correlations between monthly climate data and growth of black and white spruce when detrended using multiple-curve RCS, the traditional negative exponential or negative linear method, the C-method and when the raw ring widths were averaged across trees. Two sources of climate data were utilized: the CRU TS 3.23 dataset from 1906 through 2013 (a) and the Fairbanks station data for 1915 through 2013 (b). Winter precipitation (October–April) was not included in the analysis using the station data, as a result of gaps in the early part of the record. Bold red coefficients indicate significant correlations with temperature, while bold blue coefficients indicate significant correlations with precipitation. Significance was assessed using 'exact' bootstrap resampling and alpha = 0.05.

a.

		P. glauca				P. mariana			
Variable	Time period	4 curve RCS	Neg expo/ linear	C-method	Raw ring widths	4 curve RCS	Neg expo/ linear	C-method	Raw ring widths
Temperature	Prev. May	−0.29	−0.25	−0.20	−0.19	−0.28	−0.16	−0.10	−0.16
	Prev. June	−0.26	−0.24	−0.18	−0.13	−0.26	−0.13	−0.08	−0.11
	Prev. July	−0.43	−0.40	−0.33	−0.29	−0.45	−0.33	−0.27	−0.24
	Prev. August	−0.41	−0.39	−0.34	−0.33	−0.35	−0.29	−0.22	−0.22
	May	−0.38	−0.36	−0.32	−0.28	−0.41	−0.31	−0.27	−0.25
	June	−0.20	−0.16	−0.09	−0.07	−0.22	−0.05	0.01	−0.07
	July	−0.25	−0.21	−0.13	−0.08	−0.27	−0.15	−0.06	−0.09
	August	−0.30	−0.27	−0.23	−0.20	−0.34	−0.25	−0.19	−0.21
Precipitation	Prev. May	−0.12	−0.16	−0.18	−0.15	−0.03	−0.07	−0.09	−0.02
	Prev. June	0.01	0.01	0.01	0.05	−0.01	0.01	0.01	0.07
	Prev. July	0.13	0.16	0.17	0.15	0.09	0.13	0.15	0.05
	Prev. August	0.37	0.37	0.37	0.33	0.33	0.32	0.31	0.26
	Prev. October– April	−0.06	−0.07	−0.08	−0.10	−0.06	−0.14	−0.12	−0.06
	May	0.04	0.02	0.01	0.02	0.12	0.08	0.06	0.11
	June	0.04	0.02	0.01	0.06	0.08	0.08	0.06	0.12
	July	−0.07	−0.04	−0.03	−0.04	−0.01	0.02	0.02	0.00
	August	0.29	0.31	0.29	0.25	0.25	0.24	0.22	0.20
# of significant correlations		8	6	5	4	6	6	3	1

b.

		P. glauca				P. mariana			
Variable	Time period	4 curve RCS	Neg expo/ linear	C-method	Raw ring widths	4 curve RCS	Neg expo/ linear	C-method	Raw ring widths
Temperature	Prev. May	−0.31	−0.26	−0.21	−0.18	−0.28	−0.16	−0.08	−0.13
	Prev. June	−0.34	−0.32	−0.26	−0.21	−0.32	−0.20	−0.15	−0.16
	Prev. July	−0.49	−0.46	−0.40	−0.34	−0.49	−0.39	−0.33	−0.25
	Prev. August	−0.52	−0.51	−0.47	−0.47	−0.44	−0.41	−0.36	−0.31
	May	−0.37	−0.36	−0.31	−0.26	−0.40	−0.30	−0.25	−0.21
	June	−0.26	−0.22	−0.15	−0.13	−0.27	−0.10	−0.04	−0.10
	July	−0.23	−0.19	−0.11	−0.03	−0.26	−0.11	−0.01	−0.02
	August	−0.39	−0.37	−0.33	−0.30	−0.41	−0.35	−0.29	−0.29
Precipitation	Prev. May	0.05	0.01	−0.02	0.03	0.11	0.09	0.05	0.11
	Prev. June	−0.03	−0.02	−0.03	−0.03	−0.09	−0.09	−0.10	−0.08
	Prev. July	0.13	0.16	0.16	0.17	0.14	0.15	0.19	0.09
	Prev. August	0.43	0.43	0.43	0.42	0.35	0.36	0.36	0.28
	May	0.14	0.12	0.09	0.12	0.25	0.20	0.17	0.19
	June	−0.03	−0.03	−0.05	−0.03	0.01	−0.02	−0.03	−0.02
	July	−0.08	−0.08	−0.08	−0.06	−0.03	−0.04	−0.05	−0.02
	August	0.36	0.36	0.35	0.32	0.29	0.30	0.28	0.22
# of significant correlations		7	7	7	5	8	7	6	4

Discussion

Apparent long-term growth trends of black and white spruce depended strongly upon detrending method. Two methods (single-curve RCS and BAI) produced strong positive trends, while one method (horizontal line) showed strong negative growth trends in both species since the Industrial Revolution. The other four detrending methods produced intermediate long-term trends with important fine-scale differences.
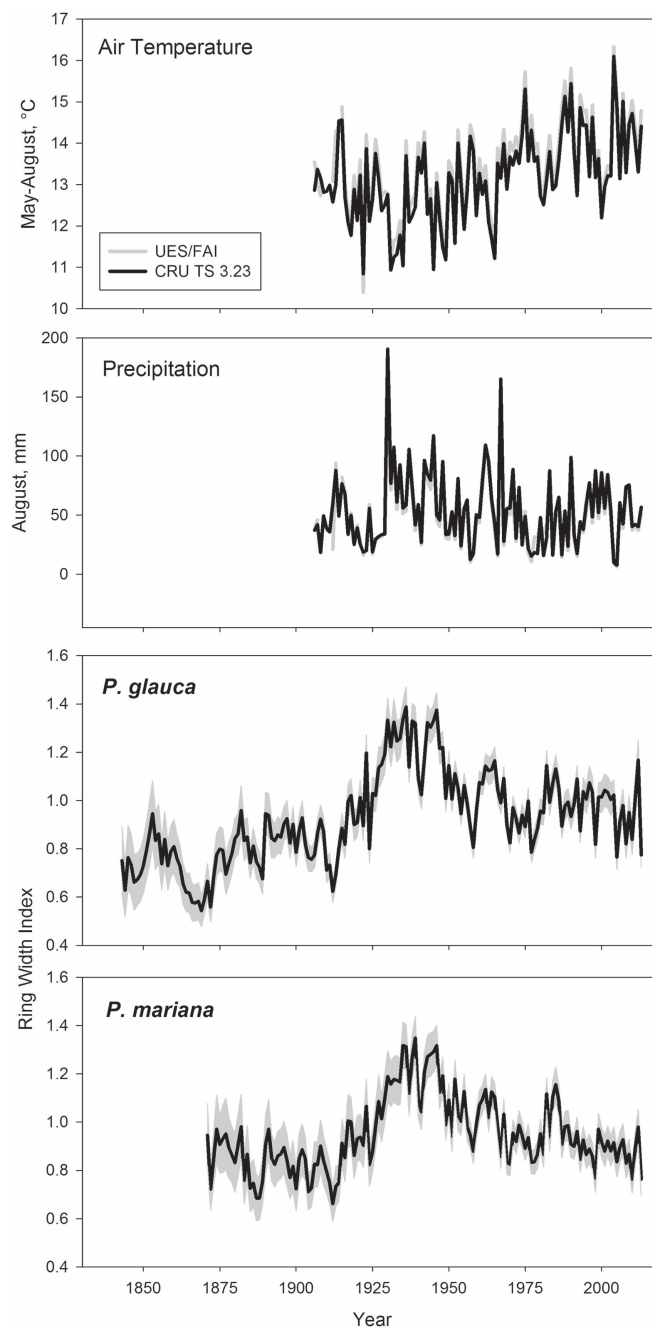
Figure 8. Trends in May–August air temperature and August precipitation in the Fairbanks climate station record and in the CRU TS 3.23 dataset for the grid cell nearest to Fairbanks, along with annually resolved four-curve RCS chronologies for black and white spruce. Gray shading around the tree-ring chronologies shows the 95% confidence intervals for the ring width indices.

The single-curve RCS chronologies were likely affected by what is known as 'modern sample bias' (Melvin 2004). Modern sample bias can emerge when a population of trees is composed of both young fast-growing trees and older slow-growing trees. The young fast-growing trees exhibit more rapid ring width decline with age, as biomass is distributed around a more rapidly increasing circumference. When a single curve is fitted across these two different classes of trees to describe the age-related ring width decline, the result is large ring width indices in the early part of the young tree chronologies and small ring width indices in the early part of the old tree chronologies. This scenario can lead to an erroneous positive trend in the overall chronology.

The BAI chronologies also showed strong positive trends over time. While converting the ring width data to BAI removes the effect of increasing circumference, it does not remove developmental or physiological effects on growth. When aligned by cambial age, BAI data for black and white spruce showed strong increases over the first ~50 years. Because relatively young trees dominate the early portions of our chronologies, the age-related trends in BAI are retained in the BAI chronologies. There was limited evidence of declining

BAI with increasing age. That may, however, reflect restriction of our analysis to trees less than 170 years old.

The horizontal line method produced a strong negative growth trend for both species. Fitting a horizontal line to each series eliminates differences in mean ring width across trees, without regard to age. When there is a strong age-related trend in the ring width data, old trees will tend to exhibit large ring width indices early in the chronology and small ring width indices late in the chronology. Meanwhile, young trees will have ring width indices that are close to 1.0. This allows the age-related decline in ring widths of old trees to dominate the overall tree-ring chronology.

Comparison of the horizontal line and raw ring width chronologies is revealing. Neither method attempts to remove the age-related trend in ring widths. However, the raw ring width chronologies were much more similar to the multiple RCS, C-method and negative exponential or negative linear chronologies. The raw ring width chronologies were probably more similar to the other methods because, over time, the continual addition of young trees with large rings compensated for the age-related ring width decline of older trees. Our raw ring width chronologies are thus a great example of getting the (approximately) right answer for the wrong reason.

The traditional negative exponential or negative linear method produced chronologies that were generally similar to the middle portions of the raw ring width, C-method and multiple RCS chronologies, but diverged strongly at the beginning (white spruce) and end of the chronologies (both species). The biases present in the traditional negative exponential or negative linear chronologies are what dendrochronologists refer to as 'end effects', which are a consequence of a poor fit of the detrending curve to the individual tree-ring series. End-effects are often most severe at the proximal end of a chronology and when ring width indices are calculated as ratios of expected growth, because a small error in fit of the curve to narrow rings can produce a very large ratio. Calculating ring width indices as residuals of expected growth and fitting more flexible spline curves, which comes with the risk of inadvertently removing climate effects on growth, have been proposed to combat end-effects (e.g., Cook and Peters 1997). Nevertheless, the traditional negative exponential or negative linear method remains one of the most widely used detrending methods.

The C-method is a variation of the traditional negative exponential or negative linear method in which the form of the detrending curve applied to each tree-ring series is defined by the expected ring width decline as a function of increasing circumference. This approach produced chronologies that were generally similar to the raw ring width, negative exponential or negative linear and multiple RCS chronologies, with more limited evidence of end-effects, particularly in the white spruce chronology. The C-method assumes constant BAI, yet our age-aligned BAI data show strong increases over the first 50 years, and our C-method chronologies tended to show lower growth over the first ~50 years than the other detrending methods. This problem could likely be corrected by eliminating the first 50 years from each of our tree-ring series, but that would have the undesirable effect of shortening our overall chronologies.

Briffa and Melvin (2011) described three different biases that may affect RCS chronologies: 'trend in signal bias', 'differing contemporaneous growth rate bias' and 'modern sample bias'. The trend in signal bias occurs when there is a consistent slope in the growth-forcing climate data over the full length of the tree-ring chronology. In this circumstance, the age-related ring width curve will inadvertently contain the climate trend, which will be removed from the chronology during detrending. The Fairbanks climate data show a strong warming trend from 1940 through 2013, with little evidence of a warming trend between 1906 and 1940. Although measured climate data are unavailable prior to 1906, it is unlikely that growing season air temperature in interior Alaska followed a consistent slope over the full lengths of our tree-ring chronologies. The differing contemporaneous growth rate and modern sample biases both stem from the assumption that a single curve can be used to detrend all of the individual tree-ring series. Our single-curve RCS chronologies were clearly affected by modern sample bias, which was corrected by using multiple-curve RCS. We are not aware of any potential remaining biases in our four-curve RCS chronologies and, as a result, we believe they provide the most trustworthy depiction of long-term trends in growth of black and white spruce in interior Alaska. This conclusion is supported by our finding that the four-curve RCS chronologies exhibited the strongest and/or greatest number of significant climate-growth correlations.

Our results highlight the value of testing a wide range of detrending methods, rather than arbitrarily selecting a commonly used approach, particularly if a goal of the study is to examine long-term growth trends. Even methods that are thought to be relatively non-invasive, such as the horizontal line method, can produce widely different tree-ring chronologies. In order to include multiple RCS among the potential methods, future studies may need to collect more increment cores than originally planned. Producing a tree-ring chronology using four-curve RCS, for instance, requires useable cores from a minimum of 160 trees (Melvin and Briffa 2014b). Sampling more trees, and trees of a wider age range, has the additional benefit of improving inferences about the tree population.

The results of our climate-growth analyses are consistent with past work in interior Alaska (e.g., Juday and Alix 2012, Walker and Johnstone 2014), as they show negative effects of growing season

temperature, positive effects of August precipitation and generally point to moisture sensitivity. The most notable feature of both the black and white spruce chronologies may be the pronounced growth peak that was centered around 1940. Air temperature between May and August was cooler on average and August precipitation was greater during the 15 years leading up to the peak than during the 15 years that followed the peak. The mid-20th century growth peak has important implications for the historical context of recent spruce growth in interior Alaska. While recent growth was certainly lower than it was during the peak, it is not near a historic low. Recent growth of white spruce is slightly greater, while recent growth of black spruce is similar to growth at the beginning of the 20th century. White spruce growth shows little evidence of a trend over the past 50 years, while black spruce growth exhibits a declining trend. If growing season air temperature continues to increase in interior Alaska and there is no change or a decrease in August precipitation, then growth of both species could well decline in the future. While there is good reason for concern regarding the future productivity of black and white spruce in interior Alaska, our conclusion that recent growth is near the long-term mean suggests that widespread drought-induced spruce mortality is probably not imminent.

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Statement of Authorship

RRP and TNH oversaw collection of the increment cores; AHB participated in sampling and measured ring widths; SMPC measured pith offsets; PFS analyzed the data and wrote the manuscript; all authors contributed to revisions.

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