TREE GROWTH HISTORY, CLIMATE SENSITIVITY, AND GROWTH POTENTIAL OF BLACK AND WHITE SPRUCE ALONG THE MIDDLE KUSKOKWIM RIVER, ALASKA

A

THESIS

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By

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Abstract

People living in the Kuskokwim River Basin often rely on wood to heat their homes, and are considering wood biomass energy generation. To help inform community decisions, we examined the growth history, climate sensitivity and growth potential of local tree species. We compared ring-width growth of 188 white spruce and 77 black spruce trees sampled along 370km of the Kuskokwim River, Alaska to mean monthly temperatures (MMT) and total monthly precipitation (TMP) at McGrath. The mean growth chronologies of both tree species were highly correlated with each other (r=0.84). White spruce trees were either significantly negatively correlated (r= -0.62) with MMT of August and June (-2) (two years prior to ring formation) or positively correlated (r=0.60) with MMT of April (-2) and November (-2). Black spruce trees were either negatively correlated (r= -0.64) with a warmth-dryness index composed of August and June (-1) MMT minus TMP of August and June (-2), or positively correlated (r= 0.60) with April (-1) and June (-1) MMTs. Negative growth responders predominate in eastern (warmer and dryer) locations while positive responders predominate in western (cooler, wetter) locations. The negative growth trend in interior white and black spruce decreases the potential for biomass-fueled energy generation.

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Acknowledgements

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Chapter 1

The Kuskokwim River: Introduction and relevance of research

1.1 Summary.

The purpose of this introductory chapter is to provide an overview of the physiographic and social conditions that establish the relevance and timeliness of this research. The Kuskokwim River itself is a principal component of the regional socio-ecological system, and is described in brief, along with vegetation, soils and climate. A brief review of previous dendrochronological studies in SW Alaska is provided for context, as well as a direct comparison to a Kuskokwim River spruce chronology compiled in the 1950's. Past studies of the potential for a commercial-scale forest products industry are included to orient the reader to the scale of the forest resources under consideration. Finally, a glimpse at a future demand for timber resource development is provided to underscore the necessity of examining the future productivity of this resource, especially in the face of a changing climate.

1.2. Kuskokwim River Basin – Regional overview

1.2.1. River characteristics, riparian vegetation and soil.

The Kuskokwim River of SW Alaska (at 1130km in length) is the second longest river in the state and at 1900m^3/s is ranked the ninth largest in the U.S. in terms of mean annual discharge (Leopold 1994; Richardson and Milner 2005). The Kuskokwim River is braided for much of its length and generally flows along a low gradient (Richardson and Milner 2005). Because it is in the rain shadow of the Alaska Range, the Kuskokwim Basin receives relatively low amounts of precipitation (aprox 42.0 cm/year), resulting in low discharge rates for such a large river (Richardson and Milner 2005). Ice jams each spring typically cause local flooding resulting in bank erosion, silt deposition, and disturbance. Occasionally late summer precipitation and increased glacial melting can also lead to flooding events which often results in additional driftwood movement.

The Kuskokwim River originates in high elevation glaciers in the Alaska Range. Vegetation in the upper part of the basin varies from mountain tundra to productive closed boreal forest. Rocky slopes and alpine tundra are predominant in higher elevations but give way to forests of white and black spruce, aspen, larch, and cottonwood in lower elevations and along the riparian zone (Oswood et al. 1995; Ricketts et al. 1999; Richardson and Milner 2005). The downriver portion of the basin has very little topographic relief and the Kuskokwim forms a large delta, creating a massive and dynamic wetland complex. The flat ground and discontinuous permafrost soils of the delta restrict drainage resulting in a myriad of thaw lakes (Oswood et al. 1995). Land cover in the delta is dominated by sedges in wetlands and alder and willow shrubs on raised surfaces.

Most of the Kuskokwim Basin remained unglaciated during the last glacial maximum, making it a part of the terrestrial and aquatic life refugium called Beringia (Oswood et al. 2000). Southwest Alaska and the now-submerged adjacent continental shelf is also inferred to be a probable refugium for white spruce at the end of the late Pleistocene, based on contemporary patterns of high genetic diversity in the region (Anderson et al. 2006). The ecology of the Kuskokwim River, however, (with the exception of salmon escapement estimates) has been little studied (Richardson and Milner 2005).

The current western limit of treeline on the Kuskokwim River effectively occurs east of Akiak (60.9° N 161.2° W), although some small spruce trees lived as far west as Bethel before they were cut down for local use (Lenz and Barker 1985). Low average temperature during the growing season combined with a short growing period are likely the most important factors limiting treeline (Alden et al. 1993). Additionally, permafrost soils which are prevalent in the Kuskokwim Delta can limit rooting depth and moisture availability causing periods of "physiological drought" (Selkregg 1974; Mead 2000).

1.2.2. Climate

Regional and local climate may limit or optimize growing conditions for trees and plants (Fritts 1976), and thus local climate data are an indispensable part of determining climate sensitivity of tree growth. Climate in the Kuskokwim River Basin can be described from two U.S. National Weather Service first-order weather stations, one at

McGrath (62°57'N / 155°36'W) and one at Bethel (60°47'N / 161°50'W). McGrath is located in the upper portion of the Kuskokwim Basin and has a mean annual temperature of -3.4° C. McGrath experiences climate characteristic of interior Alaska in winter months when temperatures are very cold and precipitation is light. In the summer, however, the climate is at least partially affected by maritime influences, and summer precipitation is more abundant than most stations farther inland (National Climate Data Center (NCDC) 2008). McGrath mean monthly temperatures range from 15.0° C in July to -22.3° C in January. Mean annual precipitation is 43.4 cm/year, 40% of which falls during July, August and September.

The City of Bethel is located in the lower (western) portion of the basin and is only about 160 km from the Bering Sea with no topographic obstacles in between. The climate at Bethel consequently is more maritime than that of McGrath (mean annual temperature is -1.4° C). During two periods of the year Bethel experiences weather with a strong interior (continental) influence. In Bethel, June and July temperatures rise considerably under the influence of warm continental air, and in late December and January, cold continental air dominates and temperatures become analogous to areas farther inland. On average, however, Bethel summer temperatures are lower and winter temperatures are higher than those in McGrath (see Fig. 1.2).

Temperatures across Alaska and the circumpolar north have been increasing in recent years consistent with global climate change (Juday et al. 2005). Both McGrath and Bethel mean annual temperatures have been steadily increasing throughout the period of instrument record (see Fig. 1.2.a). Total growth-year precipitation (Sep-Aug), on the other hand, shows no significant change at either station (see Fig. 1.2.b). The growing divergence between temperature and precipitation in the region may have consequences to plant life as increasing temperatures (leading to increased evaporation) without a simultaneous increase in precipitation effectively lowers moisture availability (Juday et al. 2003).

1.3. White and black spruce response to climate change in Alaska.

Throughout most of the 20th century dendrochronological studies in Alaska were focused on populations of trees useful in reconstructing past climates. In most cases sampled trees were white spruce at treeline carefully chosen to represent trees whose growth was limited by low growing season temperatures. Warm years resulted in larger rings and cold years in smaller rings (Garfinkel and Brubaker 1980; Jacoby and D'Arrigo 1989; Jacoby et al. 1999). More recently, however, populations of Alaska white spruce on low elevation upland sites were found to have an opposite response to growing season temperatures. Cool summer temperatures are associated with optimum growth and high summer temperatures result in temperature-induced drought stress and subsequent narrow rings (Barber et al. 2000; Juday et al. 2005, Soja et al. 2006). Following this discovery, a mixture of the positive and the negative growth response to high temperatures was found in high-elevation treeline sites (Wilmking et al. 2004). Nearly all Alaskan dendroclimatological studies, however, have avoided sampling riparian trees along major rivers because they have been typically considered a climate-complacent population (Fritts 1976; Barber et al. 2000, 2004). Furthermore, many Alaskan studies demonstrate that a complex relationship exists between tree growth and climate and that there may be various responses in a similar region or even contrasting responses through time (Wilmking and Juday 2005).

One Alaskan dendroclimatological study that included high-elevation floodplain trees in mountain headwater streams as well as treeline trees from sites across the Brooks Range, Alaska, indicated that such riparian or floodplain trees can be representative of regional climatic signal (Wilmking and Juday 2005; Wilmking et al. 2004). Wilmking et al. (2004) acknowledge, however, that differences in elevation, watershed age and soil type from site to site made it difficult to conclude that the regionally divergent signals in floodplain trees were from climatic influence alone.

A variety of relationships have also been reported for black spruce-climate interactions, suggesting that site specific conditions play an important role in determining climate response. Radial growth of black spruce populations on ridgetop and high terrace gravel sites in central Alaska is strongly negatively correlated with summer temperatures

(Juday et al. 2005). Radial growth of black spruce on low elevation valley sites near Fairbanks is positively related to winter temperatures and black spruce growth on low elevation, hilly sites is positively associated with late winter warmth and cool spring temperatures (Juday et al. 2005). Black spruce from interior locations growing on north slopes may be largely unaffected by climate warming (Bonan 1989; Soja et al. 2006)

The range in climate interactions between site type and species, as well as the observed warming trend in SW Alaskan weather stations, has important implications for spruce growth-climate interactions on the Kuskokwim River floodplain. While ongoing research by Alix and Juday[1] seeks to compare riparian white spruce from the Yukon River to climate records, no studies have been completed that compare white or black spruce tree growth from the Kuskokwim River floodplain to climate records.

1.4. Past dendrochronological studies in SW Alaska.

In the mid 20th century, J. L. Giddings and W. Oswalt conducted a series of pioneering dendrochronological studies of white spruce in Alaska. The overarching goal of their research was to build master growth chronologies from various regions across Alaska with which archeological specimens could be cross-dated (Giddings 1941, 1953; Oswalt 1950, 1954). Although they made some effort to link climate to tree-growth (Giddings 1943; Oswalt 1960), several limitations kept their results as general assertions. These limitations included a short period of instrument-based climate records, lower precision of ring-width measurement equipment of the time, and lack of computer-assisted statistical analysis tools. Giddings (1943) for example, associated warm growing seasons in particular years with larger ring-widths in tree-line spruce trees across Alaska. This generalization was consistent with the consensus of results that were influenced by the widespread standard in tree-ring research of selecting only treeline conifers limited by cold growing season temperatures. Certainly such tree growth responses to temperature were common and his analysis was performed before the “divergence problem” in tree-growth relationships began to occur in late 20th century dendroclimatological studies (D’Arrigo et al. 2008). Complexity in growth signal of trees sampled at lower elevations,

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[1] C. Alix and G. P. Juday pers communication, 2008.

however, prevented Giddings and Oswalt from making more conclusive statements about climate-growth relationships in such habitats. Despite the limitations in linking climate to tree-growth, the early Giddings and Oswalt studies did succeed in cross-dating artifacts based on regional master chronologies, confirming that regional growth patterns exist across Alaska (Giddings 1961; Oswalt 1952).

One particular study focused directly on building master chronologies of spruce growth along the Kuskokwim River (Oswalt 1954), and warranted comparison to our[2] own modern chronology of white spruce growth (see chapter 2). In 1952, Oswalt compiled 10 regional chronologies from 38 white spruce trees sampled from 20 separate stands between the Herron River (near the headwaters of the Kuskokwim) and Bethel in the west. Because his sample area completely encompassed our own, we decided to average his 10 "regional chronologies" into one which we could compare to our mean growth chronology from 8 white spruce stands sampled in 2002-2007 (see Chapter 2). Our chronology diverges from the Oswalt Kuskokwim chronology in growth patterns beginning early in the 19th century (see Fig. 1.3.a). The explanation appears to be that Oswalt intentionally selected only tree core specimens that had no obvious signal or trend in their ring-widths, a procedure that was common practice at the time because of the lack of automated detrending tools (Giddings 1943; Oswalt 1954). Indeed, Oswalt (1954) states that he selected the 38 "usable" specimens from over 290 tree-cores that he sampled himself or obtained from others. In other words, in lieu of applying a mathematical algorithm to detrend individual tree growth chronologies, researchers obtained a "detrended" chronology by selecting from their sample only those trees that exhibited no marked age-related growth trend.

As a test of this explanation for the difference in the two chronologies from the same sampling area, we removed the increasing growth trend from our 2007 chronology and then compared it to Oswalt's chronology. For this comparison we, (1) detrended our white spruce chronology using ARSTAN ("negative exponential /straight line fit" default option) (Holmes et al. 1986) and converted the ring widths (rw) into ring-width indices

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[2] C. Alix contributed tree core samples to this research project and was a collaborator in the written manuscript. G. P. Juday contributed to project design, data analysis and the written manuscript.

(RWI). (2) Normalized both Oswalt's 1952 chronology and our own detrended chronology using the subtraction method (observation - mean/ SD) so that they could be compared on the same scale.

With the obvious growth trend removed, the chronologies of the two studies are significantly correlated ($r = 0.27$, $p<0.0001$) over the 220 years that they overlap, which is remarkable given the limited accuracy of the measuring techniques used in the 1950's and the relatively small sample sizes used for the comparison (only 4-5 trees represent each regional chronology) (see Fig. 1.3.b). It is important to note at this point that we argue that the increasing growth trend beginning mid 19th century and seen in the 2007 chronology is a non-age related phenomenon and decide not to remove it for climate comparisons (see Chapter 2). Ironically, in his pursuit to select trees without age-related trends, Oswalt may have limited his selection to the few specimens that did not exhibit a significant, climate influenced growth trend.

Both Giddings and Oswalt made great contributions to fields of the ecology and archeology though their pioneer dendrochronological work in Alaska. Their research along the Yukon and Kuskokwim Rivers has been overlooked for many years, but recently there has been a resurgence of dendrochronological work in the region (Alix 2004, 2005, 2006; Alix and Brewster 2004, 2005), including this study.

1.5. Use of forest products in the Kuskokwim Valley

In order to more fully appreciate the importance of determining the future productivity of Kuskokwim Basin spruce trees, it is necessary to consider the value placed on regional forest resources by the people who live there. A look at historic and modern wood use is presented to provide such context.

1.5.1. Historic Wood Use.

Yupit Eskimos (in coastal and western portions) and Athapaskan Indians (in interior or eastern portions) have occupied the Kuskokwim River Basin for thousands of years. Forest materials have been important resources for humans in this region for as long as the area has been populated (Osgood 1936; Oswalt 1967). Trees and driftwood traditionally provided a range of important materials serving a variety of functions such as fuel wood, construction material, tools essential for subsistence activities, and crafts (Oswalt 1967; Alix and Brewster 2004; Alix 2005).

In order to appreciate the changing reliance on wood products through time, we examined interviews of ten long-time residents of Kuskokwim River communities[3]. These interviews, which focused on past and present uses of wood (especially driftwood), reveal a long history of reliance on forest products for a wide range of needs (see Table 1.1). They also indicate that while wood it still highly valued and actively harvested (both as standing trees and as driftwood) (Alaska Department of Commerce and Economic Development (ADCCED) 2008); Wheeler and Alix 2004), it is clear that many items that were once made from wood have been replaced by other materials in more modern times (see Table 1.1).

The largest scale harvest of trees from along the Kuskokwim River occurred from the early 1900's to the 1950's when wood-fired steam ships transported goods and people along the river (Lenz and Barker 1985). During this period, thousands of trees accessible from the river were cut down to support the steam ships which burned about a cord of wood per hour (Lenz and Barker 1985). After steam ships were replaced by petroleum powered watercraft following WWII, there has been no comparable large scale harvest of trees along the river.

In recent history, the greatest use of forest products along the Kuskokwim is for home heating (ADCCED 2008). In general, upriver communities rely more heavily on wood as a source of fuel than down river communities (see Fig. 1.4), likely due to the fact that tree abundance is much greater in upriver locations. Although there are still no large scale timber harvest operations in the region, there has been a history of investigations into the feasibility of developing a commercial wood product industry from Kuskokwim River trees.

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[3] Interviews were conducted in 2002 by C. Alix and K. Brewster. Some interviews required translation from Yupik to English which was completed by Anna Jacobson.

1.5.2. Wood product industrial feasibility studies.

The timber resources of Southwest Alaska, and of the Kuskokwim River floodplain in particular, were extensively inventoried in 1967 by the U.S. Forest Service (Hutchinson 1967; Hegg and Sleverding 1979). The inventory reported 252,000 acres of timberland containing a net growing stock of 343 million cubic feet in the productive areas along the river (Hegg and Sleverding 1979). White spruce was found to be the most important timber species, accounting for 72 percent of the net growing stock volume and 88 percent of the net saw timber volume on timberland (Sampson et al 1988).

The large supply of relatively accessible wood identified in the earlier inventories spurred an interest in wood-industry feasibility studies over the next few decades (Sampson et al. 1988; ADCCED 2008). In 1970, the Kuskokwim Forest Resource Committee explored the idea of using local forest products for the construction of the Bethel Housing Project, but eventually decided that outside sources would be a more economical choice (Clapp et al. 1969, 1970; Sampson et al., 1988). A study conducted in the mid-1970's determined that potential existed for a forest products industry in the Yukon-Kuskokwim River area (Zasada, 1976). In 1980, a consulting firm specifically investigated the potential of a saw mill and timber export business in the middle Kuskokwim area (Hammons, 1981). None of the several options considered were found to be economically viable at the time, but a second study done a year later found that a small saw-mill operation located close to the timber supply could indeed be profitable (Kilborn et al. 1981). Sampson et al. (1988) also discussed the potential for a forest product industry in the Kuskokwim Valley but conceded that the largest obstacle for industrial development was the remoteness of the region and the general lack of transportation.

Three active mills do presently operate seasonally along the river in McGrath, Chuathbaluk and Bethel. These mills sell a limited selection of primarily roughcut lumber, houselogs and firewood (ADCCED 2008). Despite the interest, there has been no significant development of a forest products industry in the region. The rising costs of heating oil and diesel fuel, however, in conjunction with a downward trend in rural utility cost subsidies may lead to a greater reliance on wood as a source of heat and electricity in the near future (ADCCED 2008).

1.5.3. Increasing potential for wood as an alternative energy source.

The ADCCED (2008) began tracking fuel prices across Alaska in recognition of the potentially devastating consequences rapidly rising fuel costs can have on rural Alaskan communities. Surveys of western and interior Alaskan communities (including those along the Kuskokwim River) reveal that recent rises in energy costs are "severe obstacles to community survival, sustainability and success" (ADCCED 2007). As of November, 2007 Alaskan's were paying 62% more than the national average cost for gasoline. Citizens of rural southwestern communities, however, are typically paying much more for gasoline and heating fuel than even the average Alaskan. As of November 2007, residents of McGrath were paying 13% more for fuel oil and 26% more for gasoline than the average Alaskan. Residents of Sleetmute, a village centrally located in the middle Kuskokwim region, paid 30% more for heating fuel and 40% more for gasoline than the average Alaskan. The prices have been continuously increasing in recent years. The average cost of fuel in western Alaskan communities has risen by over 26% between Novembers 2005 – 2007. Fuel retailers in the region show that demand has not decreased despite a significant increase in cost, which indicates that these communities are "reliant on a consistent minimum amount of fuel in order to simply meet basic survival needs" (ADCCED 2007).

In 2007 the Alaska Energy Authority (AEA) was assigned by the state government to investigate sustainable alternative energy sources. One result of their investigation is an increased consideration of Kuskokwim Basin trees as a source of biomass fuel for energy generation (AEA 2008). Wood energy generation is a desirable alternative fuel because it is readily available, renewable, and creates few of the environmental hazards associated with the use and storage of fuel oil and diesel (ADCCED 2008). Modern biomass combustion has additional benefits because it emits 90% less carbon dioxide than fossil fuels and is typically significantly less expensive (USDA 2004).

The Kuskokwim River spruce forests are the key to the creation a sustainable industry for biomass (wood) energy production which could potentially rescue the small communities from the crushing price of petroleum products. In 2007 the City of McGrath, the largest community in the upriver portion of the Kuskokwim Basin, initiated work on a wood biomass energy generation project (Feidt 2007; ADCCED 2008). The intent of the project is to "buffer rising fuel costs and declining power cost subsidies," and eventually allow for "a phased transition to full reliance on wood-fired heat and electrical generation" (ADCCED 2008). In a 2007 Alaska Public Radio interview, Natalie Baumgartner, the McGrath City Administrator, said the unprecedented high costs of fuel ($6.78/gallon for heating oil at the time) are "really troublesome for the residents in this whole upper Kuskokwim region." She went on to say that she was hopeful that the wood biomass project will help "mitigate a lot of the pain that the families are going through" (Feidt 2007).

McGrath may be the catalyst for a shift to wood use for community-level power generation in the region. The resulting commercial wood operations are likely to improve overall economics for a forest products industry in the area, producing additional changes. For example, with improved infrastructure in place, the cost of obtaining high quality sawlogs would dramatically decrease, although questions about the ecological impacts of a large scale forest industry may limit wood harvest to only what is required to meet energy requirements (ADCCED 2008). The increasing potential for the resource increases the need to obtain more information about climate-growth interactions which have implications for tree productivity and ultimately community sustainability.

1.6 Study area: Central Kuskokwim

1.6.1. Study area selection.

A key consideration for this project was selecting a study-area along the river that was representative of average climate conditions and included forested areas which are highly likely to be considered for future harvest. We selected an approximately 370 km stretch of the Kuskokwim River between Devil's Elbow (62° 8' N 156°14'W) and

Tuluksak (61° 6' N, 160° 57' W) (see Fig 1.1). This study area represents a large section of the forested river and encompasses an area where climate transitions from predominantly continental to more maritime influenced weather.

1.6.2. Geomorphology and soils.

From above Sleetmute (61.6° N 157.0° W) to near Napaimute (61.5° N 158.6° W), the river carves a narrow valley through the Kuskokwim Mountains, a range that has been reduced to rolling, denuded surfaces largely without the help of the last ice age (Krause 1984). Beyond the Kuskokwim Mountains, from Napaimute to Tuluksak and westward, the river flows through a broad, nearly level floodplain with no topographic obstacle to the movement of air masses from the Bering Sea inland. The central Kuskokwim floods annually or biennially to some extent, usually as a result of ice break-up which typically occurs mid-May. Krause (1984) describes the flood plain deposits of the middle Kuskokwim as consisting primarily of "well-stratified bar accretion deposits of bed-load sand, gravel and silt." Erosional surfaces bordering the main channel, (and which typically overlay bar-accretion deposits), consist of silt and fine sand which are deposited during high water or bankfull flow. The silt layer can be quite deep; Krause (1984) measured silt thickness near Aniak at depths of up to six meters. The flat, flood basins surrounding the river contain poorly drained soils made up of silt, clay and organic material.

1.6.3. Forests

The forests growing along this region of the Kuskokwim River are comprised mainly of white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.)B.S.P.). In better drained portions of the riparian zone and lower slope terraces, white spruce predominates; while in poorly drained areas underlain by permafrost and on cold, north facing slopes, black spruce predominates (Mead 2000). Mixed stands of spruce-birch (*Betula papyrifera* March), spruce-cottonwood (*Populus trichocarpa* Torr. & Gray), and spruce-tamarak (*Larix lariciana* (Du Roi) K. Koch.) also occur throughout the region (Mead 2000). Stands of cottonwood (Populus balsamifera L.) can be found on recently deposited alluvium along the river as well.

1.5 Chapter 1 Tables and Figures.

Figure 1.1.

Map of southwestern Alaska with 2002-2007 Kuskokwim River sample plot locations.

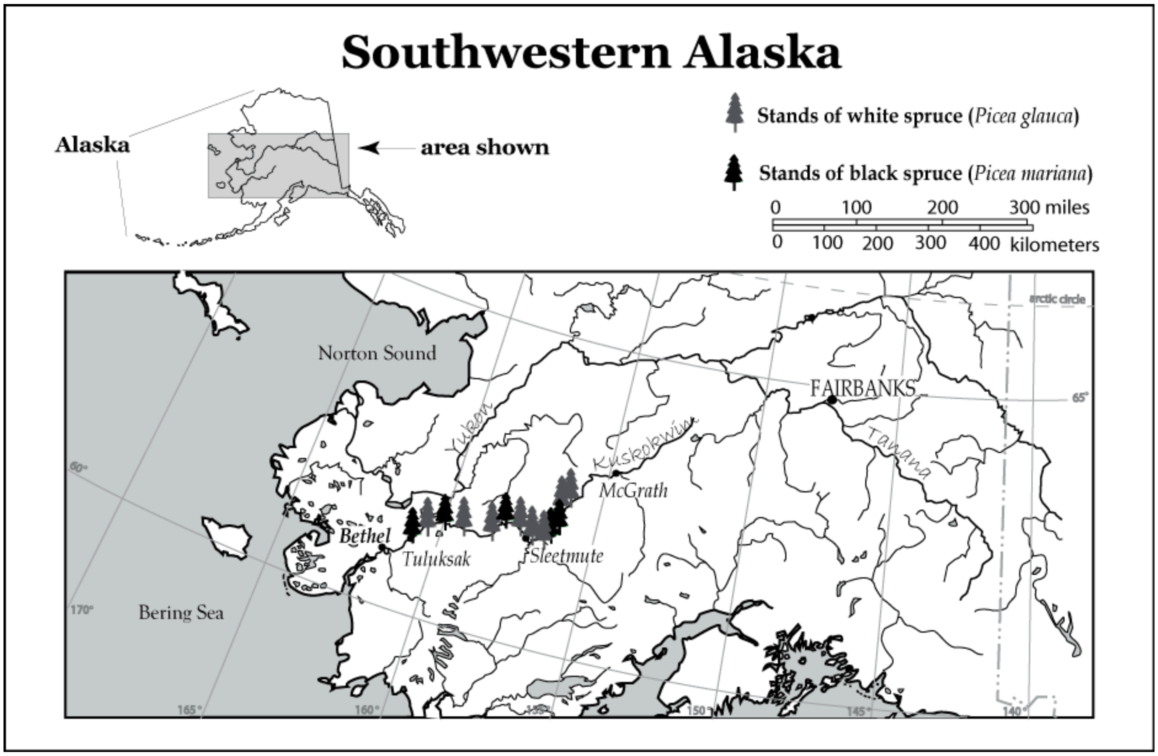


Figure 1.2.
McGrath and Bethel mean annual temperature (MAT) and total growth-year precipitation (Sep-Aug) from 1949-2006; **a**, both stations have recorded steadily increasing mean annual temperatures since 1949 though Bethel's temperatures remain consistently higher than those recorded in McGrath (by ~ 2° C); **b**, average precipitation has not significantly increased at either station from 1949-2006. On average, Bethel receives 0.8cm more precipitation than McGrath each year.

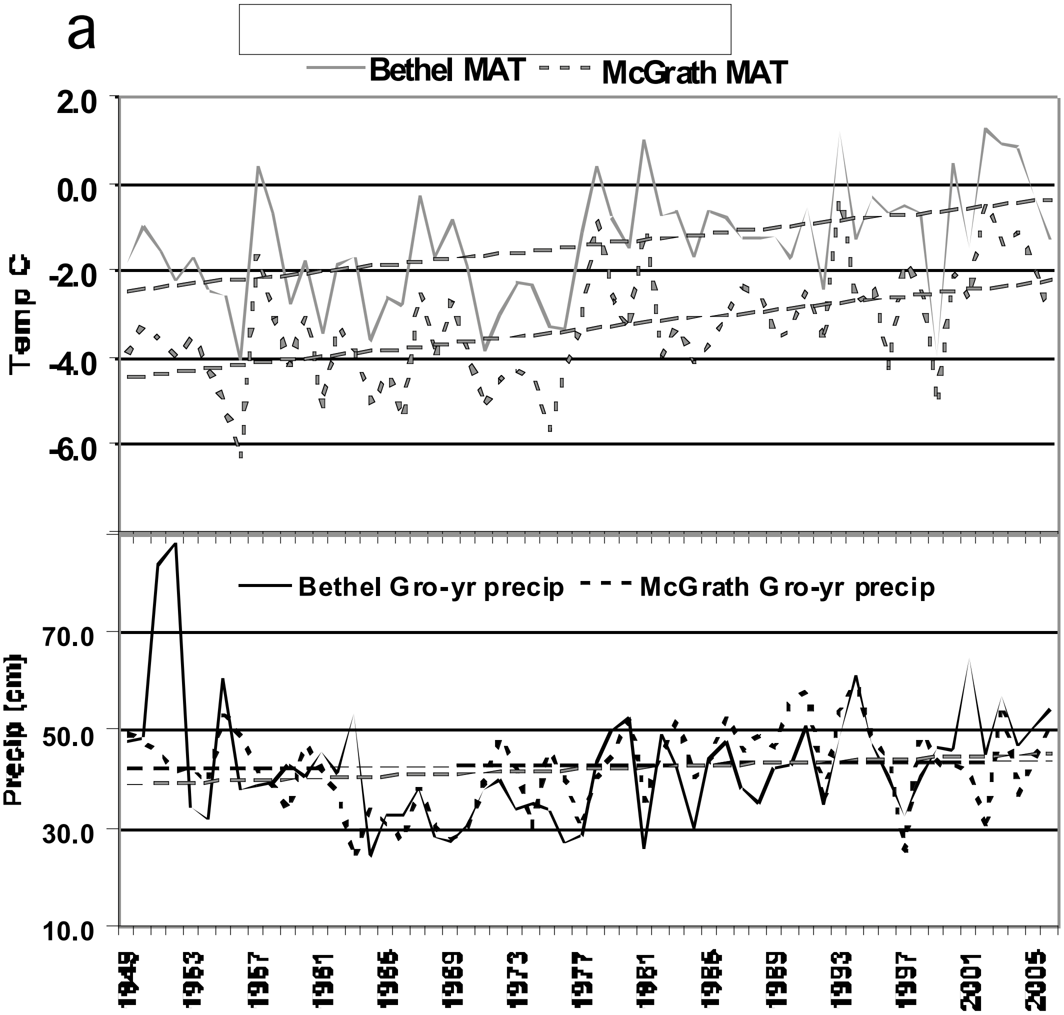


Figure 1.3.

Comparison of Oswalt's (1954) Kuskokwim spruce chronology (n=38) versus 2007 Kuskokwim white spruce chronology (n=118) ; **a**, comparison of raw rw's show a divergence beginning around 1800 where the 2007 chronology trends upward (rate of growth increases); **b**, comparison after detrending the 2007 chronology and normalizing both chronologies for examination on the same scale. The two chronologies are significantly correlated at ($r = 0.27$, $p < 0.0001$).

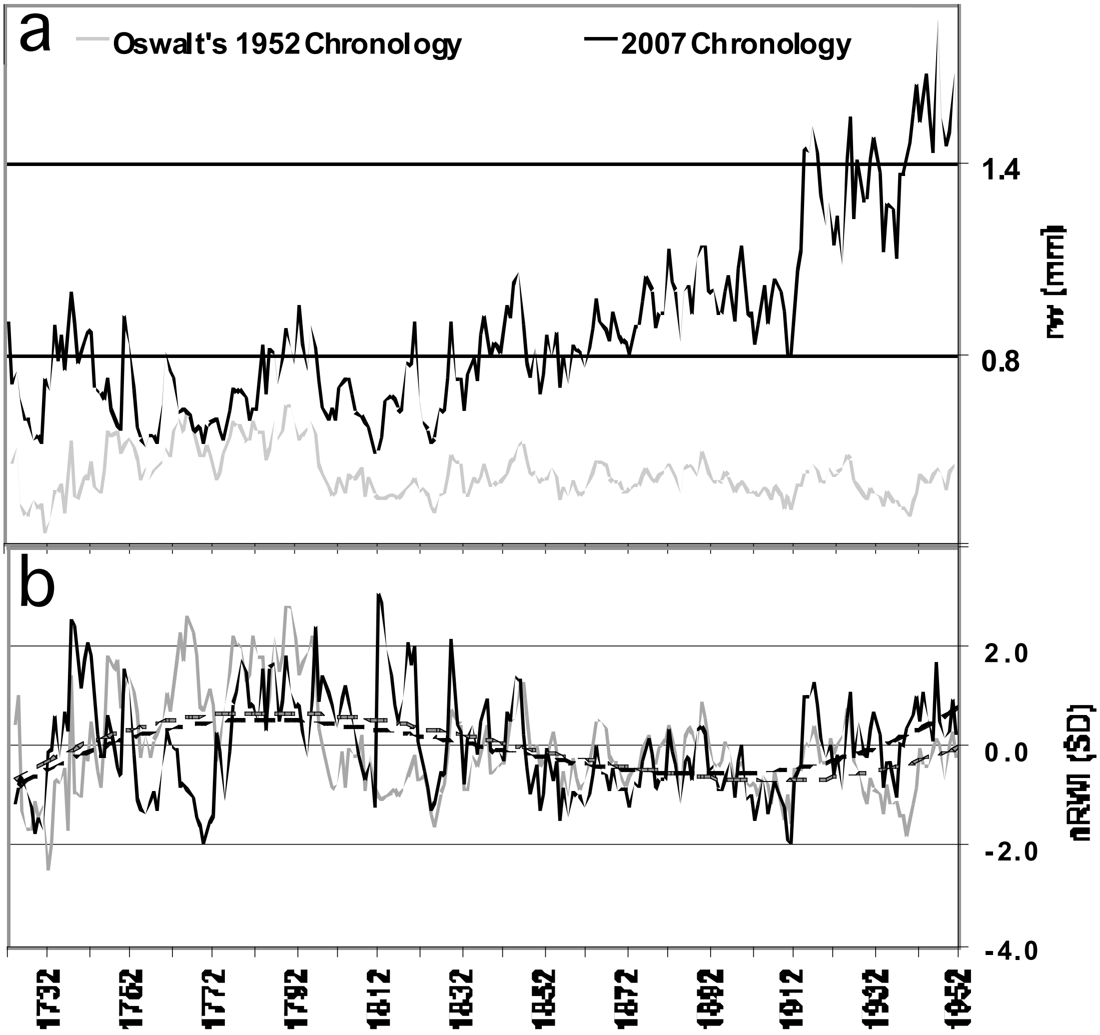


Figure 1.4.

Use of wood as a primary heating source in Kuskokwim River communities. The largest communities in each region (Bethel, Aniak, McGrath) are shaded black. Source: 2000 Census.

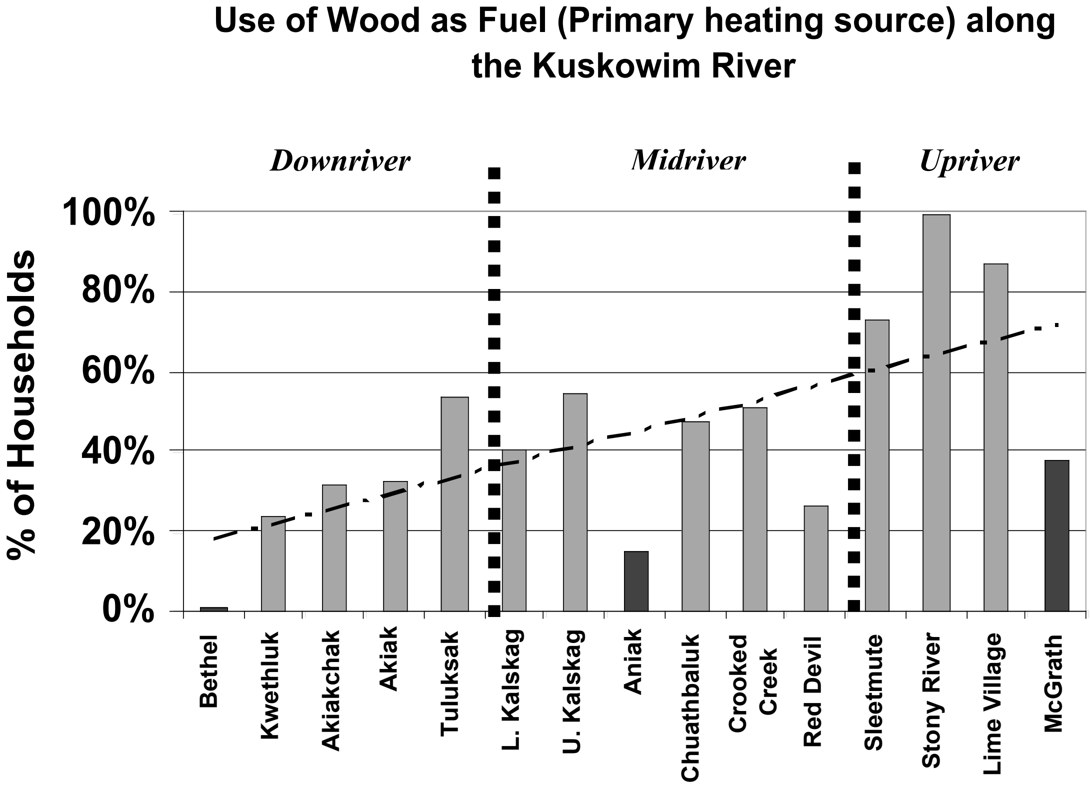


Table 1.1.

Current and historical use of wood on the Kuskokwim River based on interviews conducted in 2002 by C. Alix and K. Brewster. Interview subjects include eight men and two women who are long time residents of Kuskokwim River communities. Use was categorized as "historic" if referred to primarily in the past tense (e.g. "they used to use wood for.."), "current" if referred to as a recent use (e.g. "now they use wood for…"), and "both" when use was described as something done currently and traditionally (e.g. "they still use wood for…").
Interview subjects: 1. S. Andrewska from Sleetmute; 2. G. Billy from Napakiak; 3. A. Fredricks from Sleetmute; 4. D. Matter from Napaimute/Aniak; 5. J. Matter from Napaimute/Aniak; 6. N. Mellick from Sleetmute; 7. E. Venes from Bethel; 8. E. Worm from Napakiak; 9. J. Worm from Napakiak; 10. P. Zaukar from Sleetmute.

General use category: (Fuel, architecture or tools/objects)	**Description of use of locally collected wood**	**Primarily current or historic use?**	**Source(s)** [from interviews conducted by Alix and Brewster in 2002)
Fuel	**Cooking**	***Historic***	**G. Billy; E. Worm**
	Home heating	***Both***	**S. Andrewska; G. Billy; D. Matter; N. Mellick; E. Venes; E. Worm; P. Zaukar**
	Steam bathing	***Both***	**S. Andrewska; G. Billy; E. Venes; E. Worm**
	Smoking Fish	***Both***	**S. Andrewska; D. Matter; N. Mellick; E. Worm; P. Zaukar**
Architecture	**Bath house construction**	***Both***	**S. Andrewska**
	House/Cabin/ construction	***Both***	**S. Andrewska; D. Matter; N. Mellick**
	Kashim frame (sod home)	***Historic***	**G. Billy**
	Lumber	***Current***	**S. Andrewska; G. Billy; A. Fredricks; J. Matter**
	Smokehouse construction	***Both***	**S. Andrewska; D. Matter; N. Mellick**
Tools/Objects Implements	**Atlatl and spear**	***Historic***	**J. Worm**
	Backpacks	***Historic***	**J. Matter; N. Mellick**
	Baskets	***Historic***	**J. Matter**
	Boats	***Historic***	**G. Billy; A. Fredricks; N. Mellick; J. Worm; P. Zaukar**
	Bow & Arrows	***Historic***	**J. Worm**
	Bowls	***Historic***	**G. Billy; D. Matter; N. Mellick; J. Worm**
	Canoes	***Historic***	**S. Andrewska; P. Zaukar**

Tools/Objects Implements	**Ceremonial gifts**	***Both***	**G. Billy**
	Dance masks	***Historic***	**D. Matter**
	Dolls/Figurines	***Historic***	**D. Matter; N. Mellick**
	Fish Fences (for corralling and catching fish)	***Historic***	**G. Billy; N. Mellick**
	Fish Racks (for drying fish)	***Both***	**S. Andrewska; E. Venes; P. Zaukar**
	Fish Rafts (for cleaning fish)	***Both***	**J. Matter; P. Zaukar**
	Fish traps	***Historic***	**S. Andrewska; G. Billy; D. Matter; N. Mellick; J. Worm; P. Zaukar**
	Fish wheels (for catching fish)	***Historic***	**D. Matter; P. Zaukar**
	Ice Gaff (for self extraction from Kayak to ice)	***Historic***	**G. Billy**
	Kayaks	***Historic***	**G. Billy; J. Worm**
	Ladles	***Historic***	**G. Billy; J. Matter; J. Worm; P. Zaukar**
	Musical instruments	***Historic***	**G. Billy**
	Net floats	***Historic***	**J. Matter**
	Oars	***Historic***	**J. Matter**
	Pestle (for crushing berries etc.)	***Historic***	**J. Worm**
	Shovels	***Historic***	**N. Mellick**
	Story knives	***Historic***	**J. Worm**
	Sleds	***Historic***	**G. Billy; J. Matter; J. Worm**
	Snowshoes	***Historic***	**G. Billy; P. Zaukar**
	Spear	***Historic***	**N. Mellick**
	Tent posts and frames	***Historic***	**G. Billy; J. Matter**
	Ulu (knife) handles	***Historic***	**G. Billy**
	Yolks (for carrying water)	***Historic***	**J. Matter**

Chapter 2

Patterns of growth and climate sensitivity in Kuskokwim River spruce trees along an east-west gradient

2.1. Introduction

The riparian forest of the Kuskokwim River basin has been valued as a source of wood for centuries (Osgood 1936; Oswalt, 1967). Although the area was evaluated for industrial forest product potential decades ago, the nearly non-existent infrastructure to support such an industry (workforce, service and supply, etc.) combined with the relative inaccessibility of the region has precluded any large scale development to date (Sampson et al.1988; ADCCED 2008). Recently, however, extremely high petroleum prices are forcing communities of the Kuskokwim basin to consider alternative sources of fuel, and the hundreds of thousands of acres of timberland growing along the river have become an attractive potential source of renewable energy (ADCCED 2008).

Future climate warming at the rate of the last century is likely to decrease productivity of white spruce and would eliminate the species in areas of Interior Alaska where today it is commercially productive (Barber et al. 2000; Juday et al. 2005). White spruce is the softwood species with the greatest potential for sustained yield harvest for community biomass energy generation. Yet the fate of trees growing along rivers where moisture is not often considered to be a growth limitation, remains poorly understood. In fact, most dendroclimatological studies, including those reported in the Arctic Climate Impact Assessment (Juday et al. 2005), use mostly tree-line or upland white spruce as a basis for tree growth/climate analysis (Barber et al. 2000, 2004; Fritts 1976; Jacoby et al. 1999; Jacoby and D’Arrigo 1989). This has left a knowledge gap for the communities of southwestern Alaska which now face decisions concerning forest industry development without fully understanding the productivity potential of the resource in the face of climate change.

Whether Kuskokwim white spruce will become more or less productive in the near future is fundamentally important to decision-makers planning the future of the region. This study seeks to provide insight into the relationships Kuskokwim River spruce trees have with local climate. In this study we apply correlation analysis to help determine the extent to which temperature and precipitation influence the amount of annual radial growth these tree populations experience.

2.2 Objectives

This study evaluates the relationships between radial growth and climate parameters (temperature and precipitation) for white and black spruce trees growing along the Kuskokwim River, Alaska. We conducted a series of analyses designed to: a) determine whether or not riparian spruce trees are sensitive enough to climate variation to exhibit statistically significant changes in annual radial growth; b) compare climate-growth interaction in both white and black spruce trees including interspecies similarities and differences; c) determine if there are sub-regional differences in climate response versus one overarching, basin-wide signal.

2.3 Methods

2.3.1. Sampling.

From 2002 to 2007, we compiled tree-ring samples from 118 white spruce (*Picea glauca* (Moench (Voss)) and 77 black spruce (*Picea mariana* (Mill.)B.S.P.) growing along a 370 km stretch of the Kuskokwim River, Alaska. We sampled between 10 and 16 healthy, dominant or codominant trees as encountered from eight separate white spruce stands and five different black spruce stands. Each white spruce stand was selected for sampling based on its tendency to have large, healthy trees, level ground with river deposited silt soils, and geographic separation (~10-20km) from other sampled stands (see Figs. 2.1 and 2.2 for white spruce growth characteristics). All black spruce sites were located on river-cut banks with permafrost soils (see Fig. 2.3 for black spruce growth characteristics). For each species, we ensured that each sampled site had similar characteristics (e.g. slope, soils, distance of trees from river), as opposed to a range of various site characteristics. Maintaining similar site characteristics allowed for later examination of the year to year variability in growth rather than variability in site-related growth potential. We also recorded the position of each site (using a handheld GPS), and took several digital photographs capturing ground cover conditions and other general site characteristics. For each tree we recorded diameter at breast height (DBH) and for almost all trees, took digital photographs capturing the bole and crown. Due to time limitations, instead of measuring each tree's height we instead measured the heights of at least two dominant or codominant trees at each site and then estimated the heights of the remaining trees in that stand. We collected at least one penetrating core (from bark through pith continuing through bark on opposite side) at breast height from each tree so that no less than two radial measurements were available for each year. Ring widths (rw) were measured using a Velmex® sliding stage with 0.001mm resolution. Dating accuracy was checked by cross-dating using COFECHA (Grissino-Mayer et al. 1992). Once we were confident that each measured series (radius) was accurately dated, we calculated each year's mean ring width for each tree based on the average of all measured rings for that tree. In this study, all analysis of climate versus annual radial growth is based on these tree-mean annual values.

In order to determine how representative our sample of white spruce trees was we compared the DBH and estimated heights of the white spruce sampled during this study to data from a USDA Forest Service (USFS) inventory (see Fig. 2.1). The USFS inventory was conducted along the Kuskokwim River in 1967 and DBH and height measurements were collected on over 4,000 white spruce trees (Hegg and Sleverding 1979). We assumed that the population size structure of trees sampled in 1967 was similar to current tree size structure along the river. This assumption is correct if recruitment into and mortality within size classes was steady over the last 40 years. Ages at pith for our sample are consistent with a steady recruitment in this tree population (see Figs 2.2.a, 2.3.b. and 2.4). We compared the diameter and height distribution of the118 trees that we sampled to the complete 1967 inventory which includes trees from along the entire forested length of the river. We also compared our sample to a subset of the USFS inventory that we selected using ARCGIS® from within the geographic distribution limits of our study. Results of these comparisons show that the trees we selected were some of the largest (diameter) and tallest trees growing along the entire river or within a similar geographic distribution (see Fig. 2.1). Results of subsequent climate correlation analyses should therefore be restricted to trees categorized by these larger size distributions.

We were not able to make size comparisons to an extensive regional forest sample of black spruce because this species has not been the subject of comparable inventory data collection or reports because it has little commercial value for traditional forest products.

2.3.2. Normalization and detrending.

Detrending raw tree ring-widths is commonly done to account for a general bias of radial growth of the bole (Fritts 1976). In many instances, trees grow proportionally larger annual rings when they are young and gradually grow smaller and smaller rings as they age. If trends exist in the individual series (radius) of many of the sampled trees, the resulting average growth chronology would reflect non-climate related trendedness that could distort later correlations with climatic variables. We inspected individual tree-ring series and stand averages for age-related trends. In both species, age-related (negative exponential) trends were apparent in the early years of growth of only a few individual trees. Age-related effects were stabilized in all trees by the mid 1940's which is when the McGrath climate data becomes available, leading us to consider using either raw ring-width values or detrending methods that would least compromise any non age-related growth trends. After several trial attempts we intentionally choose not to detrend with a negative exponential curve, which is typically used to account for a general bias of radial growth of the bole (Cook 1985; Cook and Peters 1981; Cook et al. 1992; Fritts 1976). We found that fitting a negative exponential or straight line fit (ARSTAN detrending option-1) to each series (radius) had the effect of flattening the curves to the point where there was little change over the period of climate record while the actual raw radial growth rate often doubled over the tree's lifetime. Fitting a negative exponential curve artificially dampened the effect of 20th century changes in growth rates since they occur in the later portions of most trees' lives (asymptotic portion of an exponential curve) where the mathematical effect of detrending is very small in any case.

For black spruce we therefore decided to simply use raw ring-width values for correlation analysis with climate indices. For white spruce, in recognition of the broader range of tree size encountered (see Figs. 2.1 and 2.2), we wanted to allow for smaller and larger trees to contribute more equally to the average growth rate. We chose to apply the ARSTAN (Holmes et al. 1986) "horizontal line through the mean" normalization procedure (using the division method of normalization [(observation/mean)/ SD]) to each white spruce tree series. This procedure converted the individual tree's raw rws into a ring-width index (RWI) and had the effect of eliminating size related contributions to the stand or sample mean RWI, while preserving the non-age related changes in the portion of the chronology that we needed for climate comparisons. We compared all climate indices to raw ring-width data as well as normalized values (RWI). There were no major anomalies in correlations between the two forms of data, confirming that the effect of normalizing the white spruce series was modest. All future reference to white spruce radial growth measurements for the purpose of climate correlation analysis will therefore be in ring-width index (RWI) which is the result of the aforementioned normalization procedure.

2.3.3. Climate data selection.

Individual and mean ring-width (for black spruce) and RWI (for white spruce) were compared to climate records from four of the nearest 1st order weather stations (Nome, Bethel, Fairbanks, and McGrath) in order to determine which records resulted in the most significant correlations. Both white and black spruce trees from this sample were much more responsive (had higher correlations) to McGrath climate data rather than either Fairbanks or Nome. Bethel and McGrath temperature records were highly correlated with each other (r= 0.92) so McGrath records were utilized for subsequent analysis due to its closer proximity to sample locations. The McGrath weather station is less than 80 km and less than one degree of longitude from the nearest (northeastern) sampled site, making it the closest 1st order station to this population. Bethel precipitation data, while significantly correlated to McGrath (r= 0.45), yielded higher correlations only to a particular subpopulation of trees upon refined analysis (see discussion). The mean RWI of all 118 white spruce trees and mean ring-widths of the 77 black spruce were compared to the McGrath mean monthly temperature (MMT) and total monthly precipitation (TMP) records for the entire 62 year period of continuous record (1944-2006).

2.3.4. Correlation analysis and interspecies comparisons.

We compared the growth rates of the two tree species (black and white spruce) to each other using both raw ring-widths and also after normalizing the rw (subtraction method) to analyze any common trends or responses. Once opposing climate-response types were identified (see results), we compared their growth rates to identify differences between response groups.

We conducted correlation analyses of radial growth and 36 months (year of tree-ring formation plus the two years previous) of McGrath MMT and TMP. We chose to include 36 months of climate data in the analysis because conifers are determinant growers whereby photosynthetic gain in one or two growth seasons prior to ring formation may have the strongest influence on current year ring-growth (Kozlowski and Pallardy 1997). We identified mean monthly values where the correlation (r) was greater than 0.30 or less than -0.30 (threshold of significance where $p < 0.01$) for the period 1944-2006 (62 cases of comparison). We chose a rigorous significance cutoff ($p < 0.01$) to limit selection of climate parameters to only those which were likely the most influential to growth.

Our approach was to build the most parsimonious predictive climatic index (most predictive power for fewest independent variables) that was stable through time and across the range of environmental variables, and that had an allowable basis in ecology or physiology of the tree species. We began the process of constructing a predictive climatic index with the individual month with the highest correlation score of either MMT or TMP with RWI (white spruce) or rw (black spruce). We then examined the synergistic effect of progressively introducing additional independent variables with significant but lower correlation scores. We gave priority in our selection of monthly variables to temporally separate ones (non-adjacent months) because of the greater likelihood of significant independent predictive value and less probability that the correlation score of the combined terms would be affected by simple autocorrelation. We found that in nearly all cases, little unique explanatory power was added after the optimum combination of 2 independent variables was identified. In order to avoid scaling effects, we normalized the selected variables and combined them (added or subtracted) according to the sign of the correlation coefficient. Finally, we weighted each normalized independent variable by 10% increments, tried all combinations, and selected the weighting factors that maximized the correlation of the climate predictor with rw or RWI.

We plotted the radial growth measurements versus the climate indices to examine the year-to year correspondence in addition to the overall correlation score. In selecting independent variables, we gave priority to climate predictive indices that demonstrated consistent patterns of point-to-point congruence rather than overall upward or downward trend across the 62 years of climate and/or ring width data. We also examined the correlation of climate and ring width time series smoothed with a 5-year running mean, a treatment that has been used successfully in Alaska climate and tree ring series to represent trend on a quasi-decadal basis (Juday et al. 2005; Wilmking et al. 2004). We required that final selected climate indices demonstrate an increase in Pearson correlation coefficient scores of smoothed variables (climate to ring width) of 0.10 compared to raw (unsmoothed) values. Finally, we plotted the linear regression of climate predictors and tree population group growth responses in order to examine outliers.

2.4 Results

2.4.1. Sample growth characteristics.

The white spruce trees sampled from 2002-2007 represent a range of age classes but are mostly from mature, old stands (see Fig. 2.2.a). Examined as a single population, our sample of 118 Kuskokwim River white spruce trees experienced increasing rates of growth from the 1830s until the 1940's. In the last several decades, the average rate of growth has decreased (see Fig. 2.2.c).

Black spruce height, diameter and growth characteristics show that the black spruce sampled during this study were generally from relatively young though mature stands. As a grouped population, this sample of black spruce experienced increasing rates of growth from the 1840's to the 1950's when overall radial growth began to decline (see Fig. 2.3.c).

The mean growth rates of all individuals of the two tree species (raw and normalized values) were significantly correlated over the entire period that their chronologies overlap (1913-2006) ($r = 0.84$) (see Fig. 2.4).

2.4.2. White spruce: growth relationship with climate variables.

August MMT at McGrath had the highest correlation of any single mean month of temperature to the mean RWI of all 188 white spruce trees (see Fig. 2.5). Precipitation at McGrath was not significant at $p<0.01$. Comparing correlations on an individual tree basis, 83 (of 118) individual white spruce trees had a negative correlation with August MMT. Using this subset of 83 white spruce trees we correlated mean RWI with the 36 months of McGrath MMT and found that the June (-2) (from 2 summers previous to the year of ring formation) MMT was also significant ($r \leq -0.30$, $p < 0.01$) (see Fig. 2.6.b). We weighted the normalized August and June(-2) MMTs 60% and 40% respectively to maximize correlation with the mean RWI of the 83 negatively correlated trees. We labeled the 83 white spruce trees in this category "negative summer temp responders." The resulting climate favorability index for the 83 white spruce "negative summer temperature responders" is given in Eq. 2.1.

Eq. 2.1. Negative Temperature Index (NTI_{RWI}) for white spruce "negative summer temp responders"

$$NTI_{RWI} = (Yr_0 MMT_{nAug} \text{ X } 60\%) + (Yr_{-2} MMT_{nJun} \text{ X } 40\%)$$

Yr_0 is the year of ring formation, Yr_{-2} is two years prior to ring formation, MMT_{nAug} is the normalized mean August monthly temperature and MMT_{nJun} is the normalized June mean monthly temperature.

The 83 "negative summer temp responders" demonstrate a significant relationship with the NTI_{RWI}, exhibiting strong year to year correspondence and significant overall correlation ($r = -0.62$) (see Fig. 2.7.a). Each individual tree in the "negative summer temp responder" group has a negative correlation with the NTI_{RWI} index, and 76 of the 83 trees are significantly correlated at the $p < 0.05$ level. Using smoothed values, the correlation improves ($r = -0.91$) (see Fig. 2.7.d).

We examined the remaining 35 white spruce trees of the total sample which were not negatively correlated with McGrath August or June(-2) MMT. We analyzed the correlation of the mean RWI of these 35 trees with the 36 months of McGrath MMT and TMP. We found that this subset was significantly positively correlated ($r \geq 0.30$, $p < 0.01$) with the April (-2) and November (-2) MMTs at McGrath (see Fig. 2.6.a). These 35 trees were not significantly correlated with McGrath TMP. The normalized McGrath April (-2) and November (-2) MMTs were weighted 60% and 40% respectively. We labeled the 35 trees in this category "positive spring/fall temp responders." The following climate favorability index (PTI_{RWI}) correlated best to mean RWI of the "positive spring/fall temp responders" (Eq. 2.2).

Eq. 2.2. Positive Temperature Index (PTI_{RWI}) for white spruce "positive spring/fall temp responders"

$$PTI_{RWI} = (Yr_{-2} MMT_{nApr} \text{ X } 60\%) + (Yr_{-2} MMT_{nNov} \text{ X } 40\%)$$

Yr_{-2} is two years prior to ring formation, MMT_{nApr} is the normalized mean April monthly temperature and MMT_{nNov} is the normalized November mean monthly temperature.

The mean RWI of the 35 "positive spring/fall temp responders" was significantly correlated with the PTI_{RWI} ($r = 0.60$) (see Fig. 2.8.a.), and 29 of the 35 individual trees in this category were significantly correlated at the $p < 0.05$ level. When smoothed with a 5-year running mean, the relationship between the mean RWI and the PTI_{RWI} was improved ($r = 0.83$) (see Fig. 2.8.c).

2.4.3. Black spruce: relationships with environmental variables.

We correlated the mean ring width (rw) of all 77 black spruce with the 36 months of McGrath MMT and TMP records. Unlike the white spruce, the black spruce sample mean rw was significantly correlated to some months of precipitation as well as temperature (see Fig. 2.9). We correlated each individual black spruce tree's radial growth to both McGrath MMT and TMP and divided the sample into two groups based on a positive or negative correlation with climate parameters. The majority of individual trees making up the sample (66 of 77 trees) were both negatively correlated with select summer MMT (August and June(-1)), and positively correlated with select summer TMP (August (-1) and June (-2)) (see Fig. 2.10). We grouped these 66 black spruce trees together and labeled them "negative summer temp responders." We created the following climate favorability index for the 66 black spruce "negative summer temp responders" (Eq. 2.3).

Eq. 2.3. Negative Temperature Index (NTI_{BSrw}) for black spruce "negative summer temp responders"

$$\mathbf{NTI_{BSrw} = [(Yr_0MMT_{nAug}) + (Yr_{-1}MMT_{nJun})] - [(Yr_{-1}TMP_{nAug} \times 0.60) + (Yr_{-2}TMP_{nJun} \times 0.40)]}$$

Yr_0 is the year of ring formation, Yr_{-1} is one year prior to ring formation, Yr_{-2} is two years prior to ring formation, MMT_{nAug} is the normalized mean August monthly temperature and MMT_{nJun} is the normalized mean June monthly temperature, TMP_{nAug} is the normalized August total monthly precipitation and TMP_{nJun} is the normalized June total monthly precipitation.

The mean rw of the 66 black spruce "negative summer temp responders" demonstrates a significant relationship with the NTI_{BSrw}, exhibiting strong year to year correspondence and significant overall correlation using annual values ($r = -0.64$) and smoothed values ($r = -0.82$) (see Fig. 2.11). Each individual tree in the "negative summer temp responder" group had a negative correlation with the $\mathrm{NTI}_{\mathrm{BSrw}}$ index and 64 of the 66 trees are significantly correlated at the $p < 0.05$ level.

We then correlated the mean rw of the 11 remaining black spruce trees (which did not have a significant negative correlation with summer temperatures) with the 36 months of McGrath MMT and TMP. We found that this subset was significantly positively correlated ($r \geq 0.30$, $p < 0.01$) with the April (-1) and June (-1) MMTs (see Fig 2.12.a.), but was not significantly correlated to any McGrath TMP (see Fig. 2.12.b). We labeled the 11 trees in this category "positive spring temp responders." We developed the following climate favorability index for the 11 black spruce "positive spring temp responders" (see Eq. 2.4):

Eq. 2.4. Positive Temperature Index ($\mathrm{PTI}_{\mathrm{BSrw}}$) for black spruce "positive spring temp responders"

$$\mathbf{PTI_{BSrw} = (Yr_{-1}MMT_{nApr}\ X\ 60\%) + (Yr_{-1}MMT_{nJun}\ X\ 40\%)}$$

Yr_{-1} is one year prior to ring formation, $\mathrm{MMT}_{\mathrm{nApr}}$ is the normalized mean April monthly temperature and $\mathrm{MMT}_{\mathrm{nJun}}$ is the normalized June mean monthly temperature.

The mean rw of the 11 "positive spring temp responders" had a consistent, significant relationship with the $\mathrm{PTI}_{\mathrm{BSrw}}$, with both annual values ($r = 0.60$) and smoothed values ($r = 0.85$) (see Fig. 2.13). 10 of the 11 individual trees were significantly correlated at the $p<0.05$ level

2.5. Discussion.

2.5.1. Kuskokwim River spruce trees climate sensitivity; interspecies similarities and differences.

We found that on average, both tree species (including all climate response types), steadily increased rates of growth from the mid 1800's through to about the 1940s or '50s (see Figs 2.2.c, 2.3.c and 2.4.a). This growth trend is consistent with other studies that found increased growth rates in white spruce in response to warming temperatures until about the mid 20th century when growth rates begin to level off or decrease (D'Arrigo et al. 2008). Since the climate records for McGrath only date to the 1940's we could only make climate-growth comparisons for the period following this long trend in increasing growth rates. It is interesting to note that our analysis period (1940s-present) is a crucial period of divergence in climate-growth responses in other Alaskan dendrochronology studies as well (Wilmking et al. 2004; D'Arrigo et al. 2008).

Both tree species exhibited one of two response types: (1) negative correlation with summer temperatures (decreased radial growth with warming) or (2) positive correlation with spring temperatures (and fall temperatures for white spruce only). We found an east-west gradient of changing predominant response type; trees that respond negatively to warm summer temps gradually decrease in frequency as you move west where positive spring (and fall) temp responders begin to dominate (see Fig. 2.14). Stands of trees sampled in the midst of the two converging climate signals (interior vs coastal) contain a mix of positive and negative responders.

We found that in eastern (interior) locations along the river, both tree species predominantly respond to periods of hot dry summer weather with reduced radial growth. Black spruce trees, growing on permafrost soils, were more consistently sensitive to summer precipitation flux than white spruce. Trees of both species in interior locations grew at increasingly higher rates from about the 1840's through the 1950's. The hot dry summer conditions of the late 20th century and early 21st century are associated with a downward growth trend for both species (see Fig 2.15).

In locations farther west, both species predominantly responded to warm spring conditions with increased radial growth but their growth was not detrimentally impacted by the warmest summers in the period of record. White spruce trees from western stands were additionally positively influenced by warm fall temperatures as well, whereas fall temperatures were insignificant to black spruce. Western (coastward) white and black spruce tree have experienced steadily increasing growth rates over the last century and recently their growth rates have exceeded trees sampled farther inland (see Fig 2.15).

An intraspecies growth rate comparison for each response type exposed significant differences. The rate of growth for the "negative summer temp responders" from both species was significantly greater than that of the "positive spring (and fall) temp responders" of the same species from the end of the 19th century until about the 1970's. In the last three decades the rate of growth of the "negative summer temp responders" decreased the strongest while the "positive spring (and fall) temp responders" growth rates continued to increase (see Fig. 2.15).

2.5.2 Evidence consistent with drought-stress

The apparent shift in the composition of predominant response type from "negative summer temp responders" to "positive spring (and fall) temp responders" along an east-west or upriver-downriver gradient provides insight to the processes that may be responsible for differences in response. We hypothesized that the furthest inland trees which are subjected to more continental weather patterns may be experiencing drought stress during hot, dry summers, either from true moisture deficiencies or from "physiological drought stress." To test our hypothesis we reexamined the relationship between the "negative summer temp responders" of each species and the climate index used for correlation analysis, paying special attention to the particular years when the climate favorability index did a poor job explaining the realized growth. To gauge the extent to which the climate favorability index failed to predict growth, we simply calculated the residuals of the regression between the climate index versus the actual growth (residuals = normalized climate index predicted growth – normalized actual realized growth). In the case of the white spruce "negative summer temp responders" we noticed several occasions when the temperature-based climate favorability index under-predicted or over-predicted growth. We hypothesized that precipitation may have acted as a buffer to extreme temperature departures; so that a hot summer did not result in drought stress if there was well above normal precipitation available to offset the effect. Likewise, a cool summer would not result in improved growth if there was a large relative precipitation deficiency. To test this hypothesis we returned to the McGrath mean monthly precipitation values, which had previously been discounted as statistically insignificant when correlated against the entire record of growth. We found that certain months of precipitation showed signs of significance during key periods when the temperature-based predictive index alone was inaccurate. We created the following summer precipitation index for white spruce (SPI_{WS}) (Eq. 2.5):

Eq. 2.5. Summer Precipitation Index for white spruce (SPI_{WS})

$$\mathbf{SPI_{WS} = (Yr_{-1}TMP_{nAug} \text{ X } 70\%) + (Yr_{-2}TMP_{nJun} \text{ X } 30\%)}$$

Yr_{-1} is one year prior to ring formation, Yr_{-2} is two years prior to ring formation TMP_{nAug} is the normalized total August monthly precipitation and TMP_{nJun} is the normalized June total monthly precipitation.

We plotted the residuals (NTI_{RWI} – RWI) against the normalized summer precipitation index for white spruce (SPI_{WS}) paying special attention to the few years where the temperature index was particularly inaccurate (where residuals were greater than one standard deviation (SD) above or below zero) (see Fig. 2.16.a). We found that in every case where growth was more than 1 SD greater than the temperature index predicted, there was also greater than average summer precipitation (see Fig. 2.16.b). For almost all years (7 out of 9) when growth was ≤-1 SD below the mean, there was also less than average summer precipitation (see Fig. 2.16.b). In other words, the variability in annual radial growth is generally well predicted by the temperature index alone but particularly greater or less than normal precipitation can apparently influence the relationship. Surplus precipitation apparently saves the tree from a poor growth year that would otherwise occur because of high temperatures. Deficient precipitation apparently further reduces growth below the already low level typical of the warmest years.

In the initial stage of our analysis we recognized the black spruce "negative summer temp responder" population as being sensitive to McGrath precipitation indices and a summer precipitation was included in the climate favorability index for those trees (see Eq. 2.3). Yet there remained one particular string of years (1957-1960) where the $\mathrm{NTI}_{\mathrm{BSrw}}$ greatly underpredicted the realized growth (see Fig. 2.17). We noted that anomalous hot and dry summers occurred in 1957 and 1958 when our climate favorability index predicted very low growth. Yet the black spruce trees failed to decrease their average rates of growth until 1960 when growth began to realign with the index. We decided to investigate the possibility that exceptionally high amounts of winter precipitation could be responsible for saving the trees from summer drought conditions. We built the following winter precipitation index ($\mathrm{WPI}_{\mathrm{BS}}$) by simply combining the previous two years of winter precipitation TMPs (see Eq. 2.6):

Eq. 2.6. Winter Precipitation Index for black spruce ($\mathrm{WPI}_{\mathrm{BS}}$)

$$\mathbf{WPI_{BS} = (Yr_{-1}TMP_{nJan+nFeb}) + (Yr_{-2}\,TMP_{nJan+nFeb+nMar})}$$

Yr_{-1} is one year prior to ring formation, Yr_{-2} is two years prior to ring formation $\mathrm{TMP}_{\mathrm{nJan+nFeb}}$ is the sum of the normalized total January thru February monthly precipitation, and $\mathrm{TMP}_{\mathrm{nJan+nFeb+nMar}}$ is the sum of the normalized total January thru March monthly precipitation.

We plotted the residuals ($\mathrm{NTI}_{\mathrm{BSrw}}$ – rw) against the normalized winter precipitation index for black spruce ($\mathrm{WPI}_{\mathrm{BS}}$), looking closely at the string of years from 1957-1960 when the population grew more than 1 SD greater than the $\mathrm{NTI}_{\mathrm{BSrw}}$ alone had predicted (see Fig. 2.17.a). We found that much greater than average winter precipitation (between 1.0 and 4.0 SD above normal) had occured from 1957-1959 (see Fig. 2.17.b). This evidence is consistent with the hypothesis that large amounts of winter precipitation may indeed be able to "save" the black spruce radial growth from the deficiency predicted by the ordinary climate favorability index alone.

These results led us to consider further refined examination of temperature and precipitation data for the "positive responders" of both species. Since the "positive responders" of each species occurred in the farthest west stands we decided to see if there were any unique connections of this response group to Bethel climate parameters. We again correlated the mean rw (black spruce) and RWI (white spruce) of the "positive responders" from each species to 36 months of MMT and TMP but this time used records from Bethel instead of McGrath. We found that the annual radial growth of "positive responders" of both species is significantly correlated to the same months of temperature at both McGrath and Bethel. This is not surprising since the two temperature records are so highly correlated (r=0.92). Correlations with precipitation on the other hand, revealed that TMP measured in Bethel may be a significant growth factor to both species. "Positive responders" (of both species) were found to have significant (r>0.32, p<0.001) correlations with spring and fall precipitation at Bethel (see Fig. 2.18). For white spruce, June (-1 and -2) and November (-3) TMPs were significant (see Fig. 2.18.a) while for black spruce, May (-1) and November (-3) TMPs were significant (see Fig. 2.18.b). We stop short of presenting a new climate favorability index for the "positive spring (and fall) temperature responders" because after several trials we realized that there was very little additional explanatory value in the Bethel precipitation beyond temperature predictors. That is, an introduction of a combination of TMP values did improve correlations beyond what the temperature-based index produced but only marginally. This suggests that while precipitation may weakly influence average tree growth, the temperature indexes alone remain a simple, accurate, and consistent predictor of growth for the "positive responders."

The weak additional explanatory power of spring and summer precipitation (measured in Bethel), beyond temperature predictors, in each species' "positive responders" is consistent with the hypothesis that the western most located trees are responding positively to a lengthened growing season associated with warming, and yet are not generally drought-stressed. In this case, the elevated spring precipitation may be sort of a bonus: contributing to faster thawing of the soil active layer, adding to plant available moisture and helping to prevent trees from being drought stressed during the warmer summer months. The positive relationship of both species' "positive responders" to November precipitation remains somewhat of a mystery. We hypothesize that it may be related to the increased insulative value of an early season snowpack where deep-soil freeze events are avoided or delayed. Correlations between tree-growth of these populations and December snow depth are significant, but more research will be needed to help understand the processes involved.

In summary, there are several lines of evidence suggesting that the negative response to warm summer temperatures is caused by temperature-induced drought stress. (1) Radial growth is tightly correlated to just two months of average summer temperature, (2) The frequency of negative responders decreases from east (interior, dry continental climate region) to the west (cooler summer and moister maritime climate region (3) "Negative temperature responders" of both species are positively responsive (to a greater or lesser degree) to increased precipitation during June and August, suggesting that the relative lack of moisture, rather than the temperature alone, causes depressed growth. (4) Negative growth responses to summer temperatures occur in both tree species, eliminating the possibility that there is a species-specific growth inhibitor (like an inset outbreak) responsible for the recent decline in growth in interior sites.

2.5.3. Implications for Kuskokwim River spruce productivity and distribution.

The fact that radial growth of riparian black and white spruce populations examined in this study are significantly sensitive to climate is important to scientists who are trying to predict and model probable future vegetation distribution across the landscape. The occurrence of opposing (positive and negative) temperature responses should be an important component to such models. This study provides a first approximation of the longitudinal margins of each response type. If climate trends continue for the next half-century similar to what has occurred in the second half of the 20th century, it appears highly likely that spruce productivity will decrease in interior locations and increase in western locations. Our results are entirely consistent with other studies that have modeled future scenarios of vegetation distribution in Alaska in which white and black spruce expand westward into areas that are currently tundra landscapes (Rupp et al. 2001; Chapin et al. 1995, 2000; Lloyd et al. 2005).

Currently, the greatest area of productive riparian white spruce is in upriver locations (ADCED 2008) where recent growth trends and prospects in a warming climate are the most negative. Ironically, these are the locations that are also closest to considering using biomass powered energy generators. Also communities in upriver (interior) locations presently rely on wood as a fuel source more than downriver communities, and so would be more impacted if white spruce productivity continues to decrease. While it is likely that the overall potential for wood-supplied power generators in these communities will be impacted by the decreasing productivity of white (and black) spruce, it is important to note, that the potential of other tree species were not examined for this study. If other woody species retain productive potential, total wood availability could remain at levels high enough to support both community biomass-energy generators, and individual home heating, though white spruce may not be the main contributor of wood. With sufficient temperature increases, it is possible that the warmest and driest portions of the Kuskokwim Valley would experience a shift to parkland (Hogg and Hurdle 1995) or non-forest vegetation.

Given the uncertainty, it would be advantageous for communities to (1) consider developing biomass energy generators which can accommodate wood from a variety of tree species (2) consider replanting alternative native (deciduous) species which exhibit greater tolerance to warmer, drier growing seasons after harvesting the white spruce.

2.6. Conclusions.

This study provides clear evidence that growth of riparian white and black spruce trees along a major glacial meltwater river in Alaska can indeed be sensitive enough for dendroclimatological analysis. Both white and black spruce were significantly correlated with various climate indices and a combination of just a few parameters created climate indexes which were capable of describing a very large portion (between 36-41%) of year-to-year variability in radial growth.

White and black spruce growing along the Kuskokwim River exhibited similar regional growth response to similar climate indices. As grouped populations examined across the entire study area, the two species chronologies were highly correlated with each other, although a few aspects of the chronologies were distinctive to each species.

Trees of both species exhibited one of two response types (1) a negative response to warm summer temperatures or (2) a positive response to warm spring/ fall temperatures. The response was not randomly distributed across the study area but was instead geographically distinct across an east-west gradient. “Negative responders” to warming temperatures occurred in the eastern most (interior) locations while “positive responders” occurred in the western most (coastward) locations.

White and black spruce trees located farthest east are most responsive to McGrath climate station records and ring growth of both species is negatively correlated with summer temperature indices. Average radial growth of western black spruce trees is also positively correlated with summer precipitation (measured in McGrath). Instances where high summer temperatures did not result in reduced growth of white spruce were associated with greater than average precipitation in the summer. Instances where high summer temperatures did not result in reduced growth of black spruce were associated with greater than average precipitation in the summer (regularly) and sometimes additionally in the winters of the previous two years.

Ring growth of white and black spruce trees growing in western locations is positively correlated with warm spring temperatures. Western white spruce trees are additionally positively correlated with fall temperatures. Radial growth of “positive spring (and fall) temp responders” of both species is significantly correlated with Bethel precipitation records but not significantly correlated with any monthly precipitation data measured in McGrath.

In both species, the “negative summer temp responders” grew at a greater rate than the “positive spring (and fall) temp responders” until about the 1970’s, corresponding to the coolest period of the available climate record. In recent decades, the situation has reversed and the “positive spring (and fall) responders” have outgrown the “negative summer temp responders,” corresponding to the extended period of warm temperatures in the late 20th and early 21st century.

White spruce productivity in eastern (interior) locations will likely continue to decline as regional temperatures increase which could impact the sustainability of biomass (wood) powered energy generators in these locations. More western (coastward) located white spruce trees will likely continue to increase in productivity and may provide enhanced opportunity for biomass energy technology.

2.7 Chapter 2 Figures.

Fig. 2.1.

Height and diameter characteristics of Kuskokwim River white spruce trees. **a**, heights of 2,947 trees sampled during a 1967 USDA Forest Service (USFS) survey along entire river; **b**, heights of 1,561 trees from 1967 USFS survey selected based on similar geographic distribution as 2002 and 2007 plots; **c**, heights (measured and estimated) of 118 trees sampled for this study (in 2002 and 2007); **d**, diameters of 4,056 trees sampled during 1967 USFS survey along entire river; **e**, diameters of 1,561 trees from 1967 USFS survey selected based on similar geographic distribution as 2002 and 2007 plots; **f**, diameters of 118 trees sampled for this study (in 2002 and 2007).

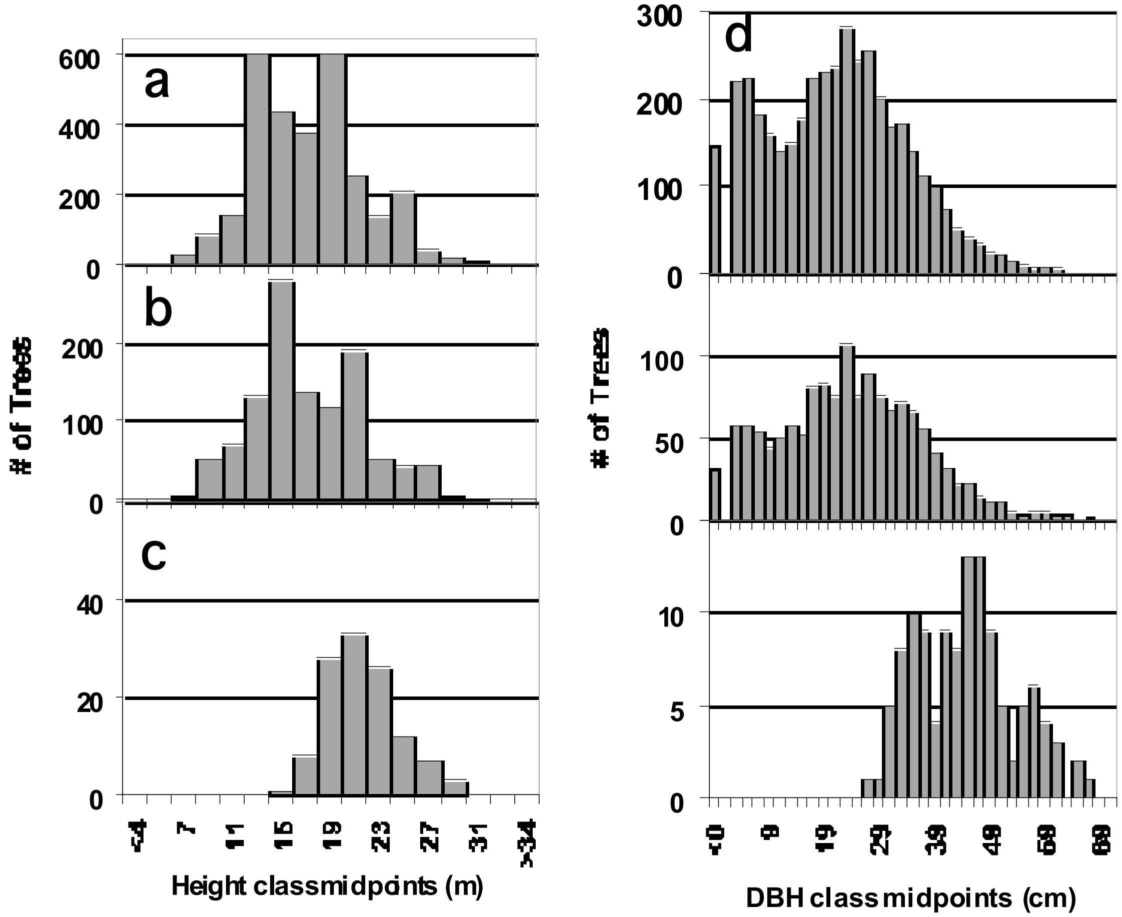


Figure 2.2.

Age and growth characteristics for all 118 Kuskokwim River white spruce trees. **a**, age (date of pith) midpoints measured or estimated* at breast height; **b**, individual tree mean lifetime rates of growth (mm); **c**, decadal mean annual increment (mm) for all 118 white spruce. 95% confidence intervals are depicted. *Date of pith estimated within 10 years if pith wasn't clearly visible (<5% of sampled trees).

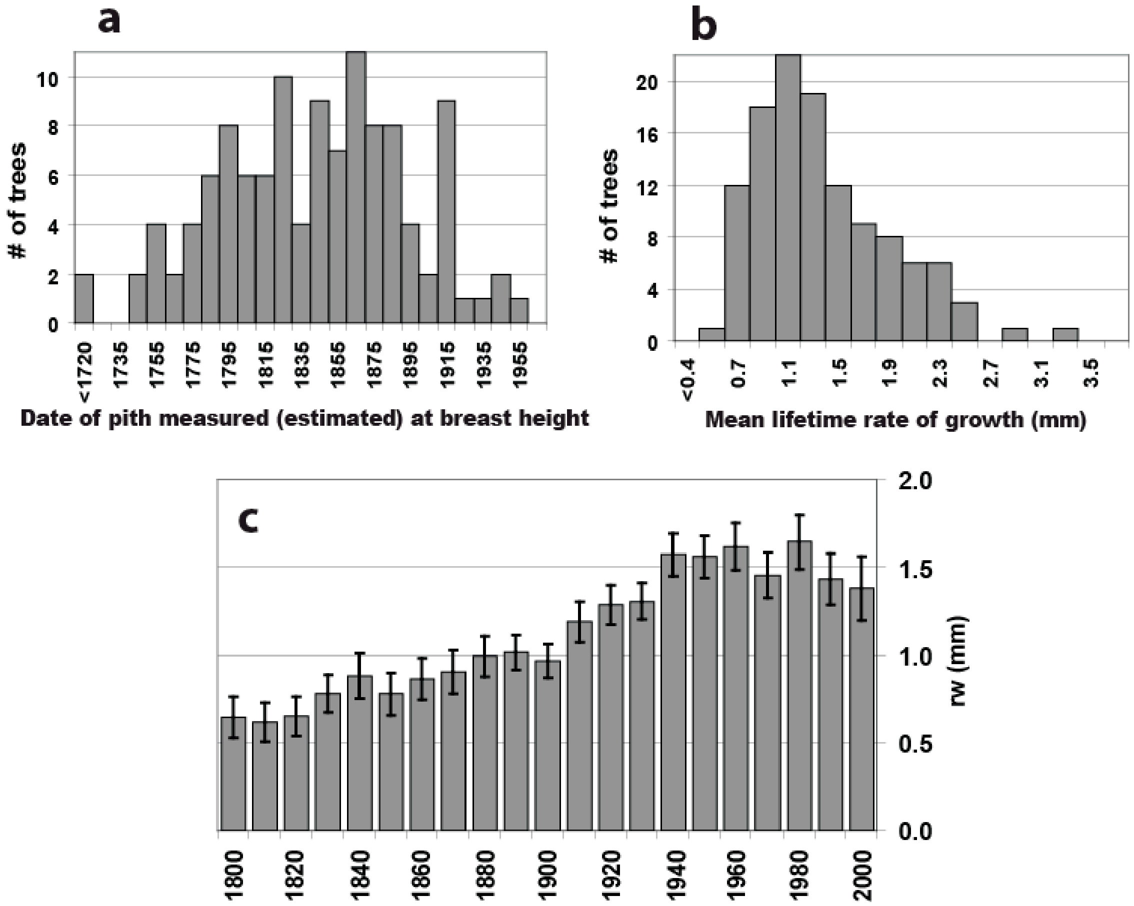


Figure 2.3.

Growth characteristics of all 77 Kuskokwim River black spruce. **a**, individual tree mean lifetime rates of growth (mm); **b**, date of pith measured (or estimated) at breast height; **c**, decadal mean annual increment (mm) with 95% confidence intervals; **d**, diameters at breast height (cm), **e**, heights measured or estimated (m).

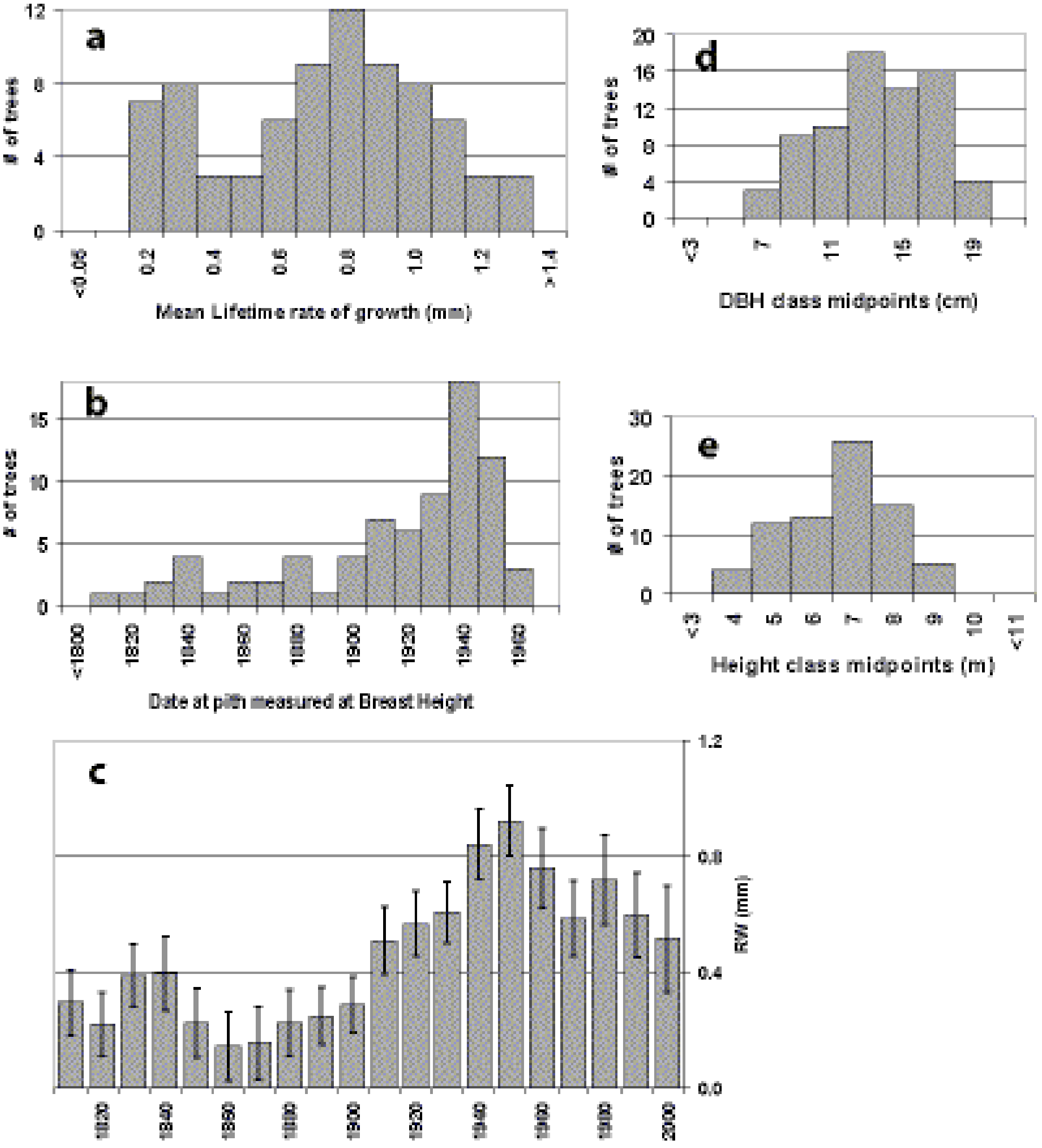


Figure 2.4.

Kuskokwim River growth chronologies: white spruce versus black spruce from 1913-2006. The number of trees contributing to the chronology (simultaneously plotted with each chronology) is an analogous measure of tree age, i.e. individual trees were included in the chronology up to their earliest year of measurable growth. **a**, white and black spruce raw ring width values (rw); **b**, white and black spruce normalized ring-widths n(rw). The chronologies are correlated at $r = 0.84$.

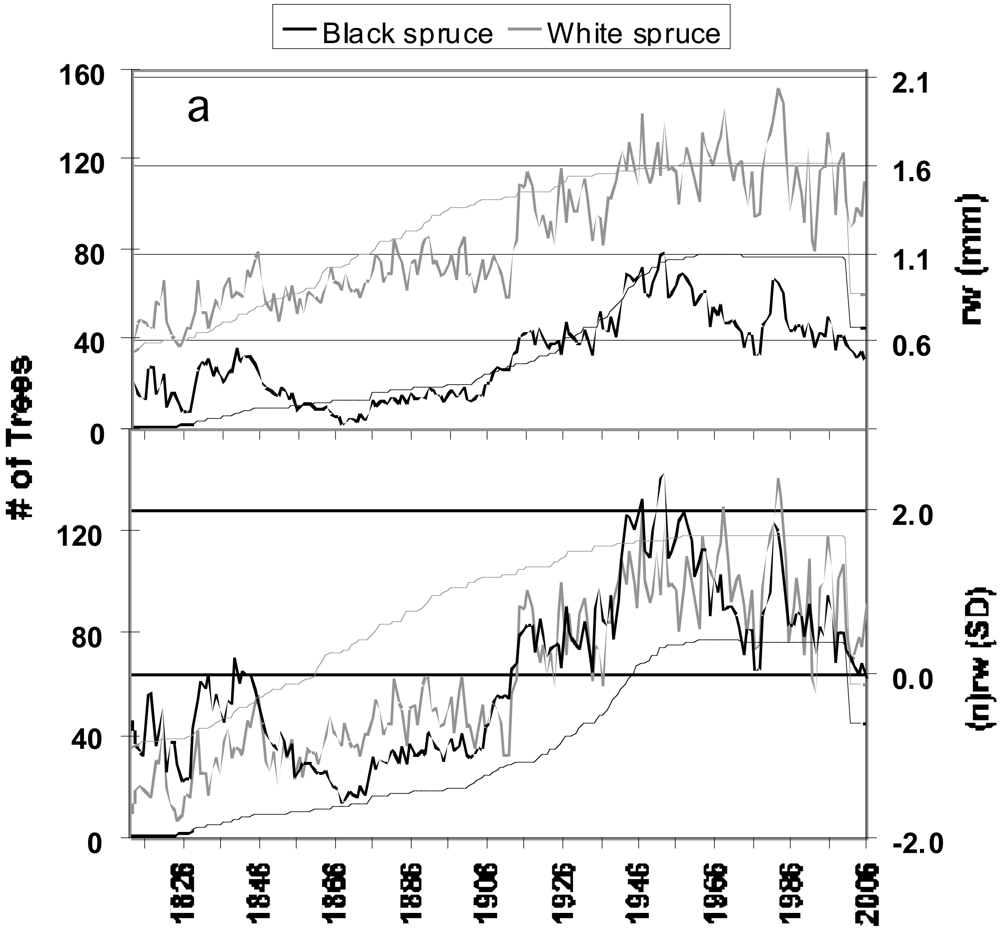


Figure 2.5

Correlation of Kuskokwim River white spruce mean RWI (all 118 trees included) to McGrath mean monthly temperature (MMT) for three years before completion of tree-ring growth. All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black. Correlation values are for the period 1944-2006. Note that correlations with McGrath precipitation variables were not significant at $p<0.01$.

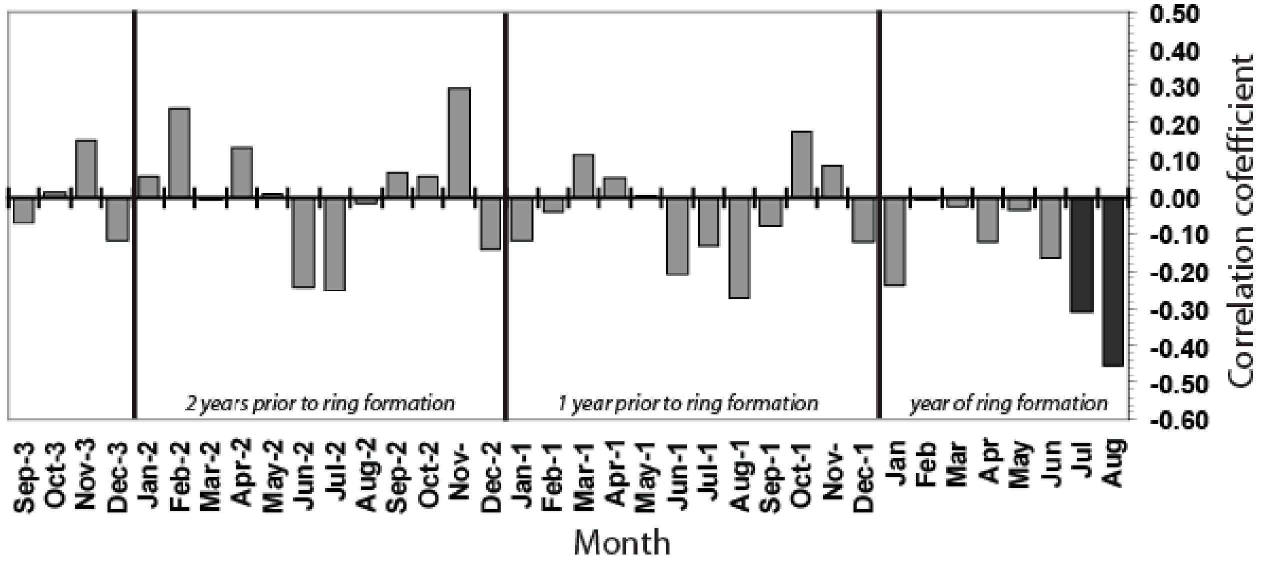


Figure 2.6.

Correlation of climate-response population sub-groups for Kuskokwim River white spruce. Correlations are between normalized ring widths (ring-width index or RWI) and McGrath MMT for three years before completion of tree-ring growth. All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black; months that were used to make up climate favorability index are labeled. **a**, mean RWI of the 35 white spruce "spring/fall temp responders;" **b**, mean RWI of the 83 white spruce "negative summer temp responders." Correlation values are for the period 1944-2006. Neither response group exhibited significant correlations (at $p<0.01$) to any values of McGrath Total Monthly Precipitation (TMP).

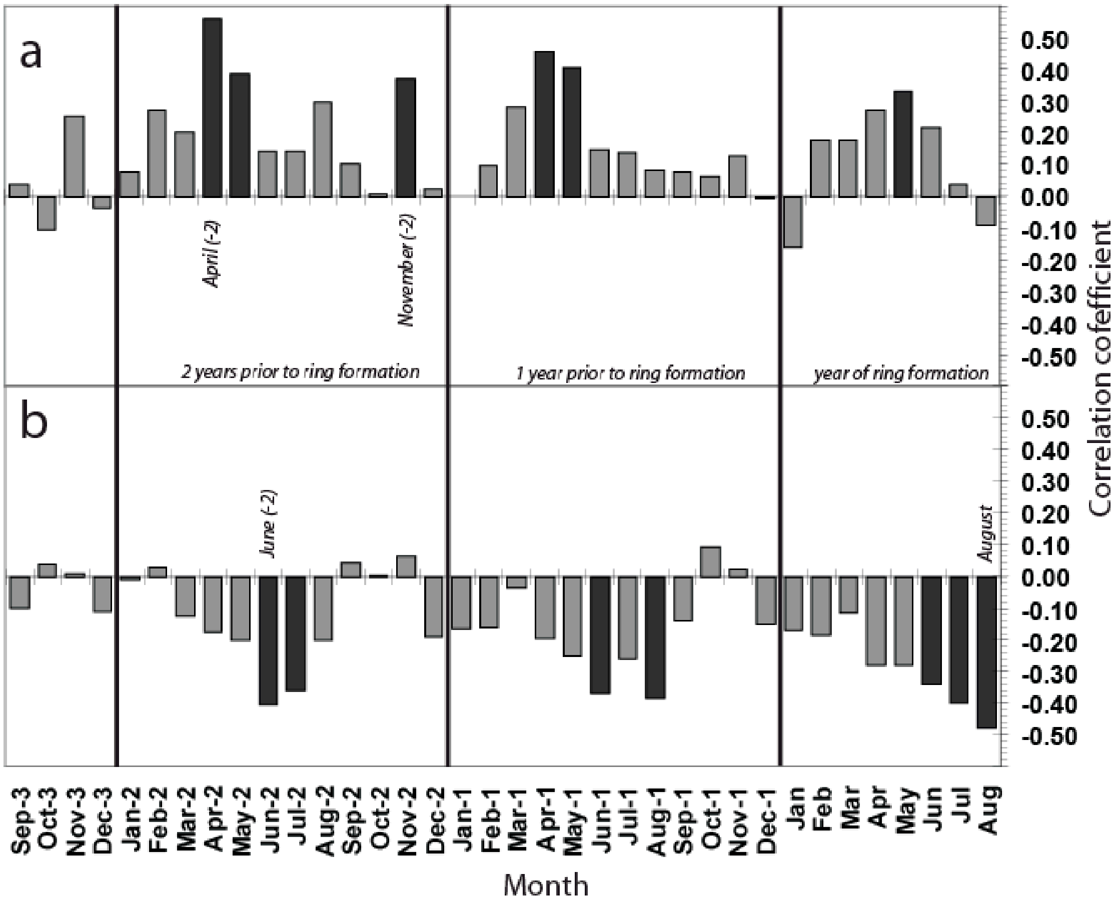


Figure 2.7.

83 Kuskokwim River white spruce “negative summer temp responders” versus a summer temperature index ($\mathrm{NTI}_{\mathrm{RWI}}$). **a**, “Negative summer temp responders” mean RWI versus summer temperature index ($\mathrm{NTI}_{\mathrm{RWI}}$) from 1944-2006, $r = -0.62$, $p < 0.001$; **b**, regression of “negative summer temp responders” with summer temperature index ($\mathrm{NTI}_{\mathrm{RWI}}$) from 1944-2006, $R^2 = 0.39$, $p < 0.001$; **c**, “negative summer temp responders” vs summer temperature index smoothed by 5-yr running mean, $r = -0.91$, $p < 0.001$; **d**, regression of 83 “negative summer temp responders” with summer temperature index smoothed by 5-yr running mean, $R^2 = 0.82$, $p < 0.001$.

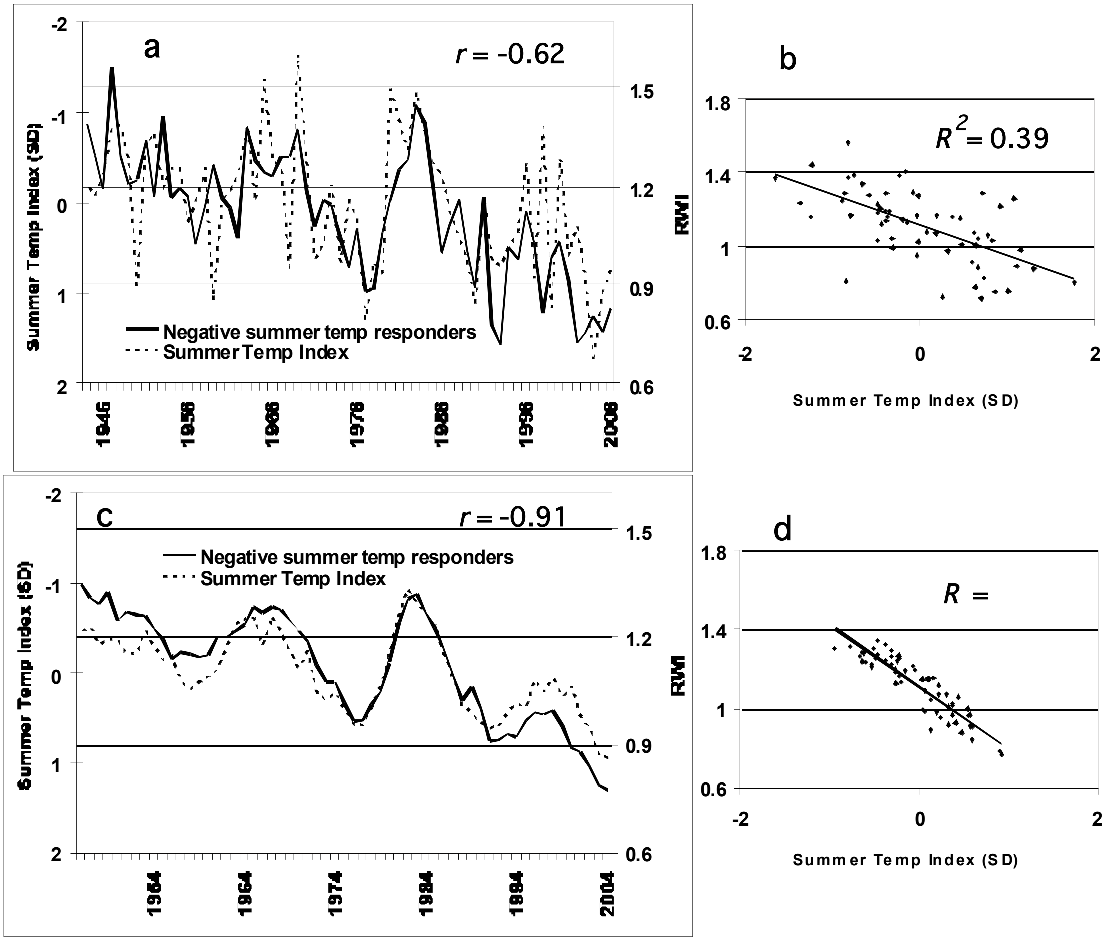


Figure 2.8.

35 Kuskokwim River white spruce “positive spring/fall temp responders” versus temperature index. **a**, “Positive spring/fall temp responders” mean RWI versus spring/fall temperature index (PTI_{RWI}) from 1944-2006; $r = 0.60$, $p < 0.001$; **b**, regression of “positive spring/fall temp responders” with spring/fall temperature index (PTI_{RWI}) from 1944-2006; $R^2 = 0.36$, $p < 0.001$; **c**, “positive spring/fall temp responders” versus spring/fall temperature index smoothed by 5-yr running mean; $r = 0.83$, $p < 0.001$; **d**, regression of 83 “positive spring/fall temp responders” with spring/fall temperature index smoothed by 5-yr running mean; $R^2 = 0.69$, $p < 0.001$.

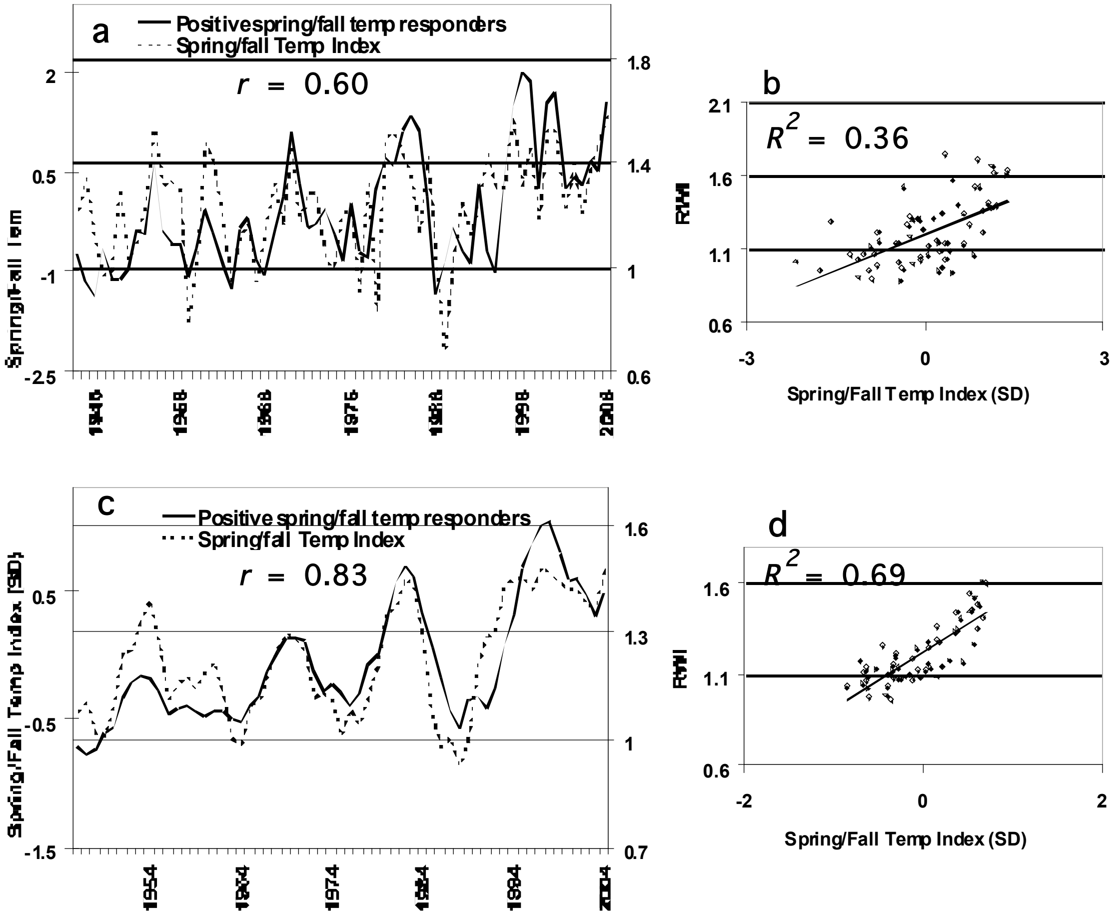


Figure 2.9.

Correlation of all 77 Kuskokwim River black spruce mean ring-width (rw) to McGrath climate variables for three years before completion of tree-ring growth. All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black. **a**, correlation of mean rw to McGrath MMT **b**, correlation of mean rw to McGrath TMP. Correlation values are for the period 1944-2006

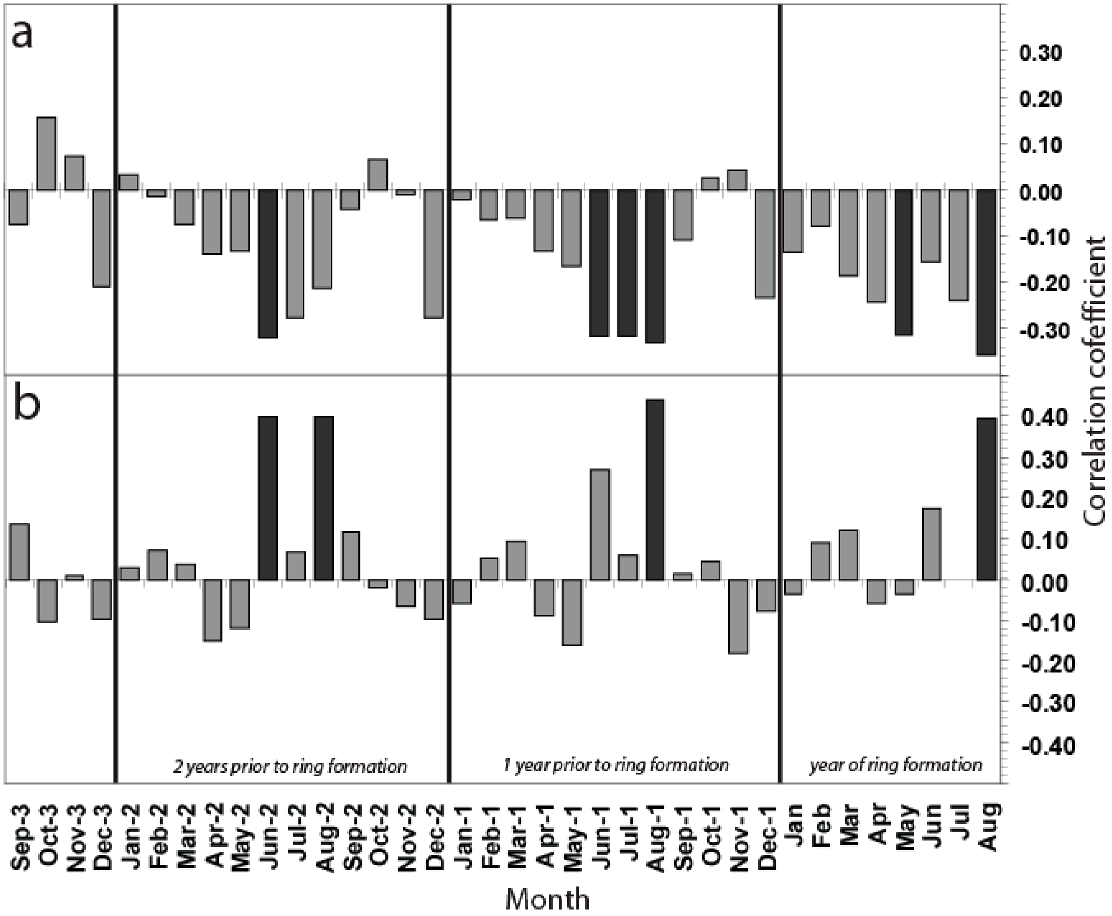


Figure 2.10.

Correlation of the mean rw of 66 Kuskokwim River black spruce “negative summer temp responders” to McGrath climate variables for three years before completion of tree-ring growth. All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black; months that were used to make up the climate favorability index are labeled. **a**, correlation of mean rw to McGrath MMT; **b**, correlation of mean rw to McGrath TMP. Correlation values are for the period 1944-2006.

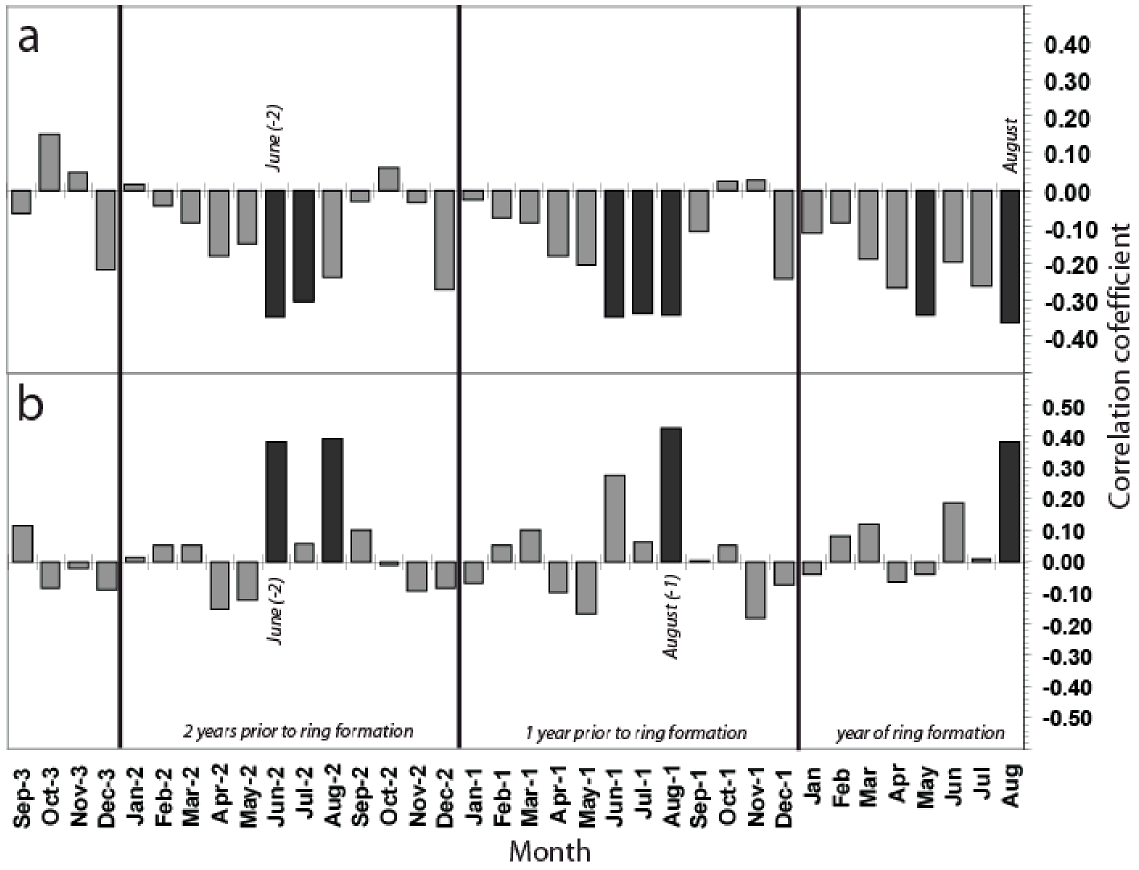

a
b
June (-2)
August
June (-2)
August (-1)
2 years prior to ring formation
1 year prior to ring formation
year of ring formation
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
Correlation cofefficient
Sep-3
Oct-3
Nov-3
Dec-3
Jan-2
Feb-2
Mar-2
Apr-2
May-2
Jun-2
Jul-2
Aug-2
Sep-2
Oct-2
Nov-2
Dec-2
Jan-1
Feb-1
Mar-1
Apr-1
May-1
Jun-1
Jul-1
Aug-1
Sep-1
Oct-1
Nov-1
Dec-1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Month

Figure 2.11.

66 Kuskokwim River black spruce “negative summer temp responders” versus normalized McGrath temp/precip index ($\mathrm{NTI}_{\mathrm{BSrw}}$); **a**, “Negative summer temp responders” mean rw versus summer temp/precip index ($\mathrm{NTI}_{\mathrm{BSrw}}$) from 1944-2006, $r = -0.64$, $p < 0.001$; **b**, regression of “negative summer temp responders” with summer temp/precip index ($\mathrm{NTI}_{\mathrm{BSrw}}$) from 1944-2006, $R^2 = 0.41$, $p < 0.001$; **c**, “negative summer temp responders” vs summer temp/precip index smoothed by 5-yr running mean, $r = -0.82$, $p < 0.001$; **d**, regression of 83 “negative summer temp responders” with summer temp/precip index smoothed by 5-yr running mean, $R^2 = 0.67$, $p < 0.001$.

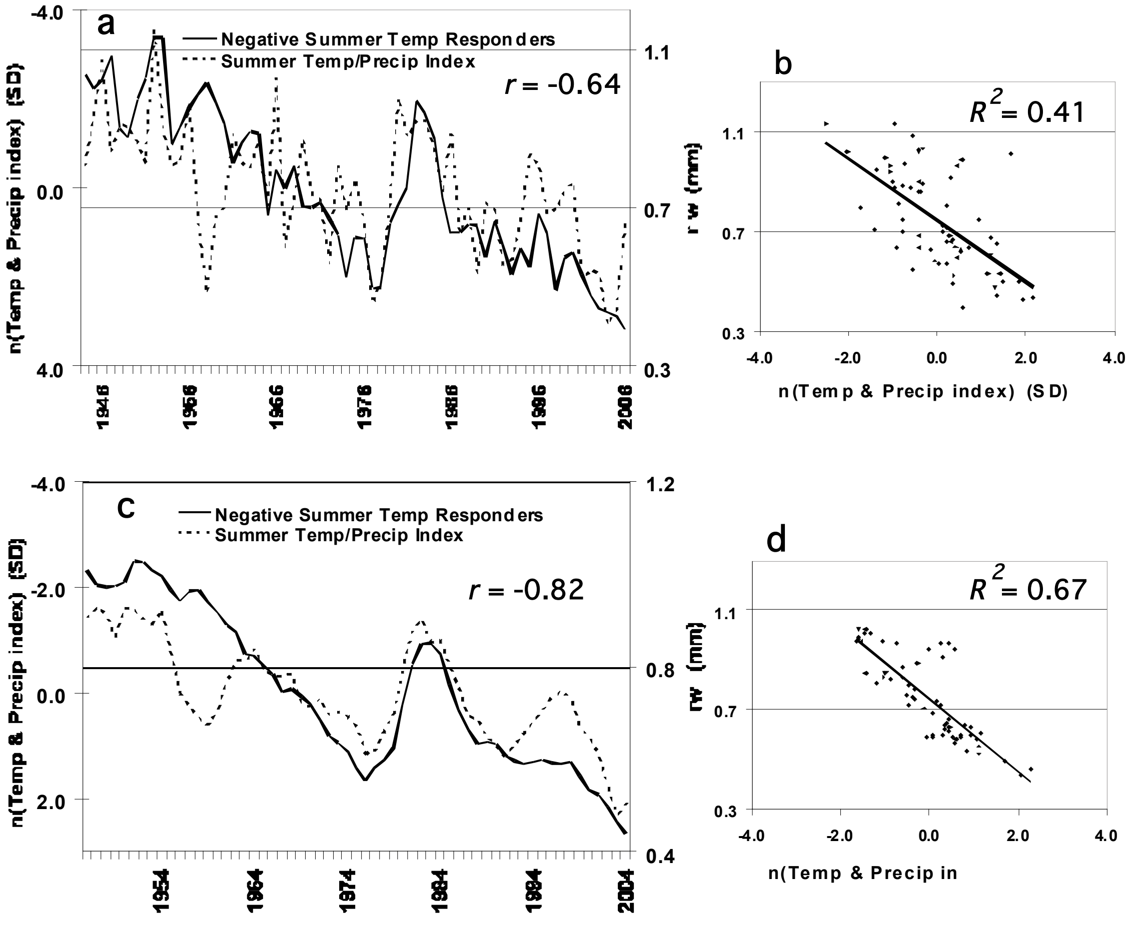
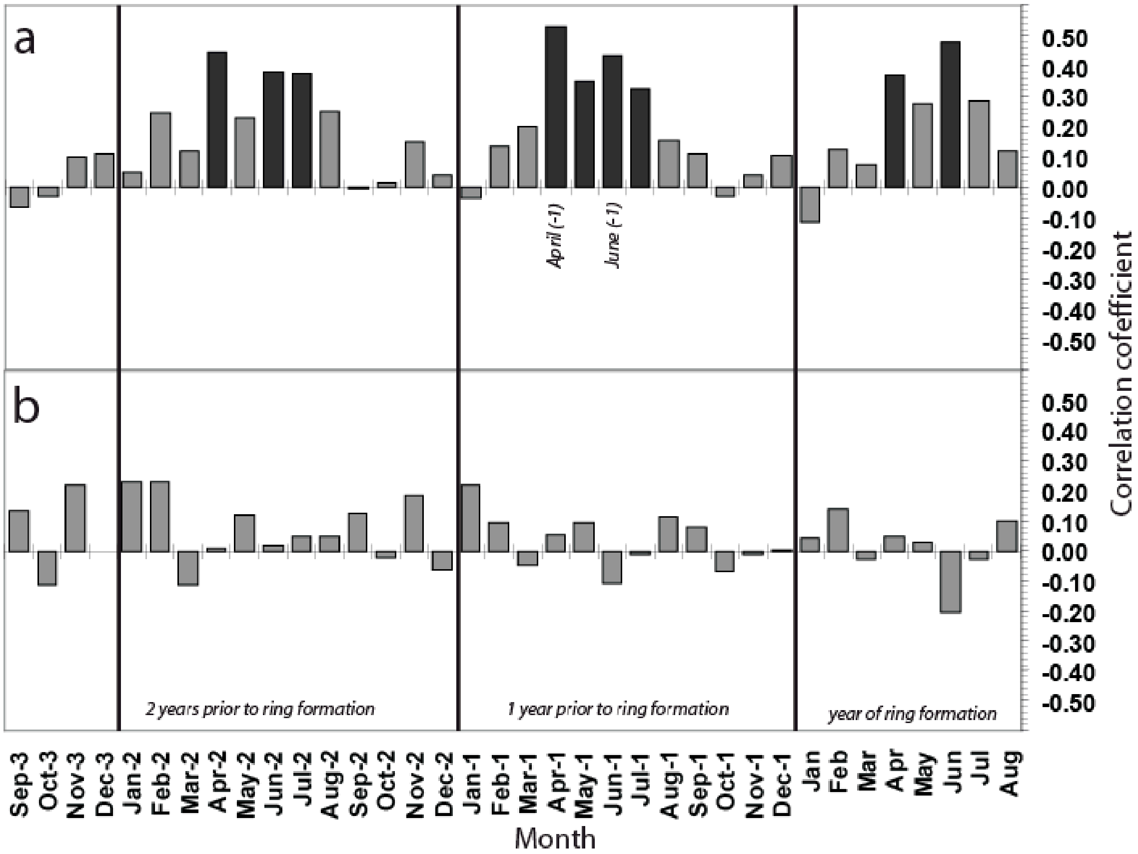


Figure 2.12.

Correlation of 11 Kuskokwim River black spruce “positive spring temp responders” with McGrath climate variables for three years before completion of tree-ring growth. All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black; months that were used to make up the climate favorability index are labeled. **a**, correlation of mean rw to McGrath MMT; **b**, correlation of mean rw to McGrath TMP. Correlation values are for the period 1944-2006.


a
b
April (-1)
June (-1)
2 years prior to ring formation
1 year prior to ring formation
year of ring formation
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
Correlation cofefficient
Sep-3
Oct-3
Nov-3
Dec-3
Jan-2
Feb-2
Mar-2
Apr-2
May-2
Jun-2
Jul-2
Aug-2
Sep-2
Oct-2
Nov-2
Dec-2
Jan-1
Feb-1
Mar-1
Apr-1
May-1
Jun-1
Jul-1
Aug-1
Sep-1
Oct-1
Nov-1
Dec-1
Jan
Feb
Mar
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Aug
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Figure 2.13.

11 Kuskokwim River black spruce “positive spring temp responders” versus McGrath spring temperature index. **a**, “Positive spring temp responders” mean rw versus positive spring temperature index (PTI_{BSrw}) from 1944-2006; $r = 0.60$, $p < 0.001$; **b**, regression of “positive spring temp responders” with spring temperature index (PTI_{BSrw}) from 1944-2006; $R^2 = 0.36$, $p < 0.001$; **c**, “positive spring temp responders” versus spring temperature index smoothed by 5-yr running mean; $r = 0.85$, $p < 0.001$; **d**, regression of 83 “positive spring temp responders” with spring temperature index smoothed by 5-yr running mean; $R^2 = 0.72$, $p < 0.001$.

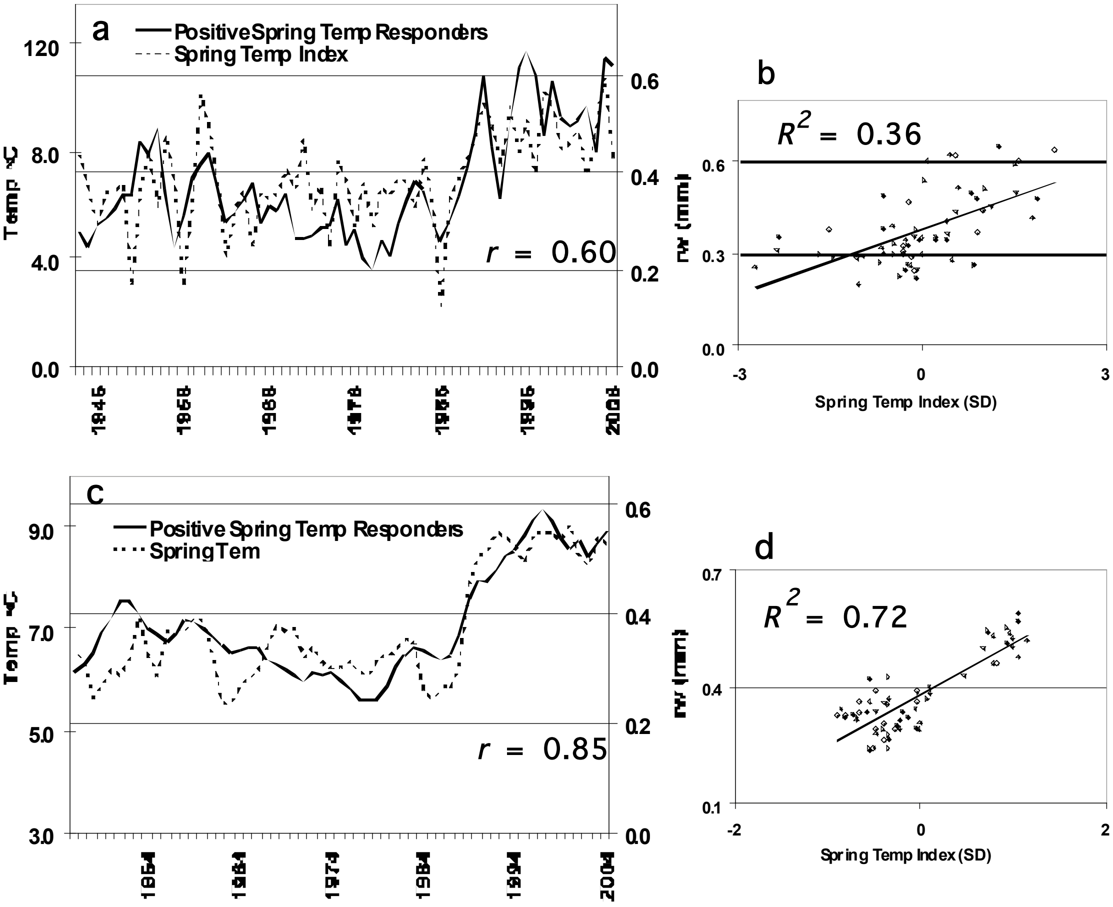


Figure 2.14.

Kuskokwim River spruce, distribution of “positive” and “negative” responders to rising temperatures.. Stands of white spruce were categorized by spatial distribution as: up-river (68 trees), mid-river (27 trees) or downriver (16 trees). Stands of black spruce were categorized by spatial distribution as: up-river (32 trees), mid-river (30 trees) or downriver (15 trees). Note the gradual decrease in frequency of negative responders (in both species) from eastern (interior) sites to western (coastward) sites.

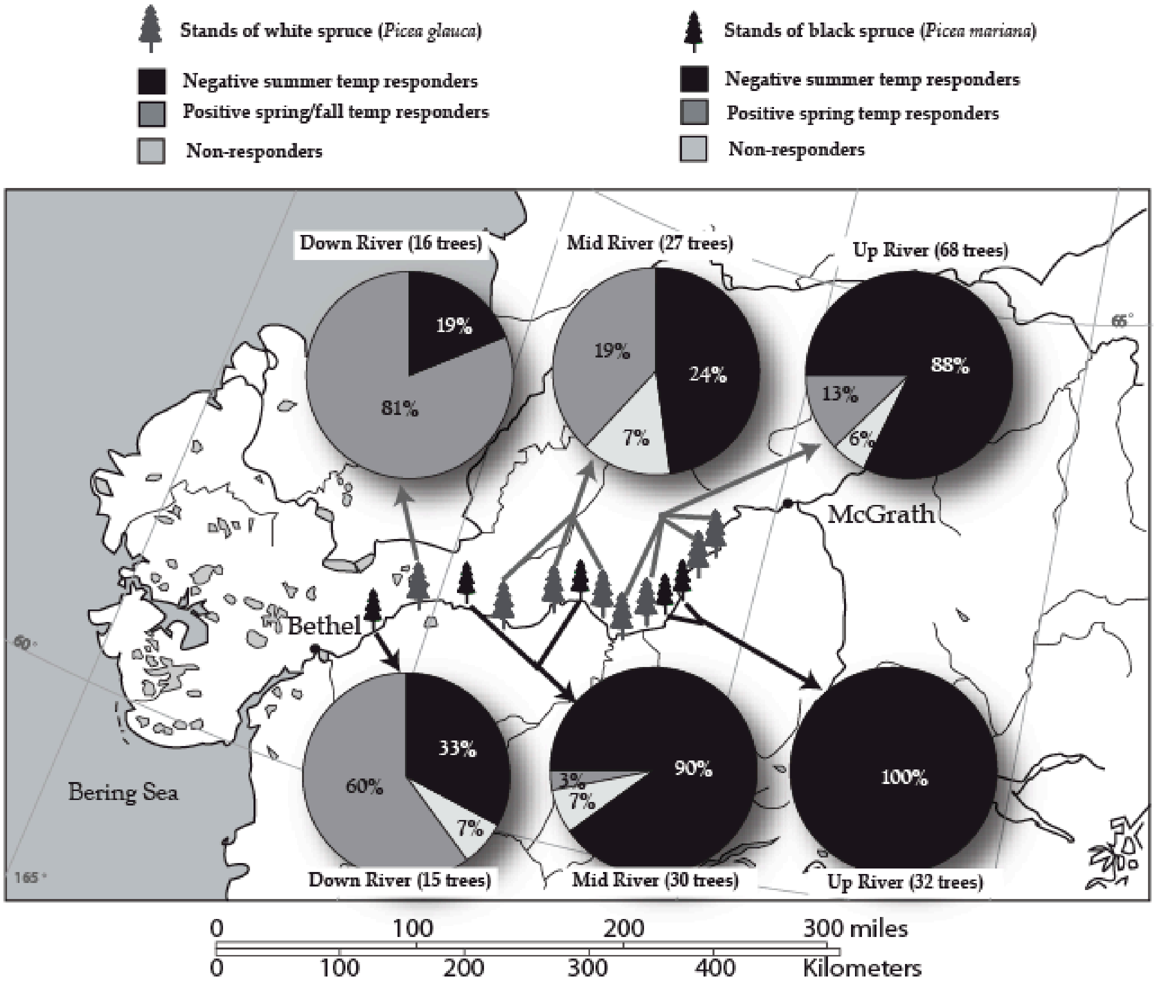


Figure 2.15.

Differences in white and black spruce growth rates by response type; **a**, rate of growth of white spruce "positive spring/fall temp responders" versus "negative summer temp responders," 95% confidence intervals depicted; **b**, rate of growth of black spruce "positive spring temp responders" versus "negative summer temp responders" 95% confidence intervals depicted.

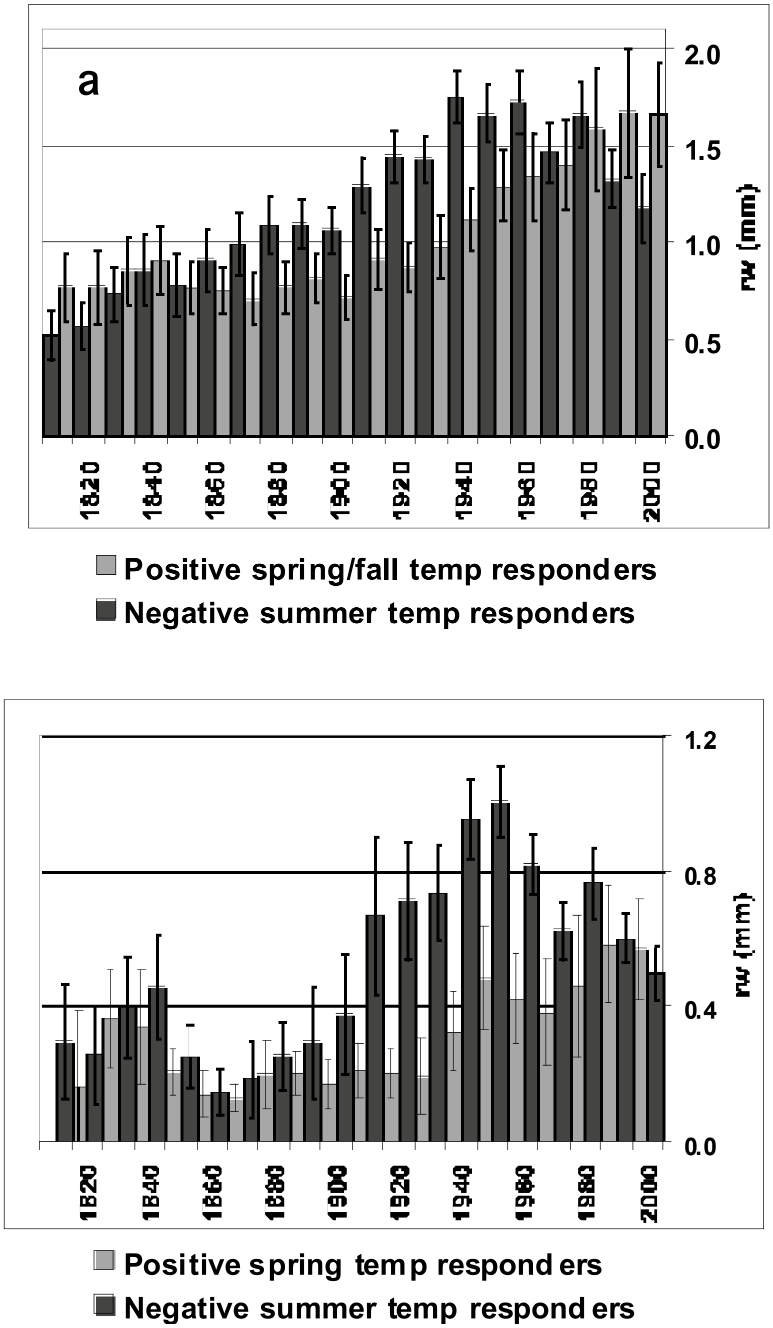


Figure 2.16.
Kuskokwim River white spruce “negative temperature responders”; **a**, mean RWI (83 trees) versus summer temperature index (NTI_{RWI}) with large discrepancies between the index and the actual realized growth circled; **b**, normalized residuals (temp index values minus realized growth (RWI)) versus summer precipitation index (SPI_{WS}). Residual values > 1 SD are emphasized. Residual values < 1 SD are emphasized and colored black.

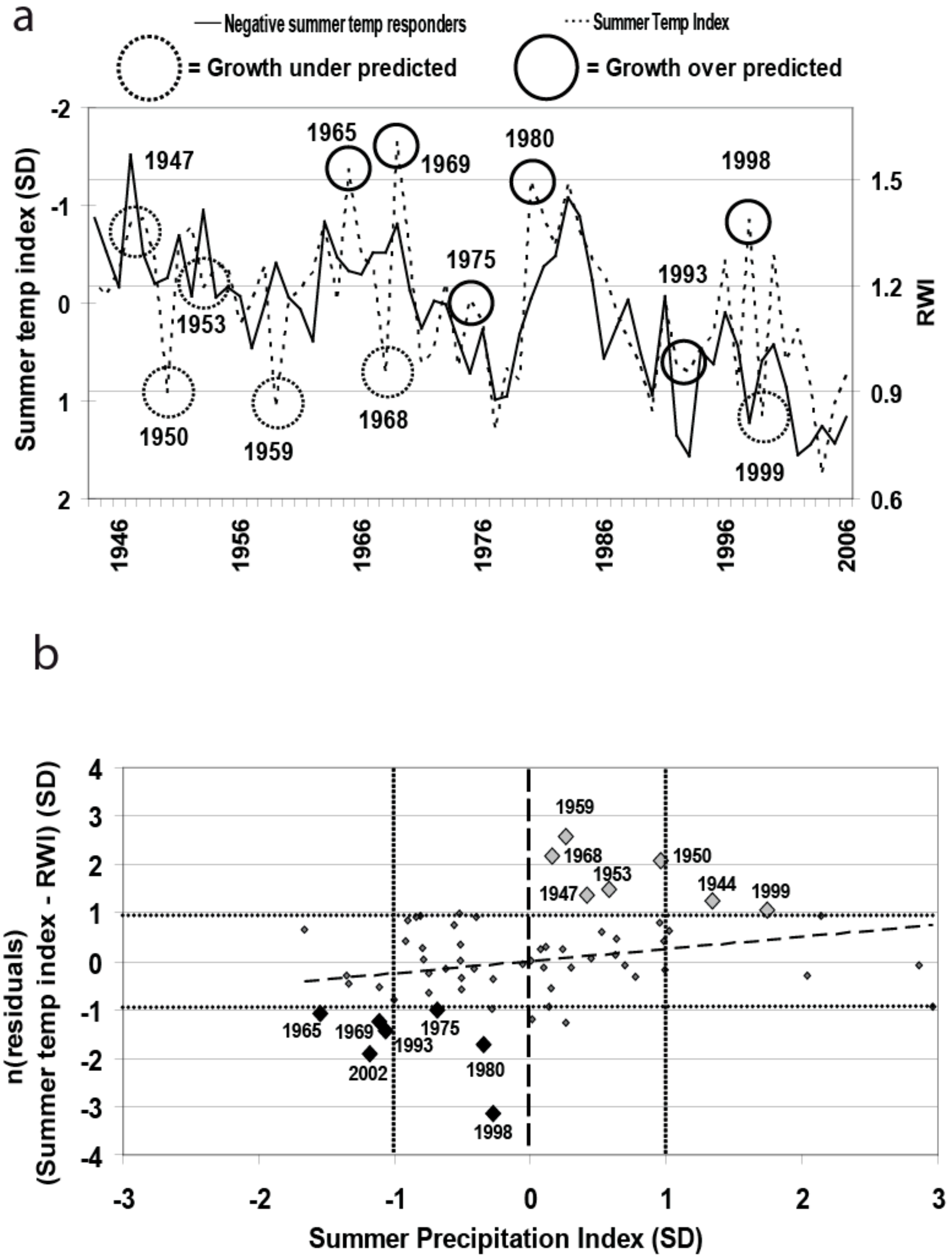


Figure 2.17.

Kuskokwim River black spruce “negative temperature responders”; **a**, mean rw (66 trees) versus summer temperature/precip index (NTI_{BSrw}) with a large discrepancy between the index and the actual realized growth circled (1957-1960); **b**, normalized residuals (summer temp/precip index minus realized growth (rw)) versus winter precipitation index (WPI_{BS}). The years 1957-1960 are emphasized.

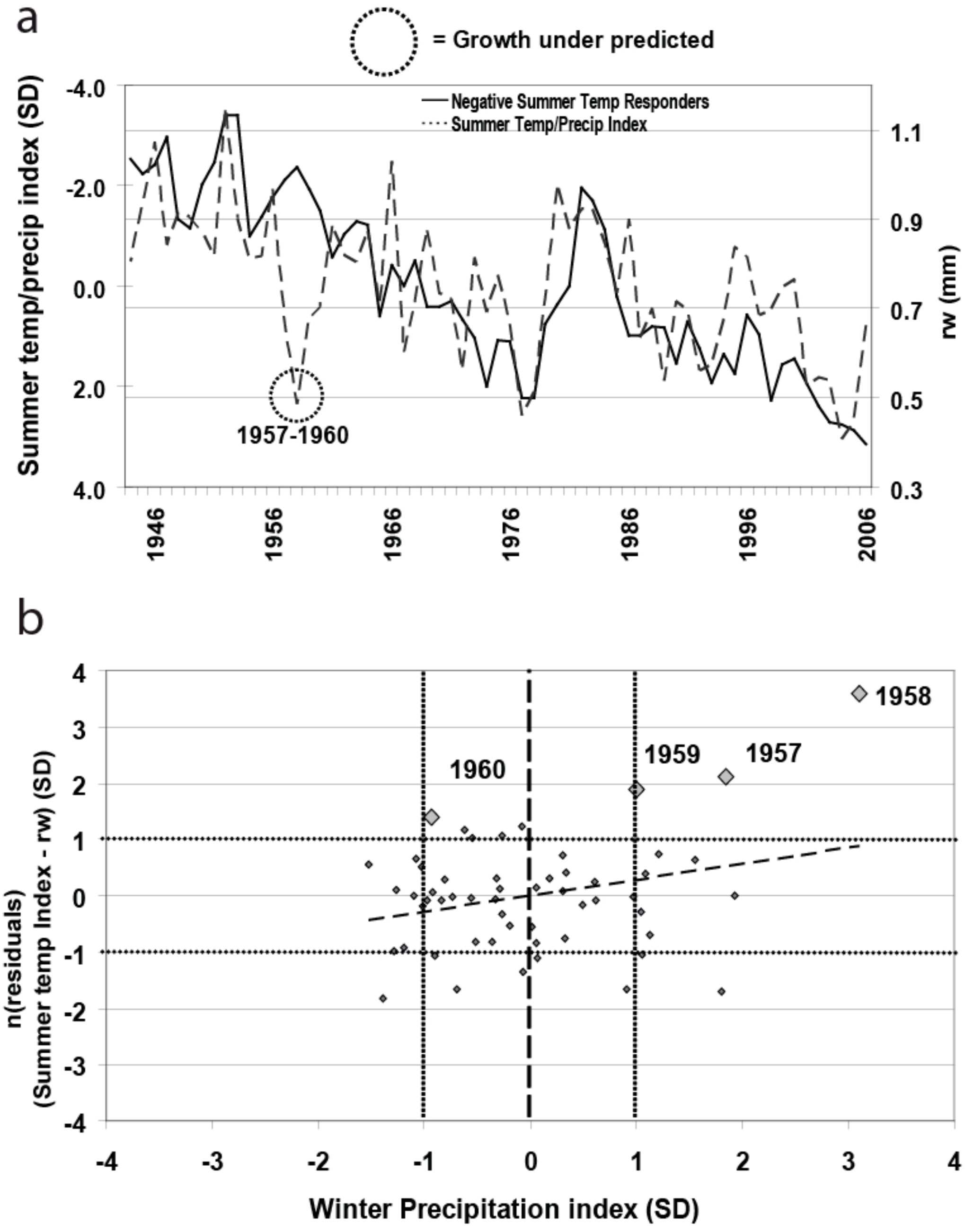
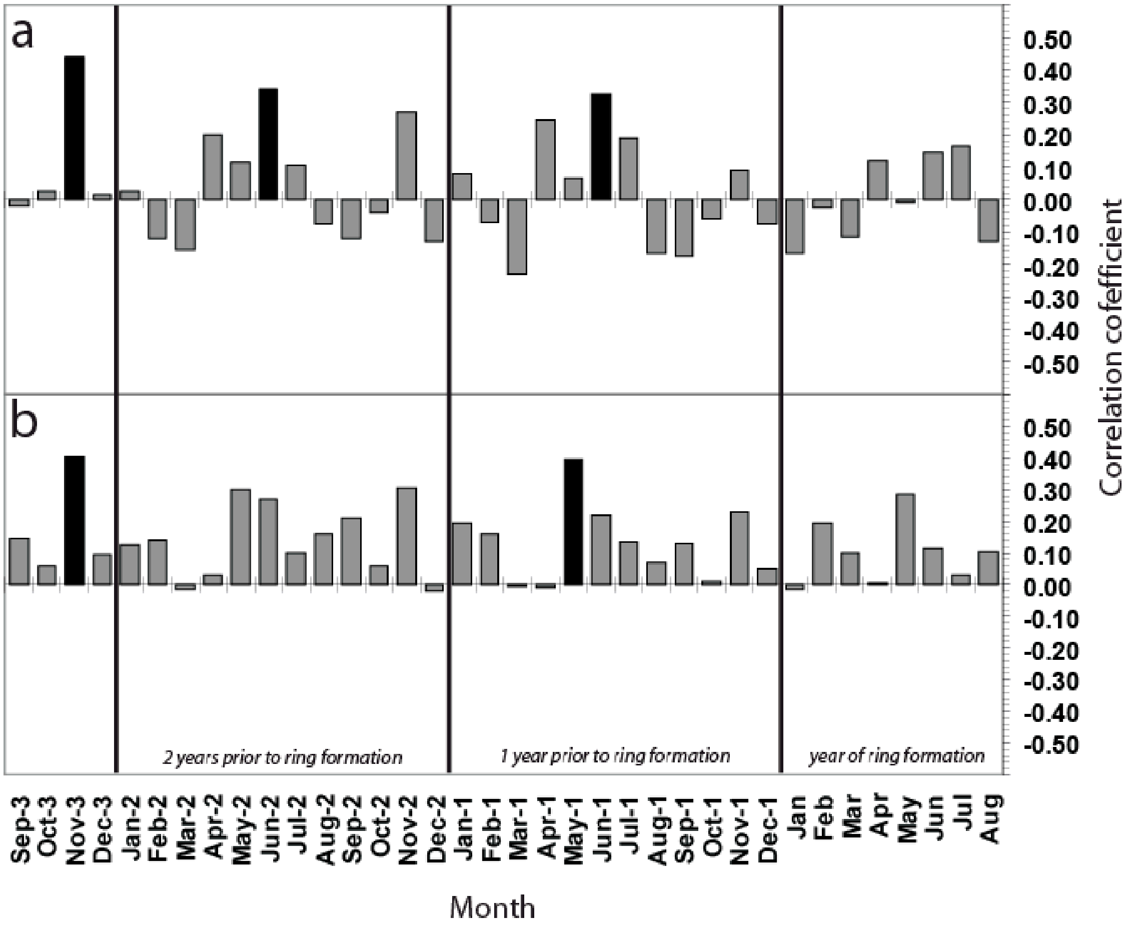


Figure 2.18.

Correlation of "positive responders" from both species to 36 months of Bethel total monthly precipitation (TMP). All values are Pearson correlation coefficients; correlations significant at $p<0.01$ are shaded black. **a**, correlation of mean RWI 35 white spruce "positive spring/fall temp responders" to Bethel TMP **b**, mean BSrw of 11 black spruce "positive spring temp responders" to Bethel TMP. Correlation values are for the period 1951-2006. Note that "positive responders" of both species were found to have significant correlations with Bethel rather than McGrath precipitation records.



Chapter 3

Implications for spruce tree growth, industrial wood product development and community sustainability.

The findings described in the previous chapter have implications for the future of forest resources development and community sustainability along the Kuskokwim River. Climate predictions indicate that hot, dry summer conditions will be prevalent in Alaska for the foreseeable future (Juday et al 2005). Consequently, it is likely that interior white spruce trees will continue to decrease their rates of growth, presumably returning to the low rates of growth experienced in the early 1800s or lower. The increasing rates of growth of downriver (westward) trees will not likely be enough to make up for the reduction in growth of interior trees. An expansion of tree-line is a slow process and may be further slowed as western areas begin to reach summer temperatures akin to those of current interior areas. The impact of the directionally changing rates of growth of these forests to local communities, however, is dependent upon the amount of future forest resource development.

If people living along the river continue to maintain their small-scale use of forest products, a gradual decrease in spruce productivity in upriver areas may be of little immediate consequence. Despite the downward growth trend of the last 60 years, radial growth of white spruce trees in eastern (upriver) locations still remains higher than in many interior Alaskan forests. Even small increases in forest product use, (e.g. increased use of firewood but no commercialized development) would not likely result in an exhaustion of forest resources. On the other hand, larger-scale, industrialized wood harvesting operations along the river are not likely to be sustainable unless the decreasing trends in growth rates changes. Communities banking on the past productivity of Kuskokwim River white spruce for biomass energy generation will likely face disappointing growth rates and slow regeneration on recently cut sites.

Additionally increasing summer temperatures may lead to more problems for Kuskokwim River forests and the communities that rely on them. Increasing annual temperatures in other locations across Alaska has led to other forest health related issues that may not be directly associated with radial growth. For example, warming temperatures on the Kenai Peninsula are associated with increased susceptibility of white spruce to insect infestation and a concurrent increase in survivability of spruce bark beetles. The combination of these factors led to unprecedented landscape-scale mortality across the peninsula (Juday et al 2005). Recent evidence from interior Alaskan white spruce forests indicates that increasing summer temperatures are leading to increased viability of forest pests (defoliators, boring insects etc) which is in turn leading to increased tree mortality there as well[4].

Increased spruce tree mortality, either as a result of drought-stress alone or from other temperature-related phenomenon (e.g. increased vulnerability to insect attack), could lead to a short term increase in quality salvage firewood or biomass-energy fuel. Greater mortality would also likely create a short-term surge of driftwood into the river system creating more available wood for down-river communities. In the longer term however, stands of what are now productive white spruce trees would no longer be available for firewood, timber, biomass fuel or other uses. The resulting changes in the amount of large woody debris into the river itself may have further ecological consequences, especially for fish and other wildlife. These consequences may be ultimately more significant to people who live along the Kuskokwim River than the decreasing potential for forest product development. While this study provides the first evidence of climate-related changes in forest resources, it is only one piece of a larger picture and more research is needed help Kuskokwim communities prepare for future conditions.

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[4] Pers comm. G. P. Juday.

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