National Park Service
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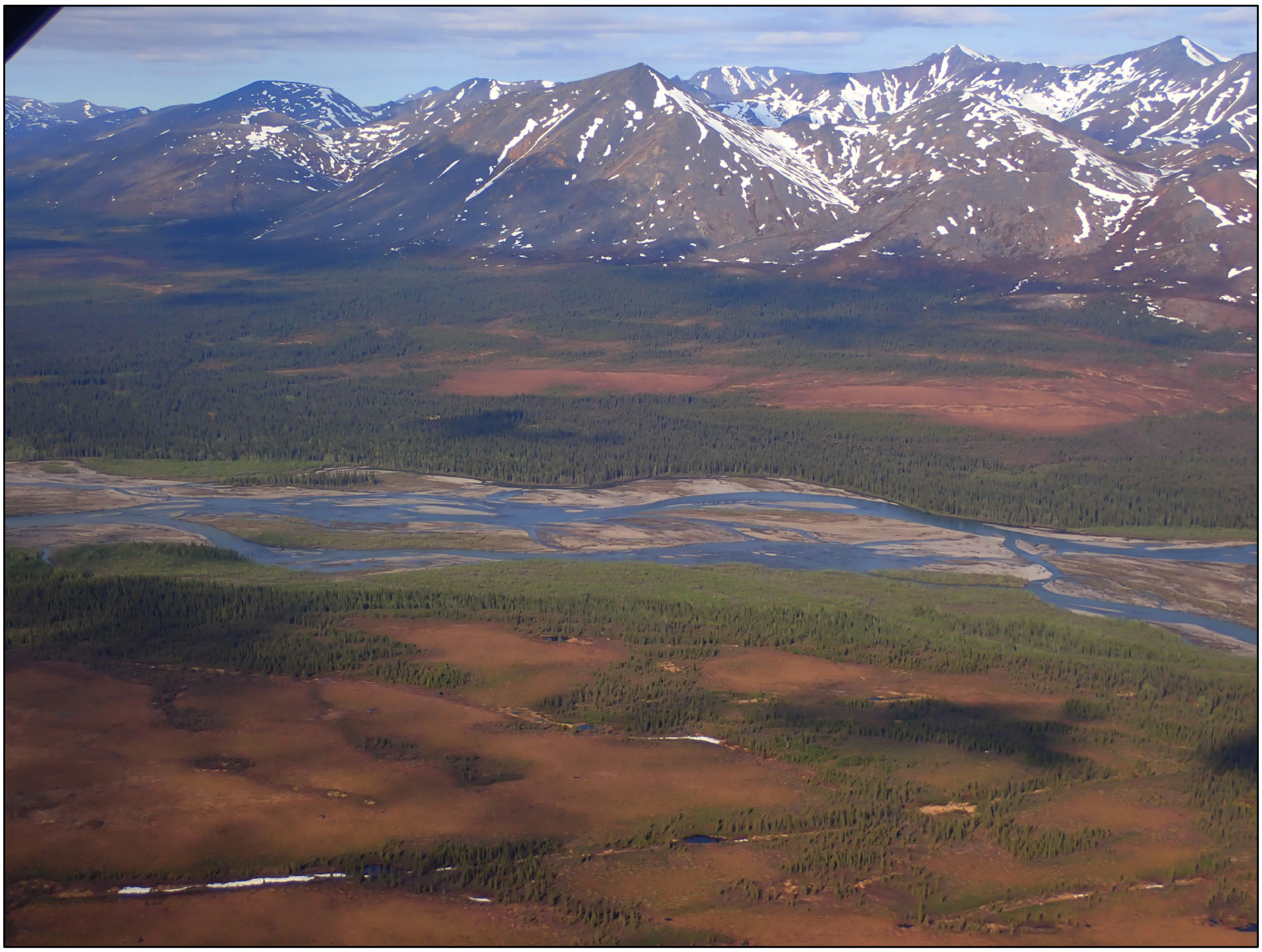
Natural Resource Stewardship and Science

Tree Investigations in the Noatak National Preserve, Alaska, 2011–2022

Old-growth and New Forests

Natural Resource Report NPS/ARCN/NRR—2023/2611



ON THIS PAGE
View of the old-growth white spruce (*Picea glauca*) forest at the Asik monitoring site, Noatak National Preserve.
NPS

ON THE COVER
White spruce forests in the Kelly River Valley of Noatak National Preserve. White spruce occur on the mountain footslope in the background, on the floodplains along the Kelly River in the photo center, and on favorable sites in the tussock tundra in the foreground.
NPS

Tree Investigations in the Noatak National Preserve, Alaska, 2011–2022

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Abstract

Tree rings in the Noatak National Preserve provide information about the growth of trees at the cold limit of tree survival in northwestern North America. The present study was based on cores and other tree measurements (tree basal area, height, and number per unit area) of white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*) trees taken from 39 permanent monitoring plots (34 with coreable trees) at three locations in the Preserve. The tree rings widths were measured and then normalized using a 50-year smoothing spline to remove the effects of growth variations through the life cycles of the trees.

Old-growth white spruce forests, which here include numerous trees over 200 years old and some that are more than 300 years old, form open stands on well-drained slopes. Stands of younger trees that became established in the 1900s are present near elevational tree-line, and in small groves on tussock tundra. These younger stands are interpreted primarily as the result of forest expansion due to climate warming, though re-establishment of trees after wildfire is also possible in the tussock tundra. On river floodplains and terraces, stands of both white spruce and balsam poplar were also initiated in the 1900s, but here the youth of the trees is probably due to colonization of new areas exposed by river channel migration. Both the old-growth and younger forests showed continuing growth (as expressed by an increase in stand basal area) between our initial visit in 2011 and re-visit in 2021 or 2022, with the greatest increases occurring on floodplains.

Tree rings showed much year-to-year variation in width, but the effect of individual cold summers was surprisingly weak. Some of the major global climate perturbations due to volcanic eruptions were visible in the tree ring record, but the resulting ring growth was generally no worse than other bad growth years within a few decades of the volcanic event. Tree ring width was statistically correlated more closely with the average warmth of several preceding growing seasons (as expressed by the annual sum of thaw degree-days) than with the current year’s or the previous year’s warmth alone. This is probably due to the cumulative effect of several years’ warmth (or cold) on the conditions in the tree rooting zone, on the amount of foliage available for photosynthesis, and the level of stored reserves in the tree.

Acknowledgments

Thanks to Celia Miller, Adrian Wakeen, Caitlin Luby, Fleur Nicklen, and Justin Terzi for help coring and measuring trees in the field, and measuring tree rings in the lab. Thanks to Fleur Nicklen and Carl Roland for help with tree core processing, measurement, software, and analysis. Celia Miller and Fleur Nicklen provided helpful review comments.

Introduction

The northern limit of trees in western Arctic Alaska occurs in the Noatak National Preserve (NOAT; Figures 1 and 2). Most of the Preserve is treeless tundra (Figure 2), and the small forested areas are of particular interest for what they can tell us about trees living at the very limit of their survival. White spruce trees (*Picea glauca*) have been in the Noatak Valley for at least 2500 years (Higuera et al. 2011). They probably colonized the Noatak Valley from Squirrel River Valley, where they arrived about 5000 years ago as a part of their Alaska-wide post-glacial expansion (Anderson 1985).

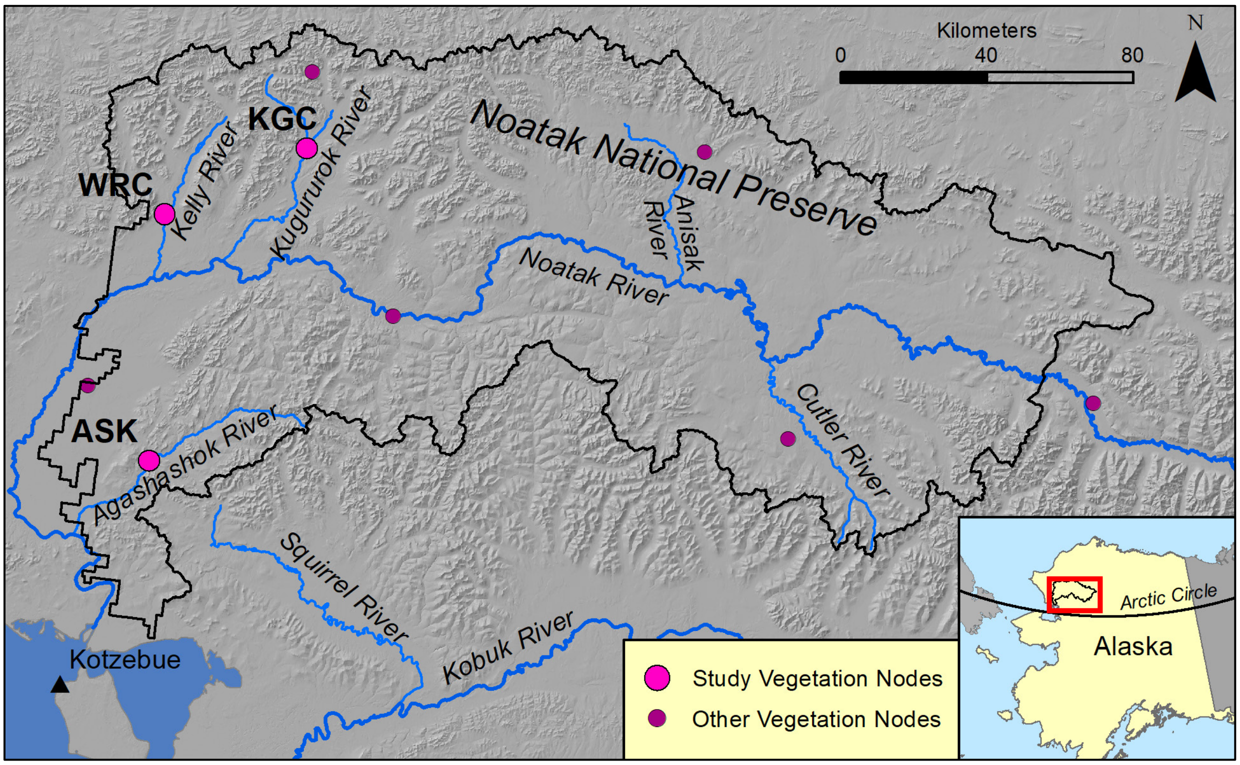

Figure 1. The three study areas at ARCN vegetation monitoring nodes in the western part of the Noatak National Preserve (NOAT): the Asik node (ASK), the Kagvik Creek node (KGC), and the Wrench Creek node (WRC). Other ARCN vegetation monitoring locations in the Preserve lacked trees.

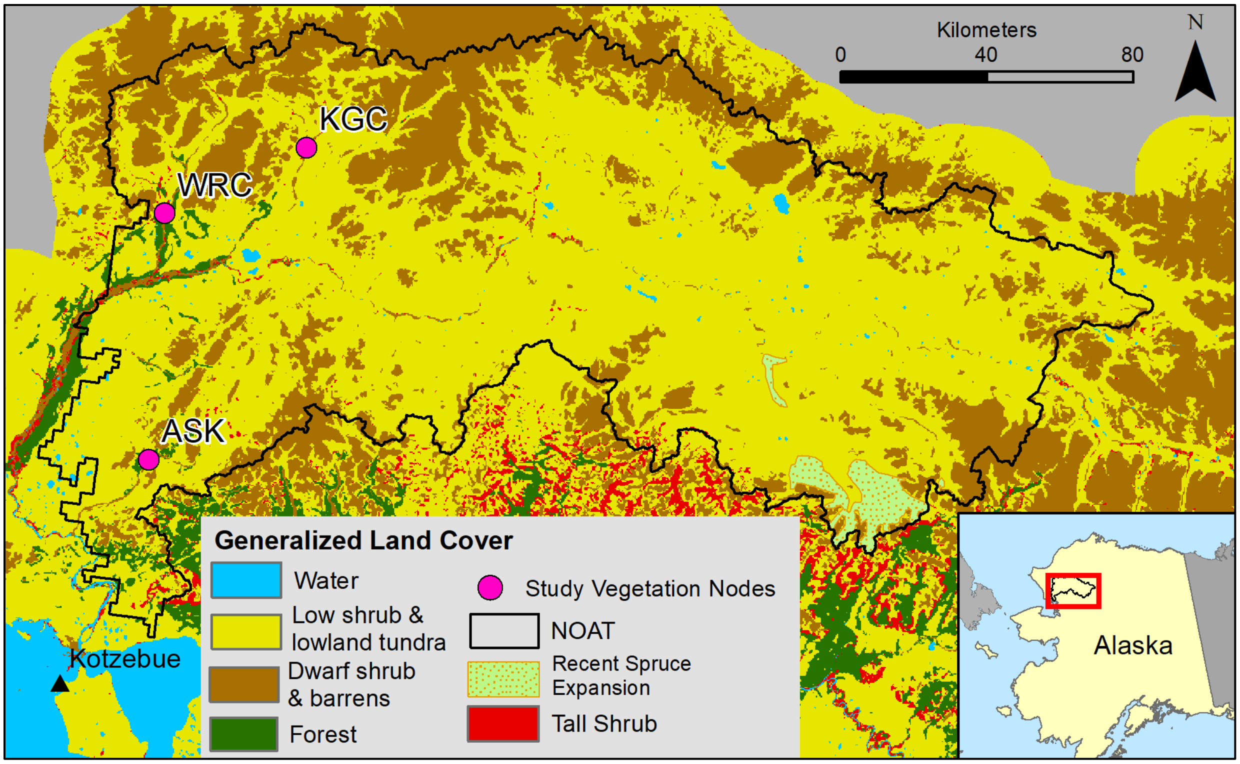

Figure 2. Vegetation of the Noatak National Preserve and vicinity, generalized from Jorgenson et al. (2009). The extent of recent white spruce expansion in the southeastern part of NOAT is from Dial et al. (2022).The three study areas are also shown: the Asik node (ASK), the Kagvik Creek node (KGC), and the Wrench Creek node (WRC).

Tree rings are a fascinating source of information about the age of trees and their growth rates. Numerous studies have been published about tree rings in northern and central Alaska, the purposes of which fall into two main groups: 1) using tree rings to date wood found in archeological studies, and 2) using tree rings to understand tree growth in relation to climate and weather. A recent example of using tree rings for archeological dating is Taïeb et al. (2022). Tree rings in pieces of wood found at archeological sites can often be precisely matched to known ring chronologies. An added benefit of archeological tree rings is that multiple overlapping samples can be pieced together to create a ring chronology that extends earlier than any living trees. A ring chronology from the Kobuk River region by Giddings (1948) was extended back 1000 years using archeological wood samples and recently extended back to AD 750 by Taïeb et al. (2021).

Though numerous studies have examined tree rings and climate in Alaska, though relatively few have taken place in the Noatak Valley. Giddings (1948) original chronology was based on a mixture of Kobuk and Noatak River trees (see also Jacoby et al. 1996, D'Arrigo et al. 2005). Arians (1997) used tree cores to study the effect of site factors (especially soil temperature) on tree growth on the Noatak River floodplain. She noted a significant increase in growth rates since 1950 in response to increasing temperatures, but hypothesized that growth was also limited by drought. Rowland (1997) cored trees in the Kelly and Kugururok River valleys to determine the ages of trees in various landform positions. The most intensive tree-ring studies in NOAT to date were by Suarez et al.

(1999) and Sullivan et al. (2015) near our Agashashok study area. They found that trees had advanced out onto wetter tussock tundra soils from drier forests over the past 200 years, and that nutrient limitations due to cold soils in the tussock tundra were the main limitations to tree growth. Wilmking et al. (2004) and Wilmking and Juday (2005) studied 67 trees with cores over 100 years long in the Noatak River floodplain at 68.0 N, 161.5 W, as a part of a tree growth-climate study across the Brooks Range. They found a positive relationship between tree growth and temperature but also some negative responses due to drought. However, the trees in NOAT (the furthest west of their study sites) were the least drought-limited of any along their east-west transect, with 76% of trees responding positively to warmth (defined as April and July temperatures of the year preceding the ring). Brownlee et al. (2016) studied carbon isotopes in tree rings and measurements of tree physiology to test whether drought-induced stomatal closures were the reason for the failure of some trees in the Brooks Range to react positively to warm temperature. They did not find evidence to support the drought hypothesis. Finally, Dial et al. (2022) used tree rings to document the rapid advance of white spruce during the past 100 years in the Cutler River region on the south side of the upper Noatak Valley, well to the east of previously known spruce forests (Figure 2). These trees were growing rapidly, and had spread down all the way to the Noatak River from the passes where they originally crossed over from the Kobuk to the Noatak Valleys.

The purpose of the present study is to report results of tree measurements, especially measurements of cores taken at permanent vegetation monitoring plots in NOAT maintained by the National Park Service (NPS). These plots were established in 2011 and 2013 at 8 general locations in NOAT, by the protocol described in Swanson and Neitlich (2016). In 2021 and 2022, NPS field crews revisited most of the NOAT monitoring plots, including all that had trees. We repeated tree and vegetation measurements and collected tree cores. In the present report I summarize the ages and sizes of trees at the various plots, to increase our familiarity with our monitoring plots and with the forests of the Noatak Preserve. I also briefly examine the variations in ring width over time in these cores, to explore the relationship between tree ring width and summer warmth as well as with historic volcanic eruptions and other known cold years.

Methods

Study Area

This study took place at three locations in the Noatak National Preserve, in northwestern Alaska (NOAT, Figure 1). The Preserve occupies a broad valley rimmed by mountains. Permafrost is continuous (Jorgenson et al. 2008). Most of the Preserve has vegetation of tussock or low shrub tundra, with alpine dwarf shrub tundra and barrens at high elevations (Jorgenson et al. 2009; Figure 2). In the lowlands of the western part of the Preserve there are forests of white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*). The latter species also occurs in small groves or thickets, often in tall shrub form rather than as trees (i.e., less than 3 m tall) in favorable locations such as south-facing slopes throughout the Preserve. Black spruce (*Picea mariana*) is widespread in Interior Alaska and in the Kobuk River Valley to the south of the Noatak Valley, but it has not been recorded in NOAT.

White spruce occurs both on floodplains and on hillslopes in the western part of the Preserve (Figure 3). The total area covered by spruce on hillslopes was estimated to be 269 km^2, or about 1% of the Preserve (Jorgenson et al. 2009). Riverine white spruce was estimated to cover 106 km^2, or about 0.4% of the Preserve. Riverine balsam poplar forest was estimated to cover less than 0.1% of the Preserve (Figure 4).

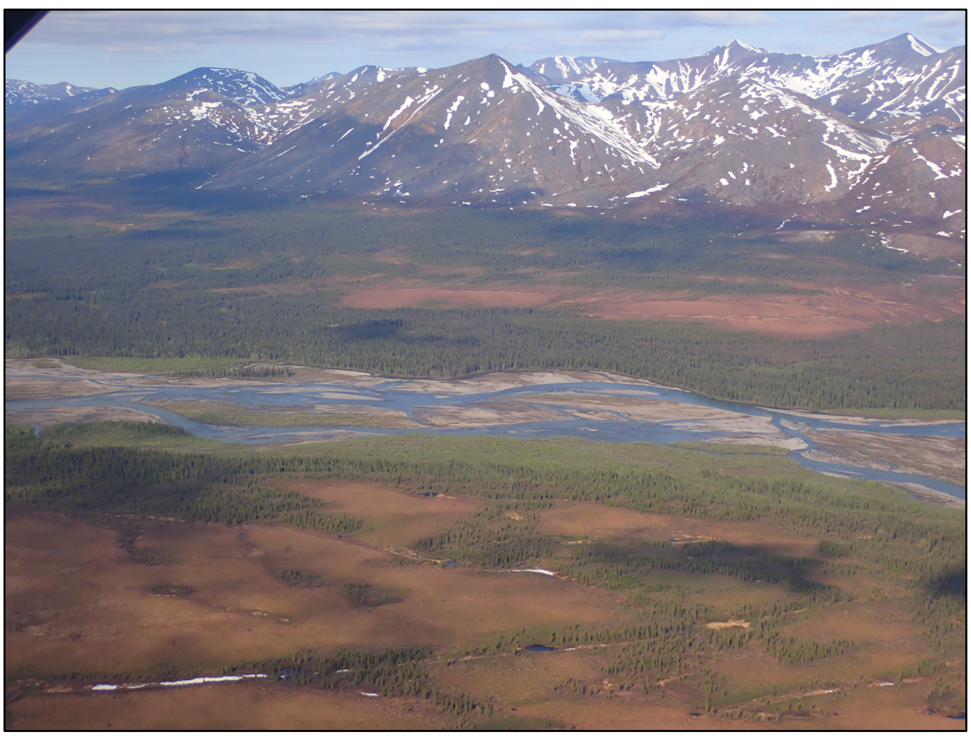

Figure 3. White spruce (*Picea glauca*) forests in the Kelly River Valley of Noatak National Preserve. White spruce occur on the mountain footslope in the background, on the floodplains along the Kelly River in the photo center, and on favorable sites in the tussock tundra in the foreground. The Wrench Creek Node “Spruce Slope Transect” is on the gentle slope at the foot of the mountains on the right, while the “Tussock Plain Transect” runs across the foreground.

Figure 4. Riparian balsam poplar (*Populus balsamifera*) trees along the Kugururok River in the Noatak National Preserve. Photo date 27 August 2009. This location is about 7 km north-northwest of the Kagvik Creek node sample area.

ARCN maintains a set of permanent vegetation monitoring plots, clustered into “nodes” near airplane access points, and this study encompasses all of the nodes in NOAT where trees were present: the Asik (ASK), Kagvik Creek (KGC) and Wrench Creek (WRC) nodes (Figure 1). Mean climatic data for these locations is provided in Table 1.

Table 1. Mean Temperature and Precipitation for the Study Area [A.]

Node	Mean Annual Air Temperature (°C)	Mean January Air Temperature (°C)	Mean July Air Temperature (°C)	Mean Annual Precipitation (mm)
Asik	−4.9 to −5.4	−17.8 to −19.3	11.2 to 11.6	407 to 428
Kagvik Creek	−6.7	−22.4 to −22.5	11.1	402 to 403
Wrench Creek	−4.7 to −4.9	−17.1 to −19.1	11.2 to 12.1	408 to 468

[A] Data from gridded modeled values for 1981–2010 by PRISM Climate Group (2020). The range given is for all forested plots at the node

The amount of summer warmth available for tree growth varies from year to year. The long-term records at Kotzebue (see Figure 1 for its location) show four exceptionally cold summers in the past 80 years (as measured by thaw degree-days, TDD, the annual sum of all daily average temperatures above freezing):1945, 1948, 1975, and 2000 (Figure 5). The general trend is also for increasing annual sum of TDD over the past 80 years.

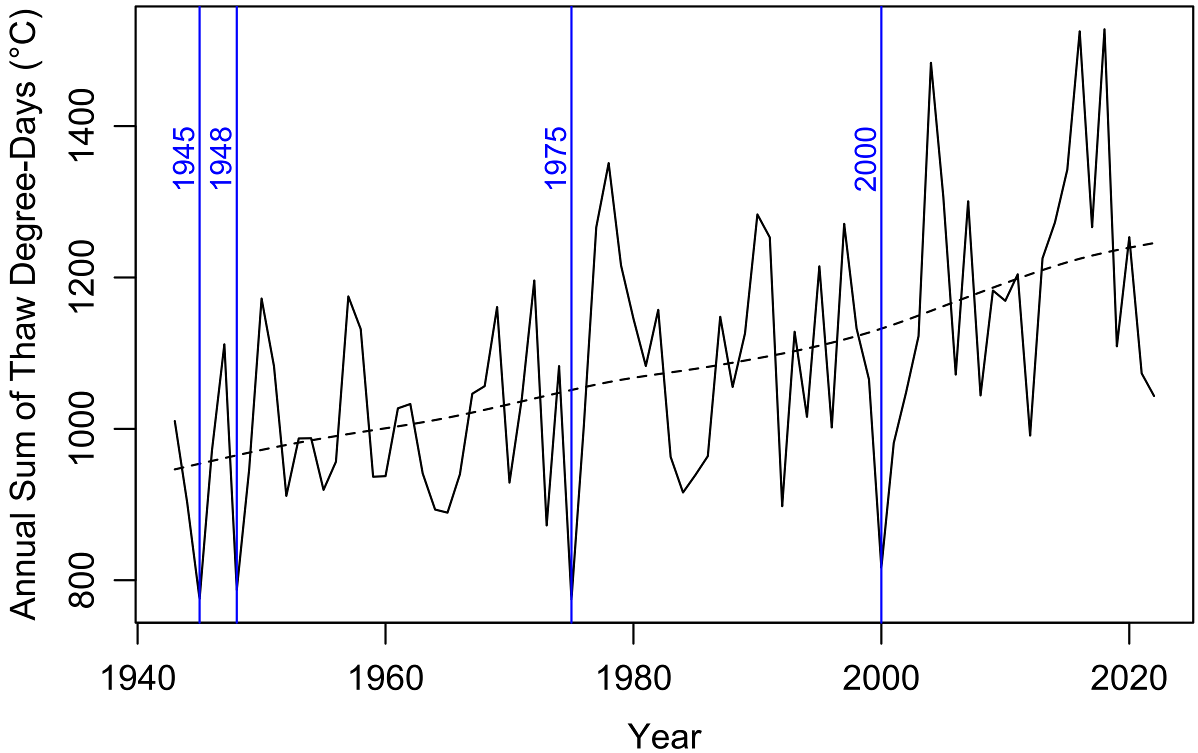

Figure 5. Plot of the annual sum of thaw-degree days at Kotzebue vs. year. Computed from National Weather Service Data (NOAA Regional Climate Centers, 2023). Vertical blue lines mark the four coldest thaw seasons since reliable records began in 1943. The trend line is a 50-year smoothing spline (Bunn et al. 2022).

At the Asik and Wrench Creek nodes, white spruce are present in riparian areas, on well-drained hillslopes, and in scattered groves among tussock tundra. Balsam poplar is also present in the riparian areas, though at low density and our plots did not have trees suitable for coring. At these two locations, tussock tundra vegetation is widespread on poorly drained soils at low elevations. Dry tundra vegetation is present at higher elevations, and our sampling transects traversed the gradient across elevational treeline. White spruce is absent at the Kagvik Creek node (it is north of the white spruce tree-line), and balsam poplar occurs in forests in riparian areas. A few scattered balsam poplar trees also occur on well-drained sites within tussock tundra at Kagvik Creek.

Field Methods

The plots were established in 2011, and tree cores were collected during re-visits to the plots in 2021 (ASK, KGC) and 2022 (WRC). Plots are arrayed on transects that correspond to major landforms, each with specific soil, disturbance, and microclimatic conditions (Figures 6 through 8). At each plot we collected data on soil and site characteristics, plant cover by point intercept on two line transects, tree measurements on an 8 m diameter circular plot, as described in Swanson and Neitlich (2016, with updates). The tree data are most relevant here, and they consist of diameter at breast height (DBH, diameter at 1.37 m (4.5 feet) above the ground) of all trees within 8 m radial distance of plot center. We also counted tree seedlings by species on four 4 m^2 square subplots within the plot.

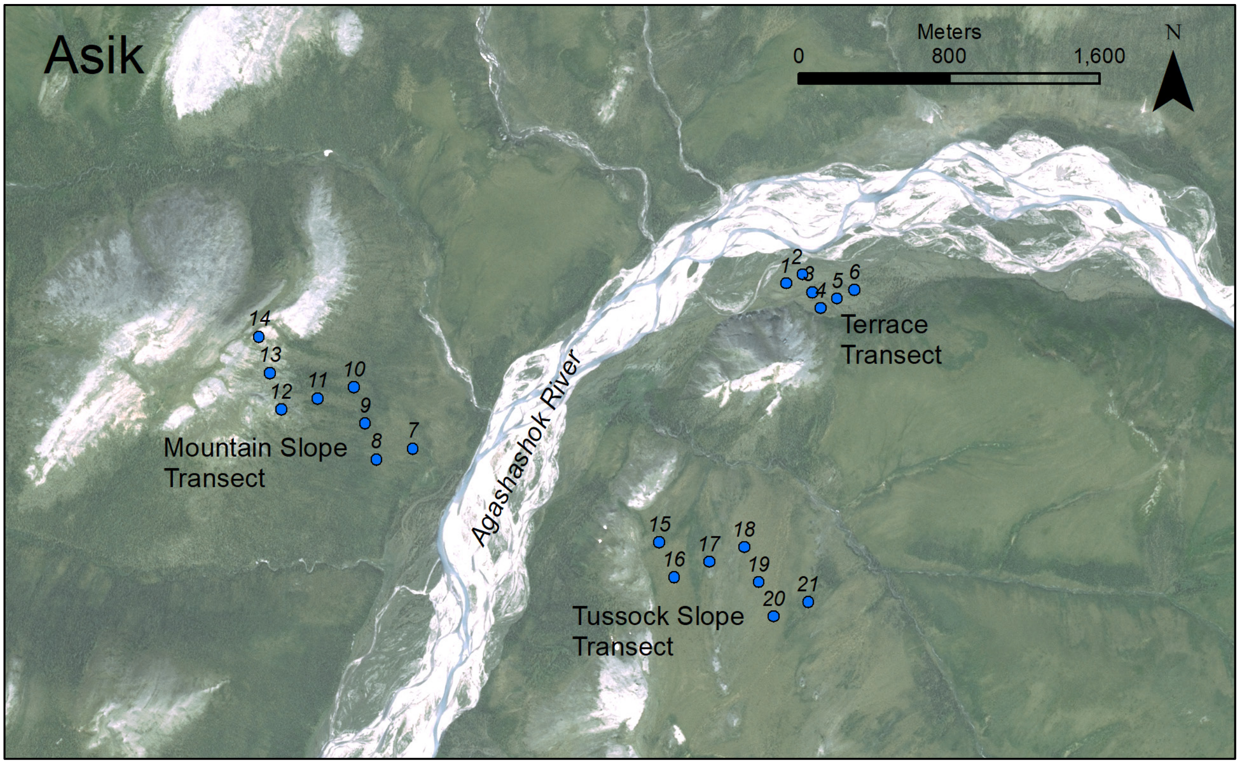

Figure 6. Plot and transect locations at the Asik Node (ASK). See Figure 1 for the general location.

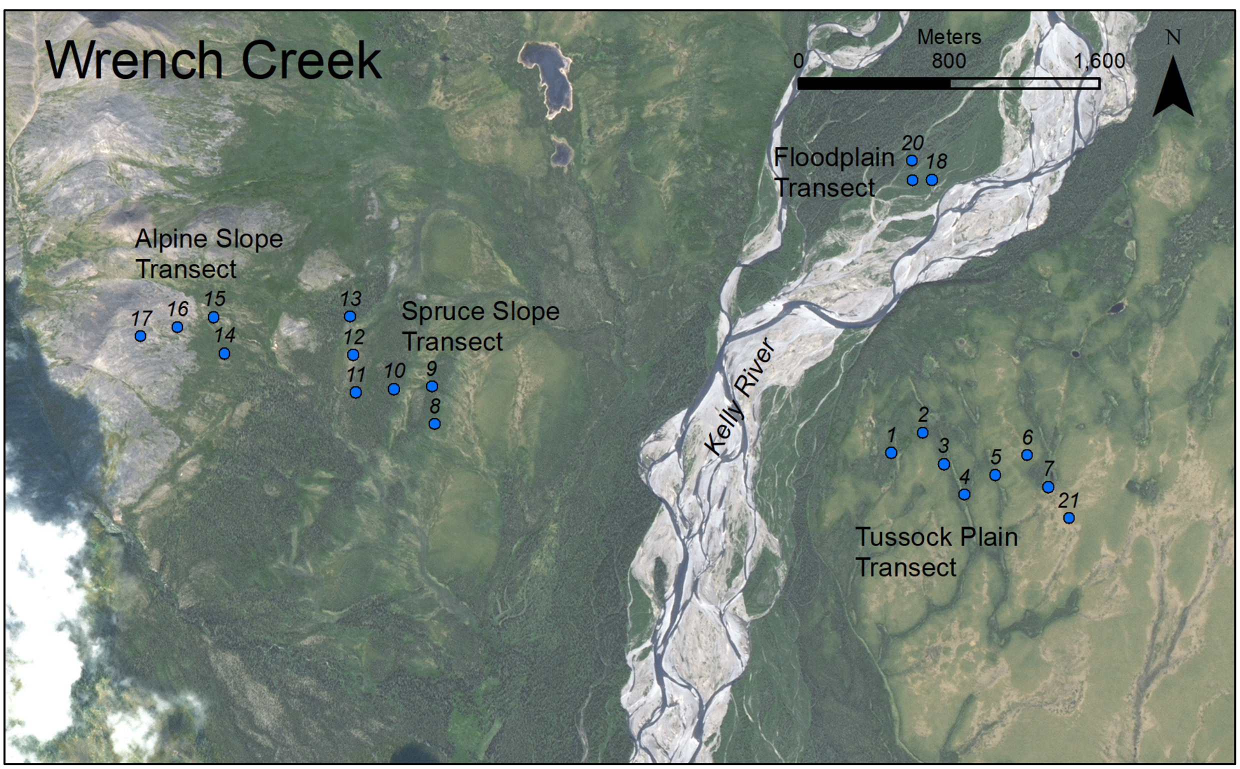

Figure 7. Plot and transect locations at the Wrench Creek Node (WRC). See Figure 1 for the general location.

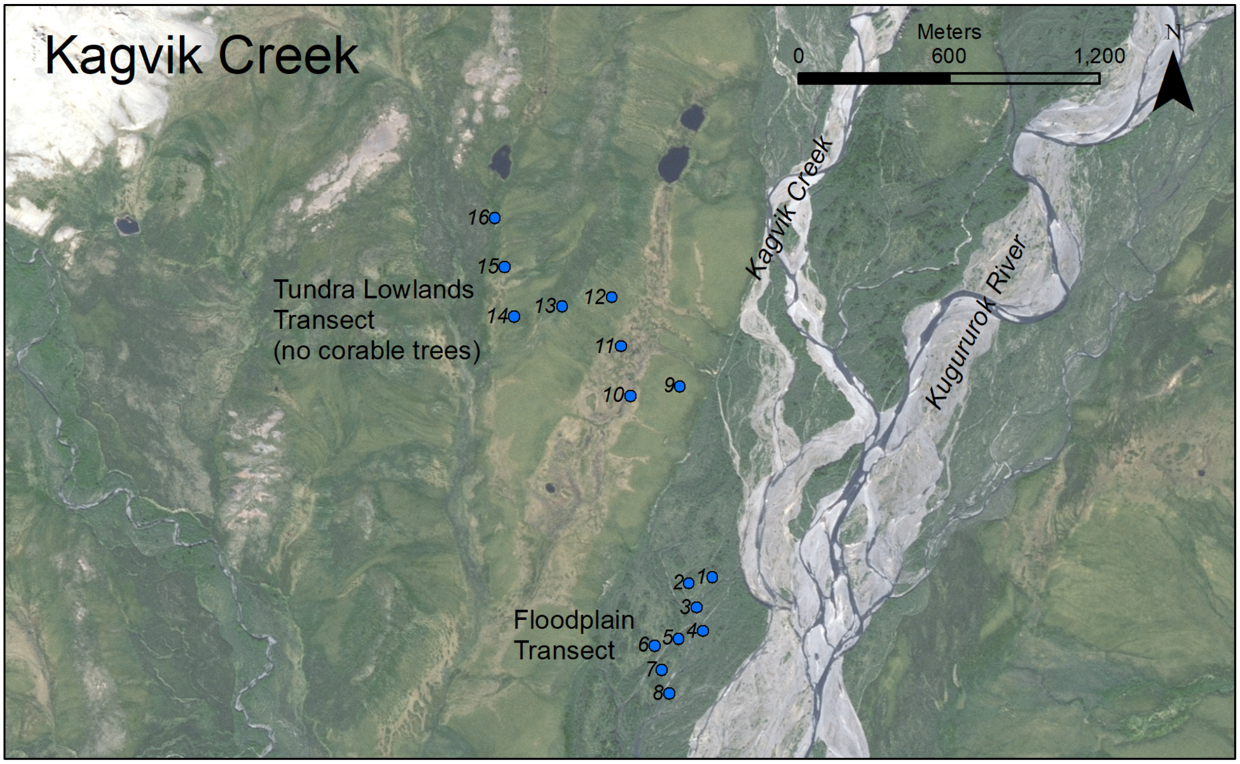

Figure 8. Plot and transect locations at the Kagvik Creek (KGC) node. See Figure 1 for the general location.

We also collected cores for ring analysis. Trees were cored outside of the main plot but within 16 m of the plot center. The largest 4 individual trees in the ring-shaped area between 8 and 16 m from plot center were cored as low to the ground as was feasible (typically 20–40 cm). Only trees larger than 5 cm DBH were cored. Trees were cored through the entire bole, yielding a core with two separate radii that were measured for annual growth.

Laboratory and Analytical Methods

Cores were glued to wooden mounting blocks, sliced with a microtome cutting device to expose a clean flat surface, and buffed with 2000 grit sandpaper (Figure 9). Cores were scanned at 3200 dpi or higher and ring widths measured using CooRecorder 9.8.1 software by Cybis. Most rings could be dated by counting inward from the bark. We also cross-dated the cores against one-another if the bark was missing and to locate missed rings. Where the core missed the pith, we estimated the age of the pith by extrapolation using CooRecorder's tool for this purpose.

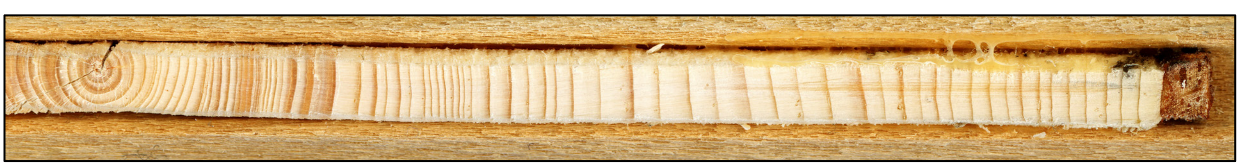

Figure 9. An example tree core, a white spruce from Wrench Creek plot 1. The pith is visible on the left and the bark on the right. This tree was cored in 2022 and the pith was determined by ring counts to be from the year 1944.

Annual ring widths vary between trees due to site conditions, and through the life of a tree due to intrinsic factors (such as tree age) that are unrelated to external factors such as weather. To be able to aggregate the data from multiple cores and identify the years or groups of years that represent generally good or bad growth conditions, we must normalize the ring widths (to place them on a common scale) and de-trend them (remove the effect of changing intrinsic ring growth rates through the life of the tree). A basic method for accomplishing both of these tasks is to compute a 50-year smoothing spline for the ring width from each core, and then compute the relative deviation of each ring from its corresponding smoothed value (Cook, 1985; Speer, 2012; Figure 10). I used the "caps" (Cook and Peters smoothing spline) function from the dplR package (Bunn et al. 2022) with settings of 50 years and frequency response f = 0.5, which are close to the original settings chosen by Cook and Peters (1981). This procedure fits a curve that retains half of the variability at a frequency of 50 years (i.e., would dampen a 50-year sine wave by 50%); it effectively eliminates any variability with a frequency greater than about 100 years and has little effect on variability at frequencies of less than about 20 years (Cook and Peters 1981; recall that the "frequency" of a wave refers to a full peak-and-trough cycle). The result of this ring-width normalization process is a dimensionless ratio of each year's ring width relative to the typical value for the 50-year period surrounding it. This method allows us to identify individual good and bad years and groups of years up to about a decade in length. Unfortunately, it also removes any long-term effects of climate change on tree growth, so we are not able to evaluate whether tree growth rates have changed across multiple decades or centuries.

Detrending methods have been proposed that retain the long-term tree growth signal. These range in complexity from fitting a simple negative exponential curve to each core (to remove the commonly observed decline in ring width over time, Fritts 1969) to multiple-curve regional curve standardization, where trees are grouped into growth-rate classes and standardized growth rates through the life of the tree are computed for each class (Sullivan et al. 2016). The choice and application of these long-term detrending methods are complex, inference can be difficult, and large data sets are often needed. Thus for the purposes of this report, I limited my analysis to the annual- and decadal-scale anomalies that are visible after application of a simple 50-year smoothing spline.

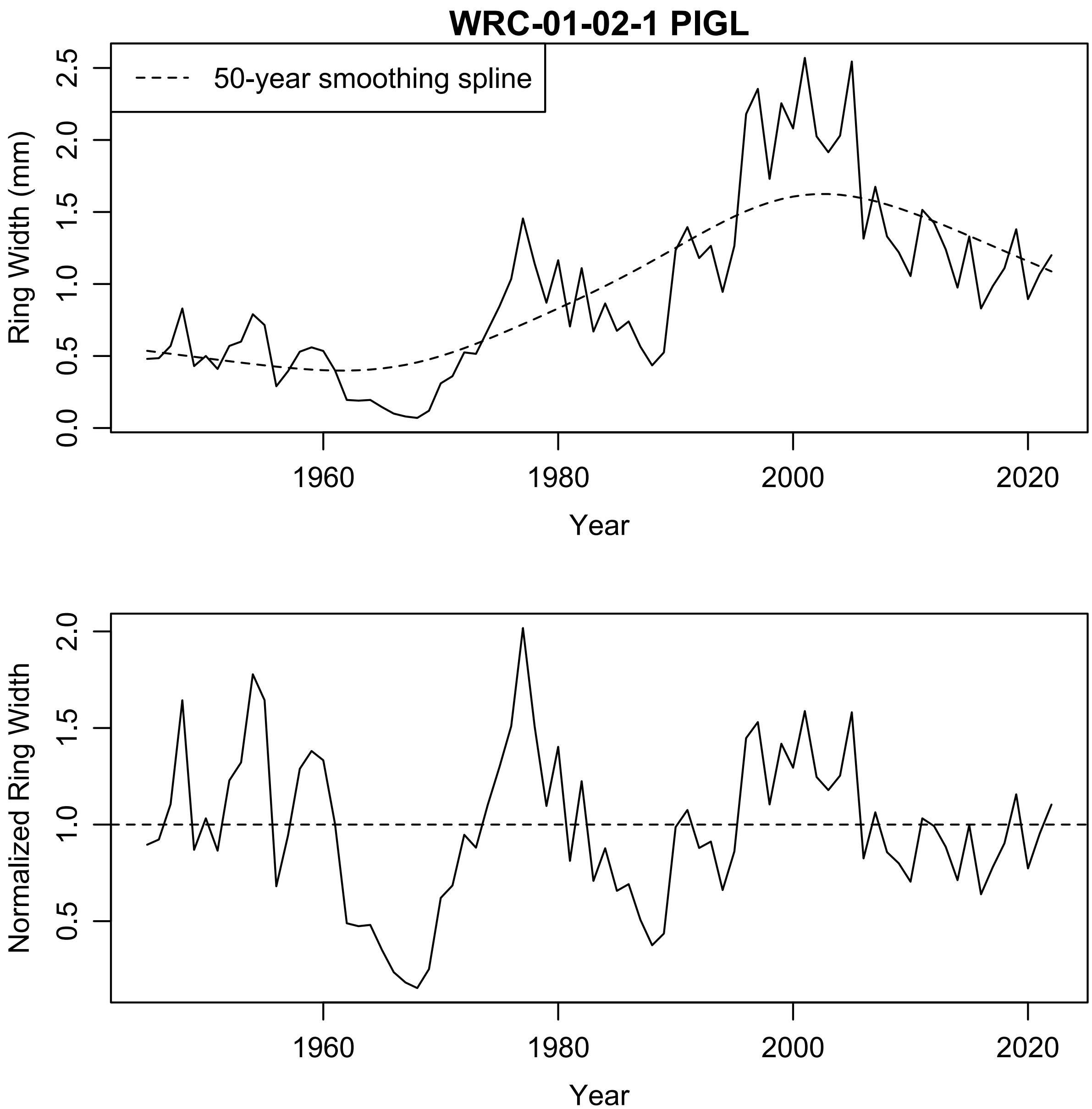

Figure 10. Example of tree-ring normalization by a 50-year smoothing spline. This core is the example shown in Figure 9. The upper plot shows raw ring widths vs. year and the 50-year smoothing spline. The lower plot shows the normalized ring widths vs. year; the normalized ring widths were derived from the data in the upper plot by dividing each ring width by the same year's value for the smoothing spline.

To briefly explore the relationship between tree ring width and summer warmth, I used data from Kotzebue, Alaska, the nearest weather station with long-term records (NOAA Regional Climate Centers, 2023; for its location see Figure 1). Temperature records at Kotzebue are nearly continuous since 1943. I computed the annual sum of thaw degree-days (TDD; base temperature 0 °C) by interpolating between the monthly mean temperatures and calculating the area under the curve (Figure 5). To make the comparison as fair as possible, I subjected the TDD sums to the same 50-year smoothing spline normalization as the ring width data. and tested the relationship of normalized

TDD to the current and previous years' normalized ring width by linear regression. To test the effect of multi-year warmth on tree ring width, I correlated the normalized tree ring widths with the weighted average normalized TDD from multiple preceding years, and I tested different numbers of preceding years: e.g., prior years 1 and 2, 1 through 3, etc. I weighted the years using a Gaussian (normal) curve out to one standard deviation, i.e., the most distant year received a weight proportional to the height of the Gaussian bell curve at one standard deviation from the peak. For example, the weights for prior years 1 through 4 would be 0.30, 0.28, 0.24, and 0.18, the values for a normal distribution from the peak (0.30) out to one standard deviation (0.18), adjusted so they sum to one.

I also compared tree ring width to the major volcanic eruptions as summarized by Sigl et al. (2015). Sigl et al. estimated the sulfate loading in the northern hemisphere are each year in the past 2,500 years. Peaks in atmospheric sulfate concentration are due mainly to volcanic eruptions and are responsible for volcanic global cooling events.

I computed tree basal area from the measured tree diameters in the plots. Basal area is the area occupied by the actual diameters of the trees, measured at breast height, and correlates closely with tree biomass. The basal area of all trees on each plot was computed from the diameter and summed. Basal area per plot was converted to basal area her hectare by dividing by the plot area (188.5 m^2) and multiplying by the size of a hectare (10,000 m^2). The count of seedlings in the four 4 m^2 subplots (16 m^2 total) was similarly summed and converted to seedlings per hectare.

Results

Tree Ages and Size Distribution

The tree ages reported here are actually “pith ages”, derived from the dates of the pith at 20 to 40 cm above the ground (median height: 34 cm), where the cores were taken. Thus they represent the year when the trees reached this height, and not year of tree seedling germination. In some cases we were unable to estimate the pith age, in which case I report the year of the oldest ring, flagged with an “m” in the figures to indicate this is a minimum age and the tree is older by an unknown amount.

Asik Node

Terrace Transect

The ages of the trees varied greatly between the different locations, and the ages were strongly associated with landforms at the three study sites (Figures 11–13). On the Terrace transect the cored trees all dated from the 1900s (Figure 11) and were 3.2 to 7.1 m tall (Appendix A, Table A1).

Mountain Slope Transect

On the lower portion of the Mountain Slope Transect, (plots 7 through 11; Figure 12), trees were very old, with two of the cored trees established prior to the year 1700. The cored trees ranged in height from 5.4 to 12.6 m (Table A1), and, surprisingly, the oldest tree (pith year 1686 at 29 cm above the ground) was nearly the shortest of the cored trees on the transect at 5.5 m. The second oldest tree (pith year 1695 at 42 cm above the ground) was the tallest of the cored trees on the transect (12.6 m). This old-growth forest was open-canopied (Figure 14), and dominated by trees with a DBH of less than 20 cm (Figure 15). Seedling density (count individual trees per hectare less than 1.37 m tall) greatly exceeded the density of tall trees on most plots (Table A2).

In the vicinity of treeline on the Mountain Slope Transect (plots 13 and 14), trees were much younger: all cored trees began life in the 1900s (Figure 13). They were also smaller: the cored trees were 3.2 to 4.5 m tall, and all trees on the plots had DBH of less than 7 cm. And the density was lower at 265 and 424 and trees ha^{-1}, as compared to over 1000 trees ha^{-1} at some of the lower-elevation plots on this transect (Appendix A, Table A2).

Tussock Slope Transect

Only 3 of the 7 plots on this transect had trees of core-able size available (Figure 13). Of the seven available trees, all dated from the 1900s except one, which had rings dating back to 1847 and no pith available to date. Trees here occurred in small groves on favorable sites, and the cored trees ranged in height from 3.3 to 8.1 m; the 1847 tree was the tallest. Seedling density on most plots exceeded the density of trees greater than 1.37 m tall.

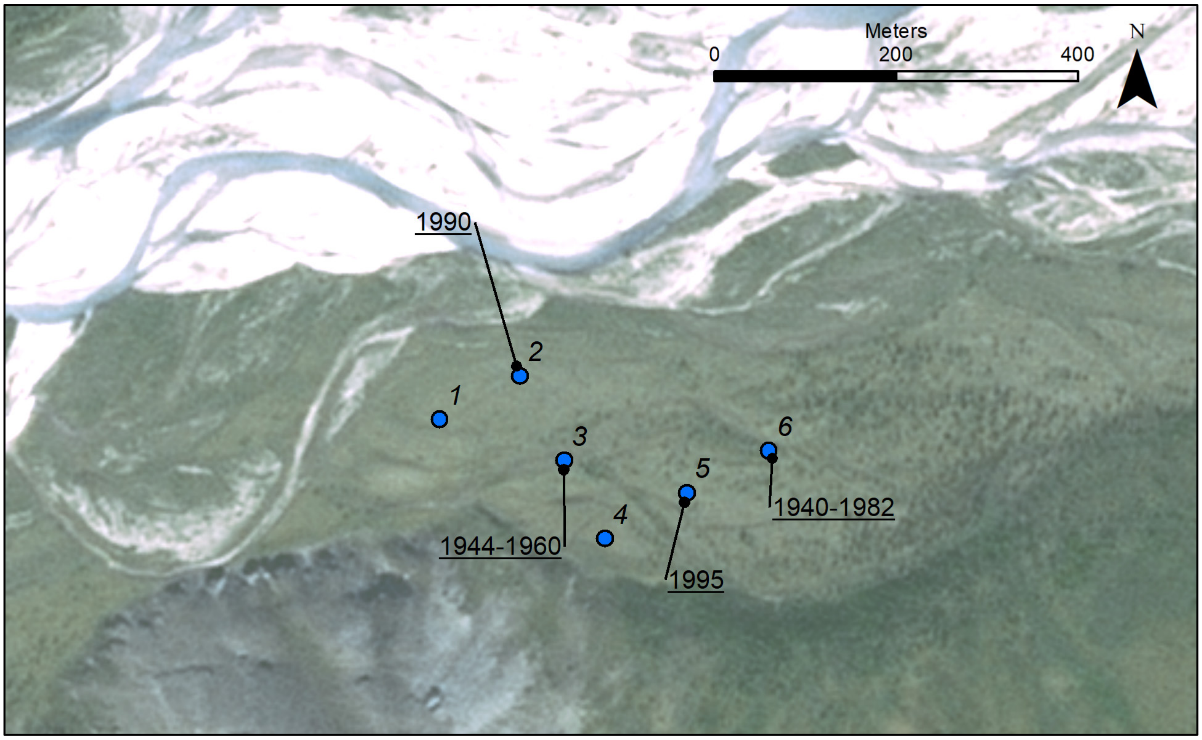

Figure 11. Pith years of trees at the Asik node, Terrace Transect. Ranges are given where more than one tree was available to core. See Figure 6 for the transect location.

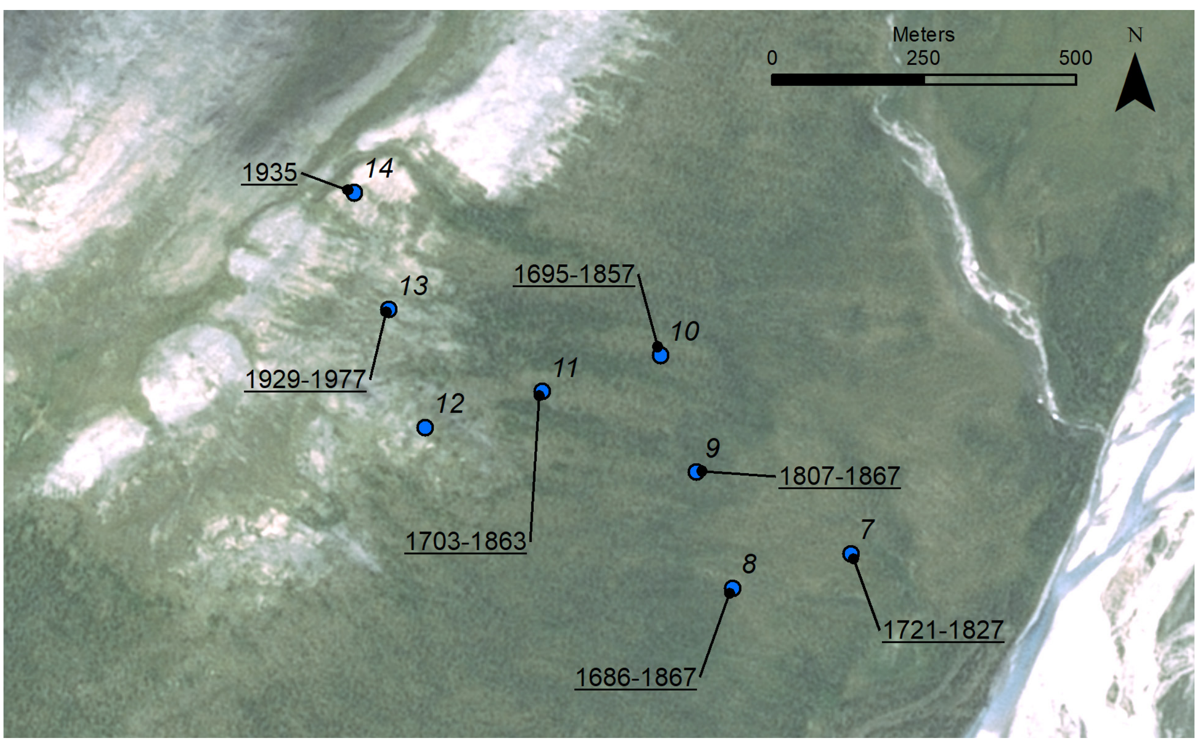

Figure 12. Pith years of trees at the Asik node, Mountain Slope transect. Ranges are given where more than one tree was available to core. See Figure 6 for the transect location.

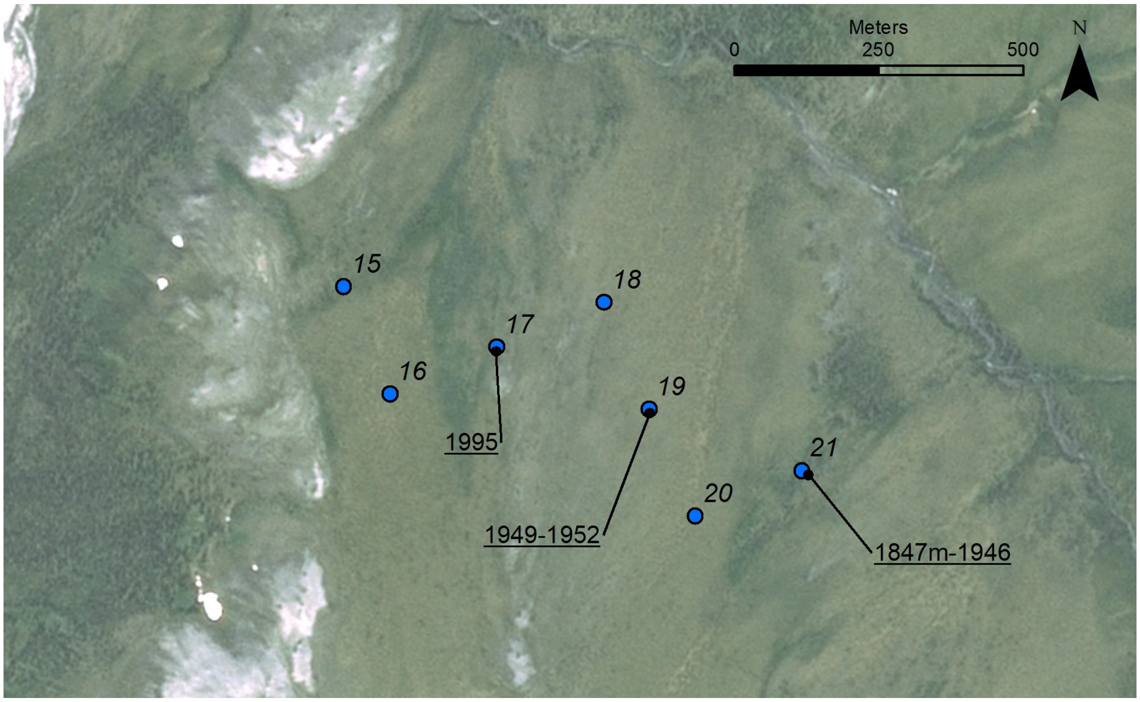

Figure 13. Pith years of trees at the Asik node, Tussock Slope Transect. Ranges are given where more than one tree was available to core. An “m” indicates the pith age could not be estimated; the age is that of the oldest ring on the core, and the tree is actually older by an unknown amount. See Figure 6 for the transect location.

Figure 14. View of the old-growth forest on the Asik plot 11, on the Mountain Slope Transect.

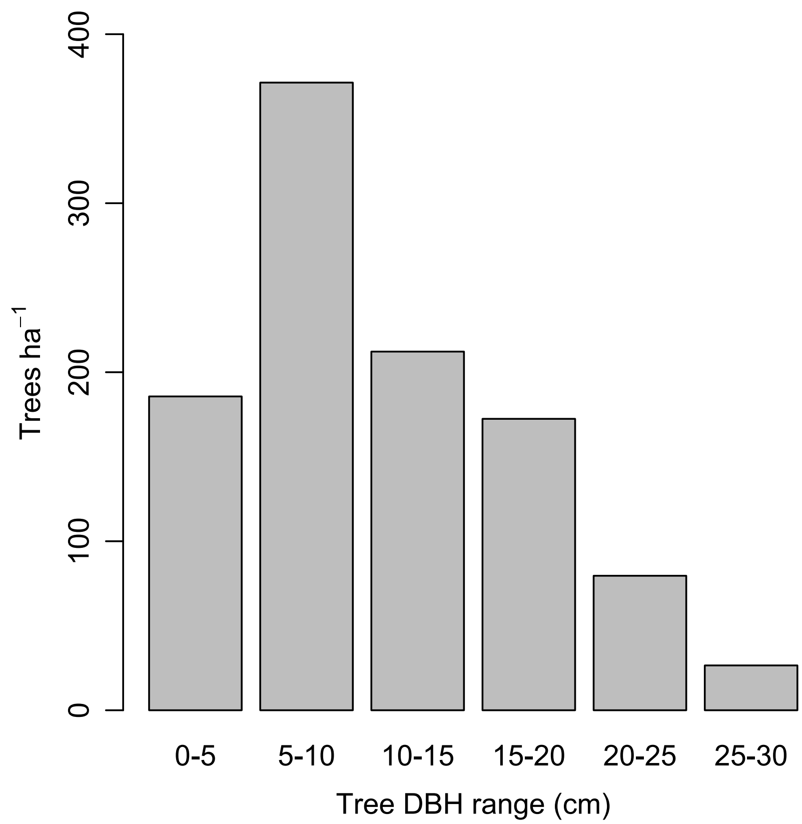

Figure 15. Diameter distribution of trees in old growth forest on Asik plots 7 through 11 (the Spruce Slope Transect).

Figure 16. Sparse white spruce forest near treeline, view from Asik plot 14. The growth form of the tree on the left was due to abrasion by blowing snow: long branches covered by needles near the ground, few needles up to about 0.5 m height, and a normal conical crown above that.

Wrench Creek Node

<u>Floodplain Transect</u>
Trees on the Floodplain Transect dated from the late 1900s in the forest near the active river channel (plot 18 in Figure 17), and from the early 1900s in the forest farther from the active channel (plot 20 in Figure 17). As would be expected, the older trees (plot 20: 7.6 to 9.0 m) were taller than the younger trees (plot 18: 3.9 m to 4.9 m; Table A1). All trees suitable for coring were white spruce. Seedlings were abundant (Table A2).

<u>Spruce Slope Transect</u>
As was the case at Asik, the mountain slope white spruce forests were the oldest in the area. At Wrench Creek they were not as ancient as at Asik, but nonetheless there were 6 trees more than 200 years old spread across three plots (plots 9, 10, and 11; Figure 18). These old trees ranged from 5.4 m to 10.3 m tall (Table A1). Trees on plots 9 and 11 (which are most clearly old-growth forest) were predominantly less than 25 cm in diameter (Figure 19). Seedling density exceeded the density of trees greater than 1.37 m tall on most plots (Table A2).

<u>Alpine Slope Transect</u>
On the Alpine Slope Transect trees were present only at the lowest plot (15), where the two available trees dated from the 1950s (Figure 18) and were 6.3 and 8.0 m tall (Table A1). Trees here were very sparse, with just one present in the plot.

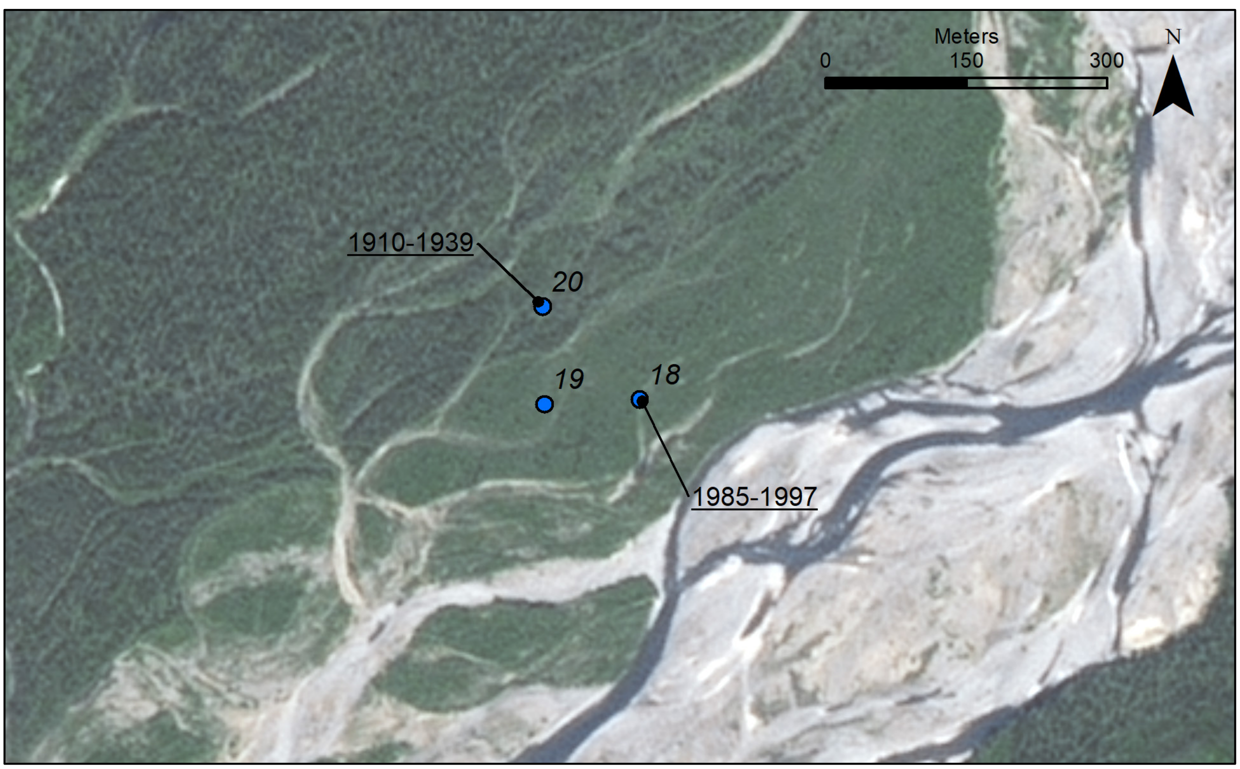

Figure 17. Pith years of trees on the Floodplain Transect of the Wrench Creek node. See Figure 7 for the transect location.

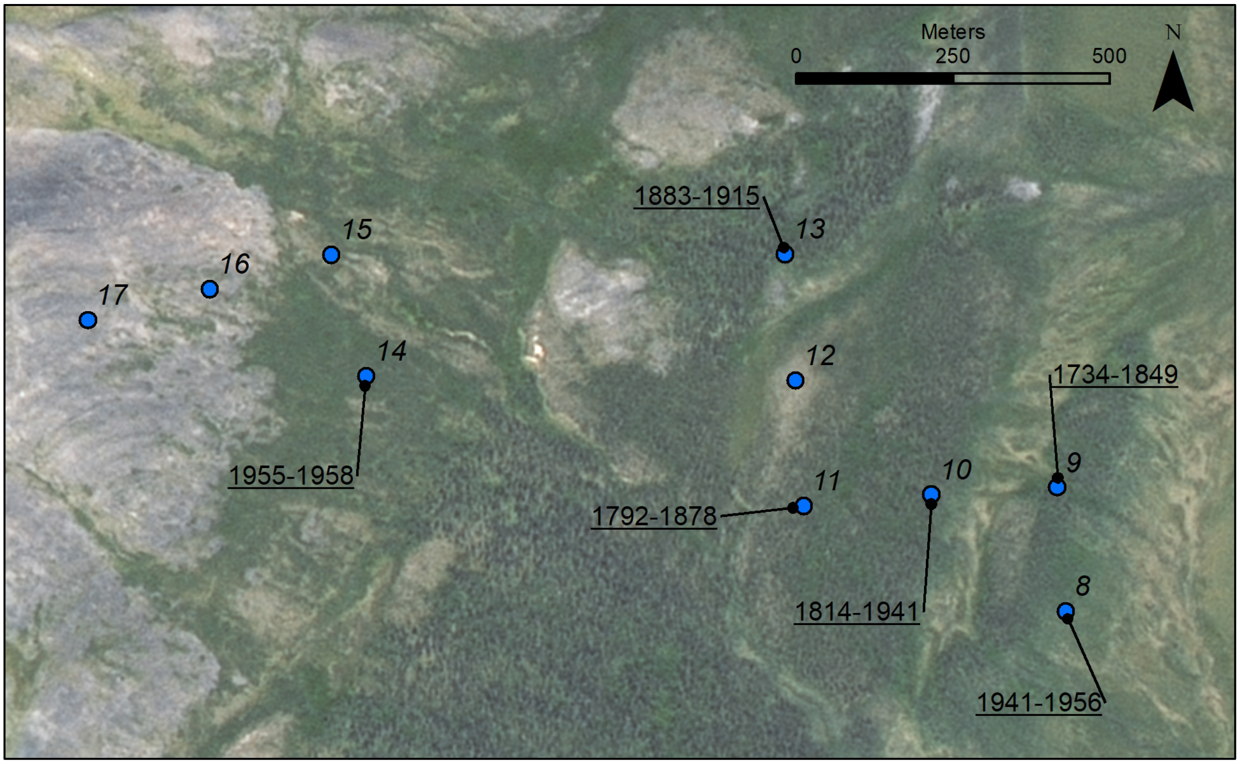

Figure 18. Pith years of trees on the Spruce Slope (plots 8 through 13) and Alpine Slope (plot 14) Transects of the Wrench Creek node. See Figure 7 for the transect location.

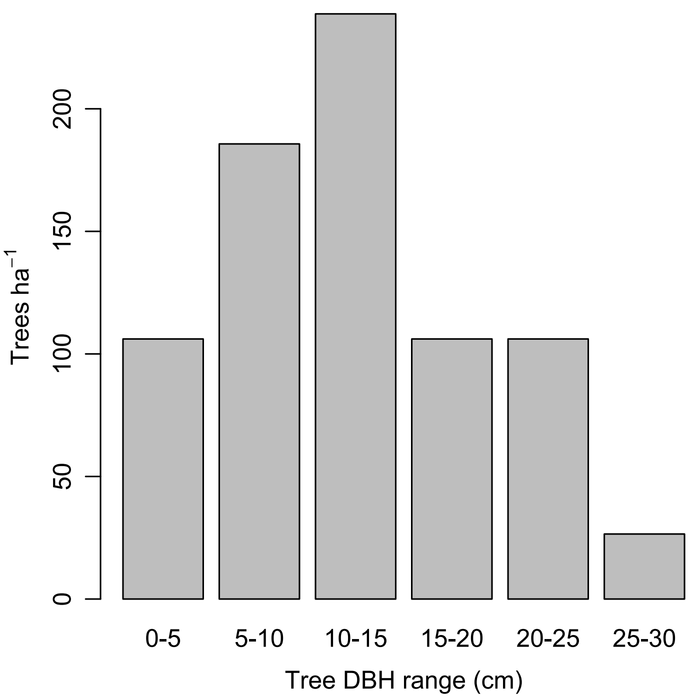

Figure 19. Diameter distribution of old growth forest at the Wrench Creek node, Spruce Slope Transect, plots 9 and 11.

Tussock Plain Transect

Most of the trees on the Tussock Plain Transect dated from the 1900s (Figure 20) and were 6–10 m tall (Table A1). One tree was distinctly older, from 1835. Similar to the Tussock Slope Transect at Asik, trees here occurred in small groves on favorable sites, and the cored trees ranged in height from 4.0 to 10.1 m. The 1835 tree was the tallest, but not by much as several others were 8 to 9 m tall. Seedling density exceeded the density of trees greater than 1.37 m tall on most plots.

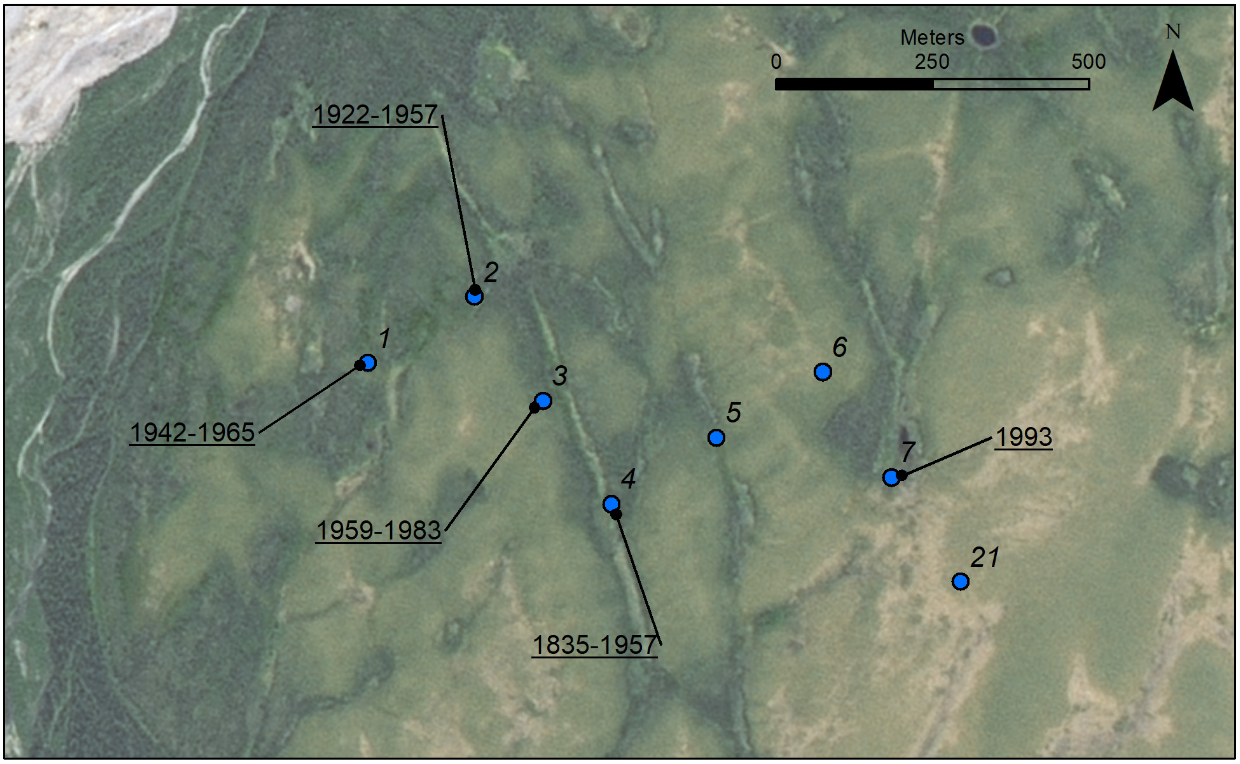

Figure 20. Pith years of trees on the Tussock Plain Transect of the Wrench Creek node. See Figure 7 for the transect location.

Kagvik Creek Node

The core-able trees at the Kagvik Creek node were all on the Floodplain Transect and all balsam poplars. Pith ages ranged throughout the 1900s (Figure 21). Heights of the cored trees ranged from 4.1 m to 9.3 m (Table A1). The tallest tree (9.3 m) was actually not very old, with a pith date of 1984 at 29 cm above the ground. Small trees less than 10 cm diameter dominated (Figure 22), but seedlings were not abundant, generally fewer per hectare than trees more than 1.37 m tall (Table A2). Note that the term “seedling” here is a bit misleading, because most young poplars originate as sprouts from roots.

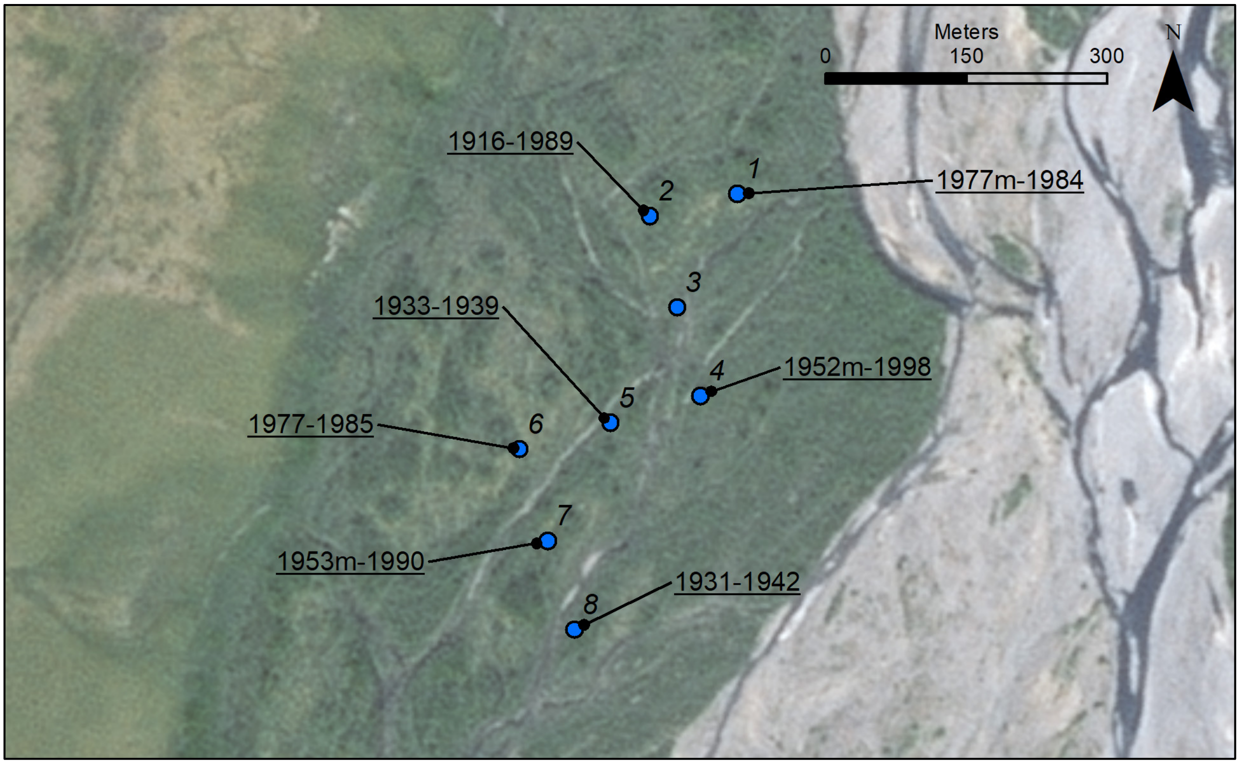

Figure 21. Pith years of trees on the Floodplain Transect of the Kagvik Creek node. An "m" indicates the pith age could not be estimated; the age is that of the oldest ring on the core, and the tree is actually older by an unknown amount. See Figure 8 for the transect location.

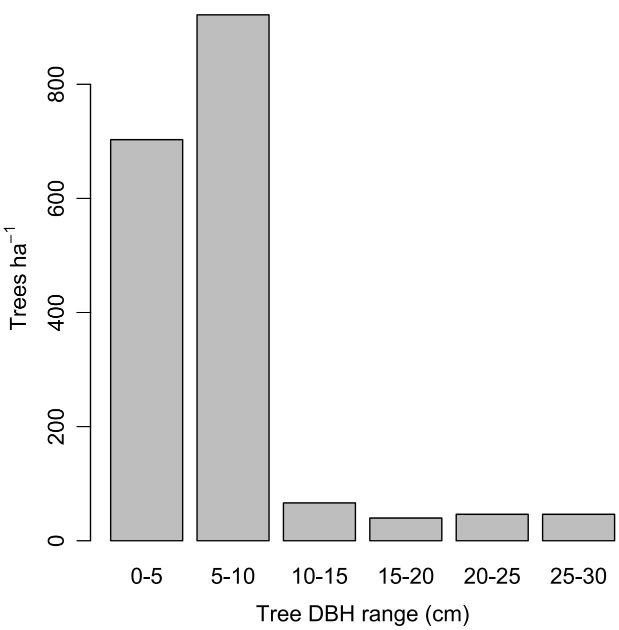

Figure 22. Diameter distribution of balsam poplar trees on the Floodplain Transect of the Kagvik Creek node.

Tree Growth Rates

Long-term Radial Growth Rates by Landform Type

The long-term tree radial growth rates differ by the landform types. At the Asik node, The Mountain Slope trees were very old but had slow growth rates, many less than 0.5 mm yr^{-1} (Figure 23). Some of the Tussock Slope trees grew faster; note how the oldest one (left-most yellow line in Figure 24) increased its growth rate greatly around 1970. The Terrace trees (blue) were young and grew more rapidly, about 1.5 mm yr^{-1}. Most treeline trees ("mountain slopeTL", brown lines) grew slowly at first but picked up the pace in the 2000 decade.

At Wrench Creek, trends were similar. The Spruce Slope trees grew faster here than at Asik, but were still generally slower-growing (and older) than the other landform types (Figure 23). The exception was the Spruce Slope trees that began life around 1950 and grew at rates close to 1.5 mm yr^{-1} in the 2000 decade. Most of the Tussock Plain and Floodplain trees grew relatively rapidly, around 1.5 mm yr^{-1}, though some of the floodplain trees showed conspicuously slowing growth rates in the past 20 or 30 years. And again, the treeline trees (Alpine Slope Transect) suddenly began to grow much faster around the year 2000.

At Kagvik Creek, all cored trees were balsam poplars on a floodplain (Figure 25). The trees that became established around 1950 had moderate growth rates or growth rates that slowed with time. The younger trees that started growing around 2000 generally showed growth rates increasing to about 1.5 mm yr^{-1}.

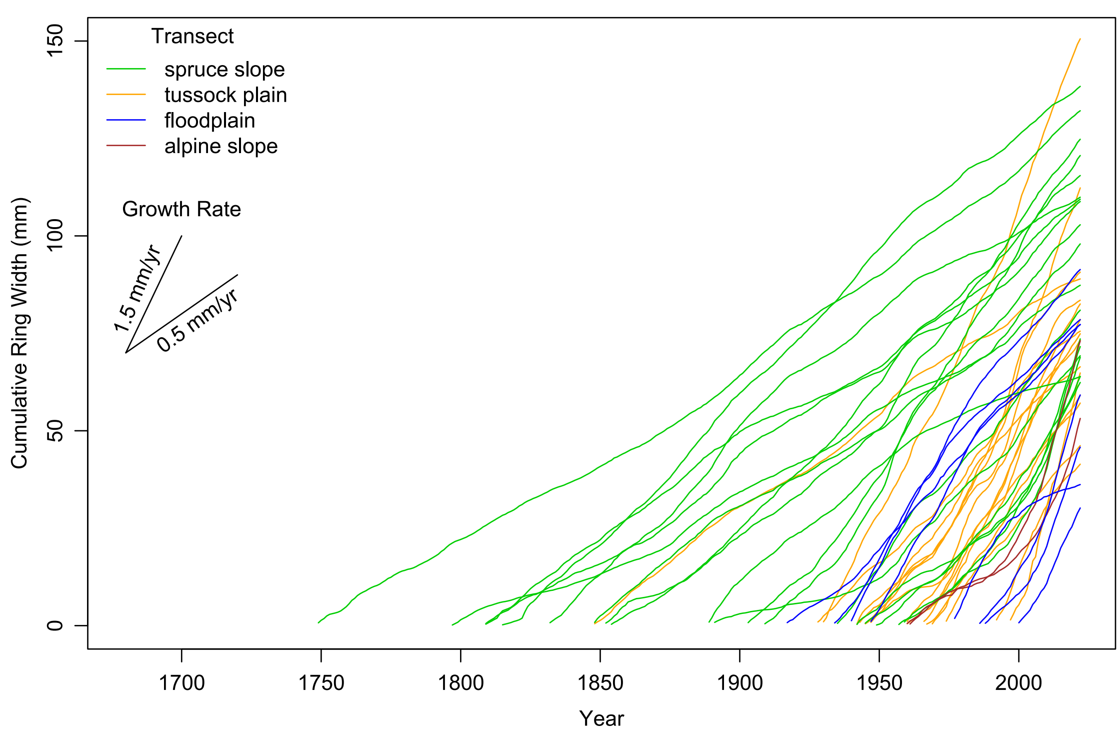

Figure 23. Cumulative tree ring width of white spruce vs. year at Wrench Creek.

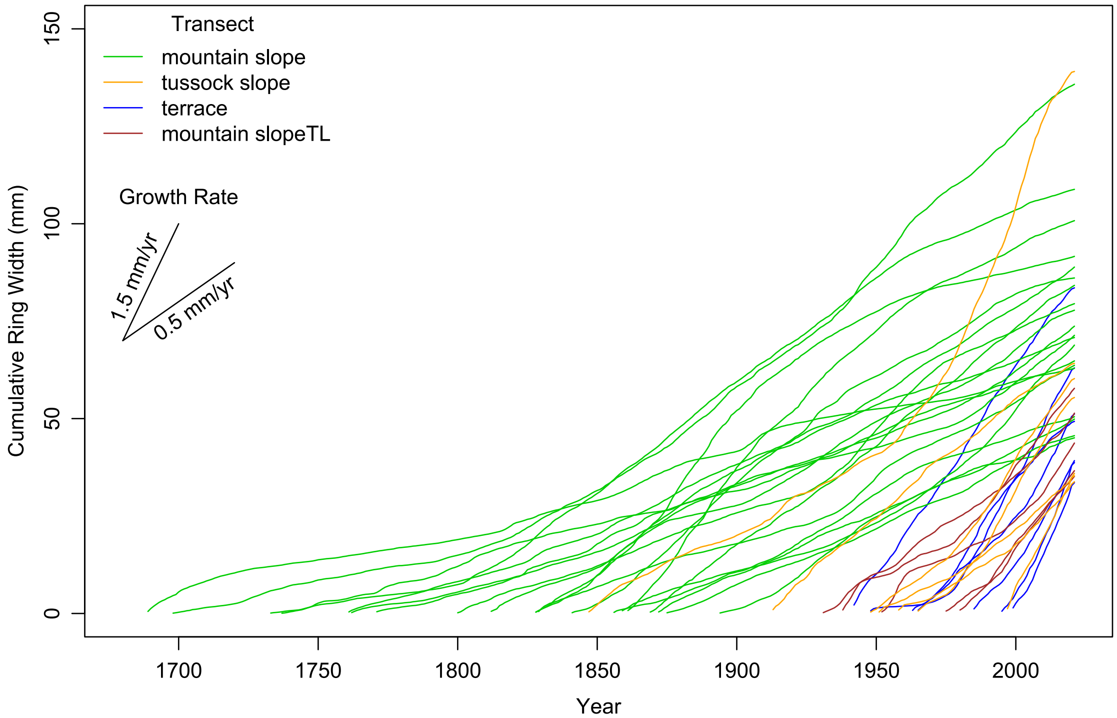

Figure 24. Cumulative tree ring width vs. year of white spruce at Asik. “mountain slope TL” refers to the treeline plots on the Mountain Slope Transect, plots 13 and 14.

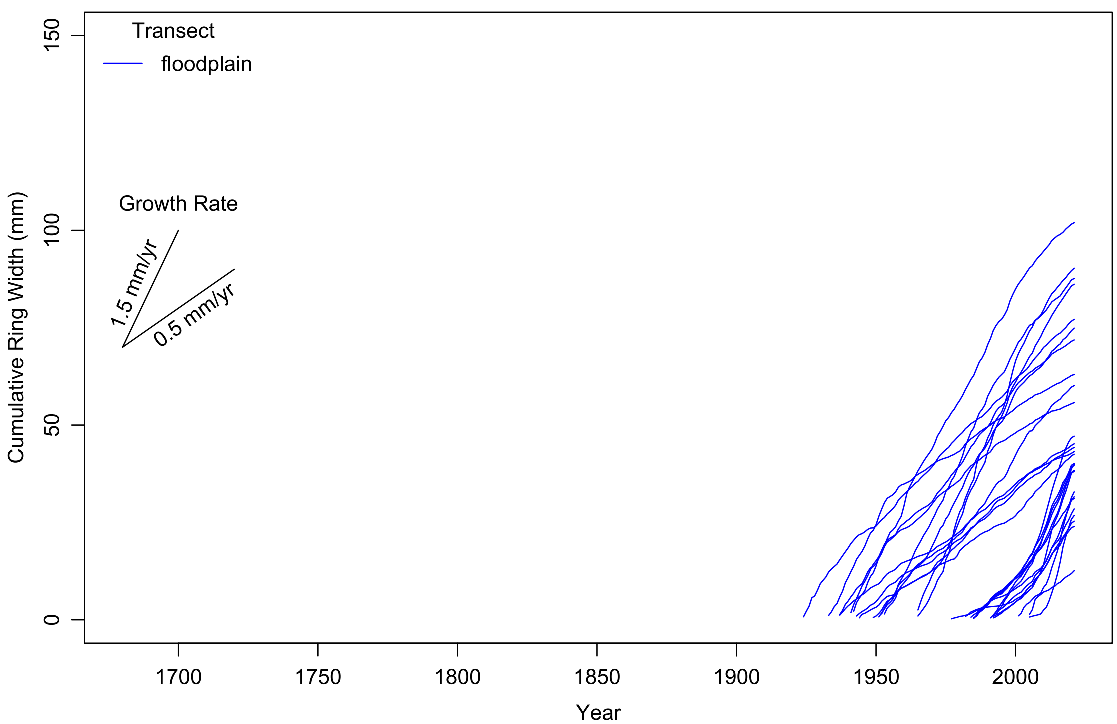

Figure 25. Cumulative tree ring width of balsam poplar trees vs year at Kagvik Creek.

Tree Heights and Ages

Simple plots of tree height vs. age suggest slow height growth that varies modestly by location and landform (Figures 26 to 28). Height growth appears to be a little faster on terrace, floodplain, and, surprisingly, the lowland tussock landforms than on the mountain slope landforms where the old-growth trees are. The balsam poplar trees at Kagvik Creek appear to accomplish most of their height growth in the first 20 years after they reach coring height (20–40 cm).

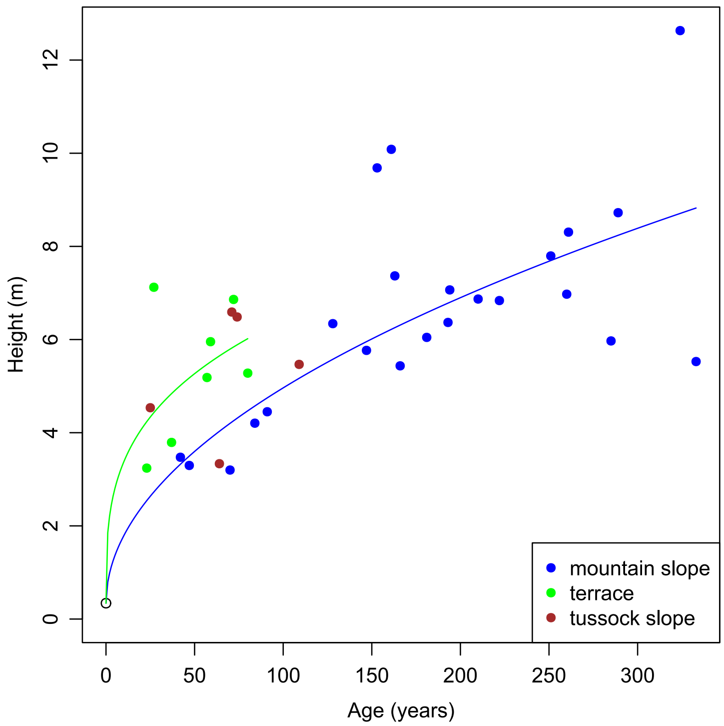

Figure 26. Tree height vs. pith age at Asik. Trendlines are of the form $x = ay^b$, where x is tree height, y is the pith age in years, and a and b are regression coefficients.

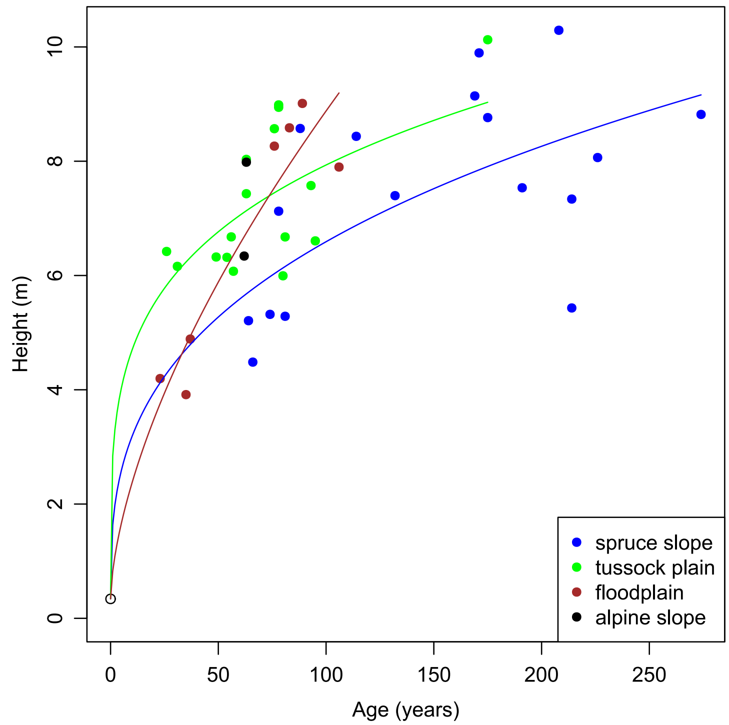

Figure 27. Tree height vs. pith age at Wrench Creek. Trendlines are of the form $x = ay^b$, where x is tree height, y is the pith age in years, and a and b are regression coefficients.

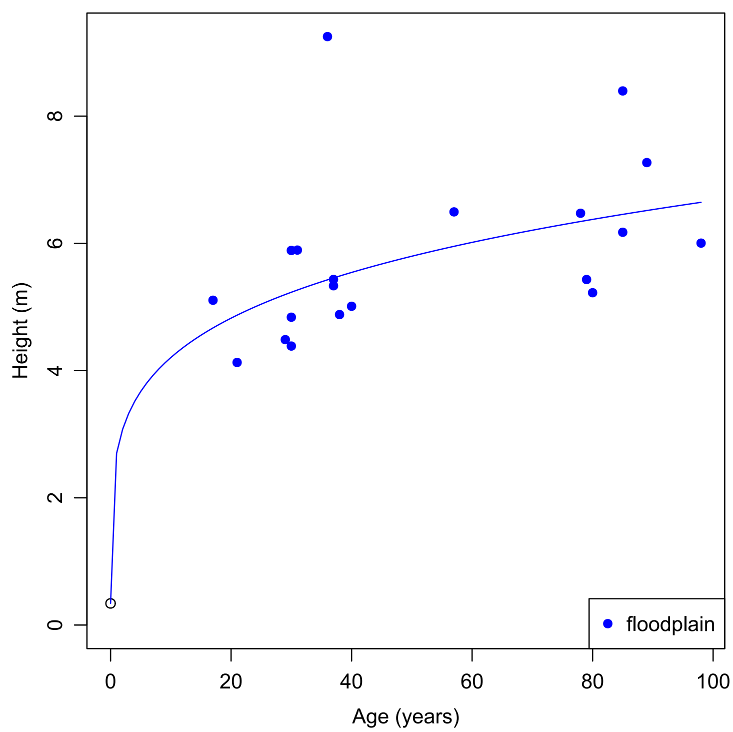

Figure 28. Tree height vs. pith age at Kagvik Creek. The trendline is of the form $x = ay^b$, where x is tree height, y is the pith age in years, and a and b are regression coefficients.

Tree basal area growth between 2011 and 2021–2022

The diameter growth observed in the cores resulted in overall increase in tree basal area over most of the study area between our two plot visits (Figure 29 and Table A2). The largest growth in basal area was on the floodplains at Kagvik Creek and Wrench Creek, and the Spruce Slope Transect at Wrench Creek.

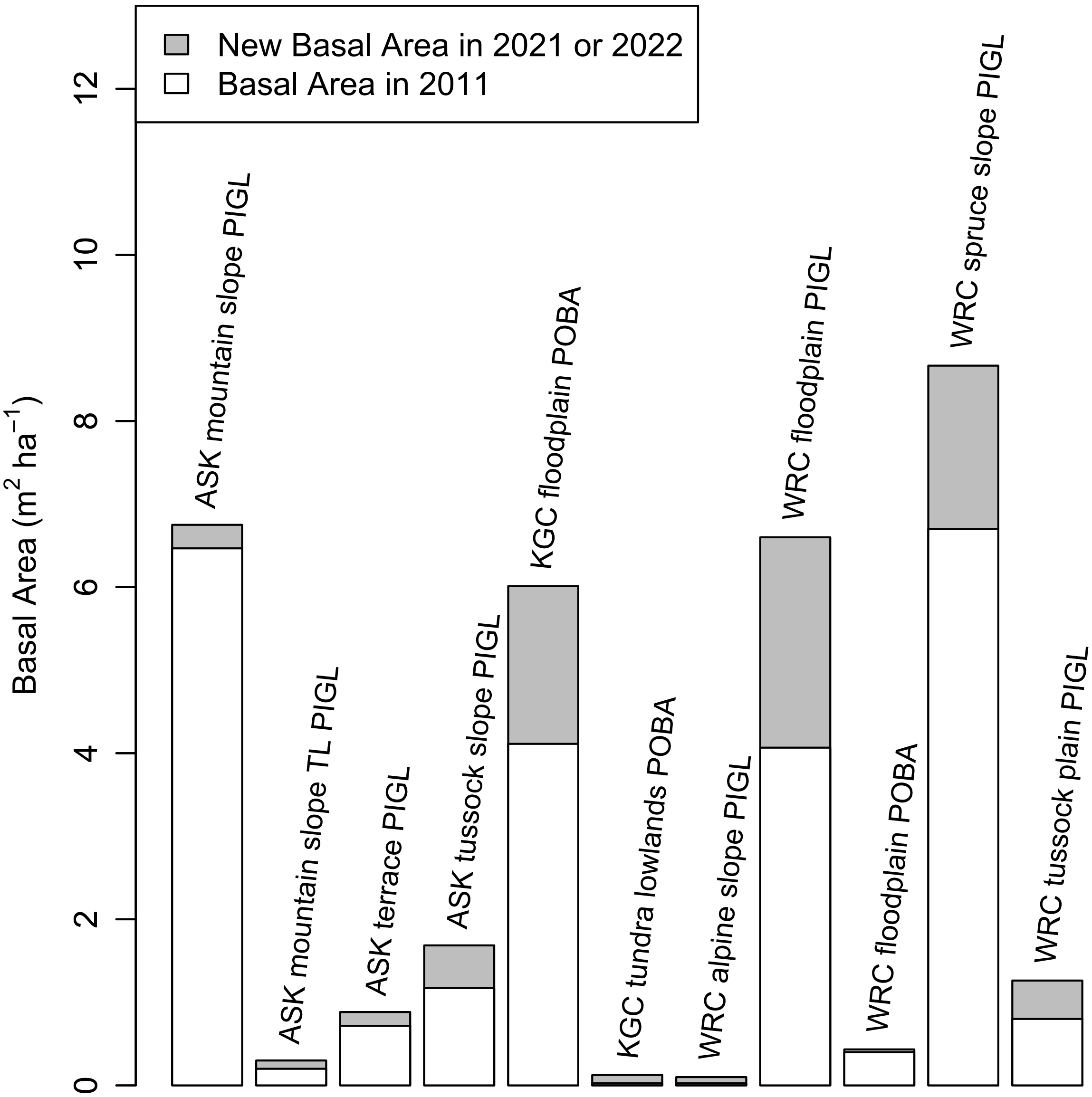

Figure 29. Average basal area by transect in 2011 and at the time of resampling (2021 for ASK and KGC, 2022 for WRC).

Variations in Ring Width Over Time

Ring wide histories

Years with consistently wide or narrow rings using the ring widths are visible on plots of ring widths vs. year (Figures 30–33). These plots summarize multiple cores that were normalized using the 50-year smoothing spline. Normalization removes the long-term trend in tree growth rate, which can be due to local factors such as tree age and competition, or (unfortunately) global factors like long-term climate change. Figures 30 through 33 summarize normalized ring widths for all of the trees on each transect. The median ring width is shown by the black line, and the shaded region shows the 20th- to 80th-percentile range in normalized ring width. The dashed horizontal lines at 0.8 and 1.2 help identify the extremes, e.g., when the black line goes above 1.2, the median of all the trees on the transect had growth rates of more than 1.2 times the long-term value (50-year spline) for each individual tree. To understand the potential causes of the years with thin rings (i.e., poor growth), I have marked the years known to have had global cooling effects in the Northern Hemisphere due to volcanic eruptions, and also the four coldest summers since 1943 (when consistent records began at Kotzebue), based on the annual sum of thaw-degree-days in Kotzebue.

The Slope Transects

On the two Spruce Slope Transects (Figure 30), the long-term record allows us to judge the effect of multiple volcanic eruptions, and they are not very impressive. The 1991 Mt. Pinatubo eruption was probably not the cause of poor growth in 1994–1995, because the time lag was too long. The 1912 Novarupta (in Katmai National Park) and 1883 Krakatoa eruptions coincided with a short dips in growth that were no deeper than other non-volcanic dips within a few decades before and after the eruptions. The 1815 Tambora eruption, famous for the 1815 “Year without a summer” in Europe, had the clearest effect on tree growth, especially on the Spruce Slope Transect at Wrench Creek. Interestingly, the poor growth year was the following year, 1816. The effect of the 1783 Laki eruption was again ambiguous, as it appears that poor growth began before the eruption.

The effect of cold summers was apparent but not highly impressive either: 1975, the coldest summer in Kotzebue since records began in the 1940s, was associated with a brief dip in ring growth, though at Wrench Creek bad years in adjacent decades were worse. The two cold summers in the 1940s occurred during a time of declining productivity that bottomed out in 1949. The cold summer of 2000 had no obvious ill effects.

The Tussock Transects

The shorter record from the tussock transects (Figure 31) shows a generally similar story. The Mt. Pinatubo eruption had no immediate effect, while the Novarupta eruption was visible on the two available trees and Krakatoa on one. Productivity fell during and after the cold summers of the 1940s, other cold summer had mixed effects.

The Terrace and Floodplain Transects

These short time records (Figure 32) show no obvious relationship to the volcanoes or cold summers. One interesting commonality is the poor growth in 1994–1995, which is apparent in the transects on other landforms also.

Treeline Transects

The decline in growth in the 1940s was visible on the treeline plots (Figure 33), while other cold years and Mt. Pinatubo's eruption had ambiguous effects.

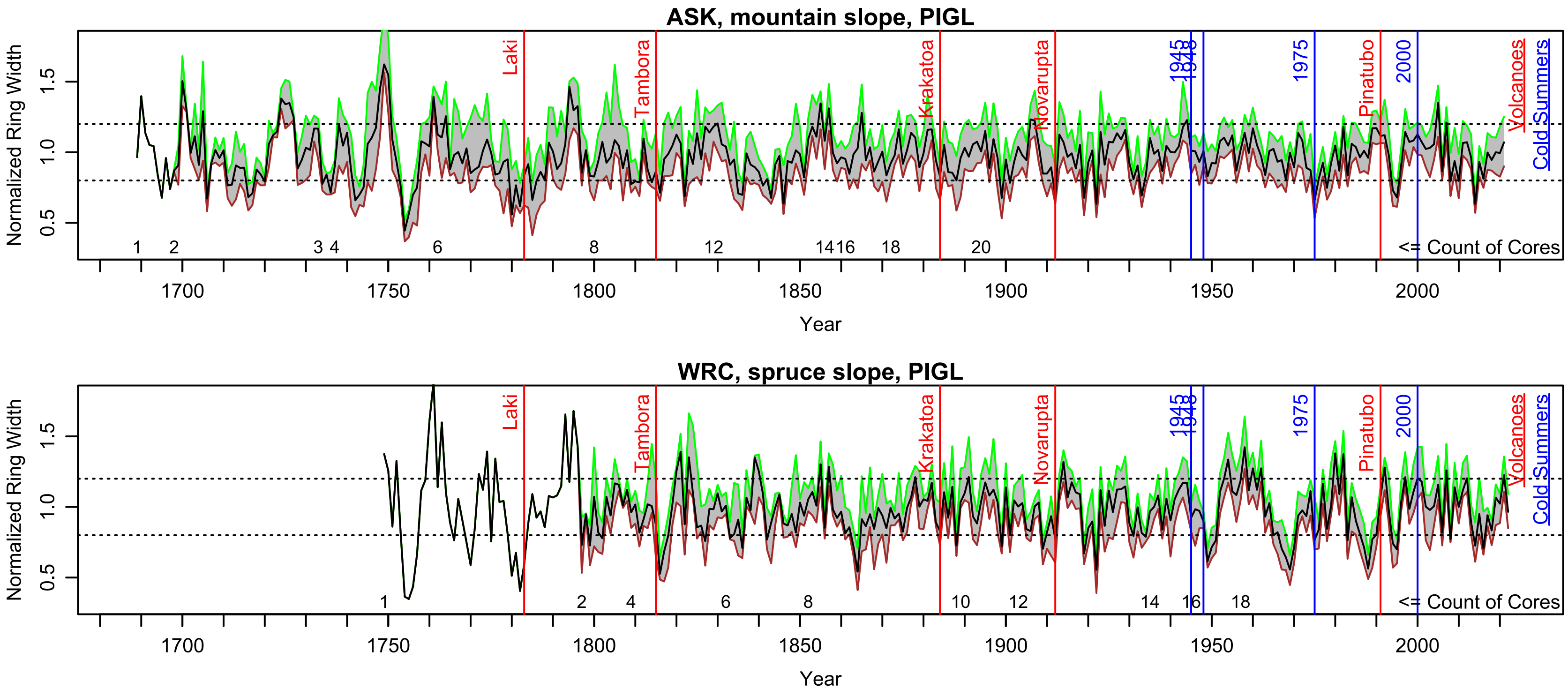

Figure 30. Normalized white spruce (PIGL) tree ring widths vs. year on the mountain slope transects Asik (ASK) Mountain Slope and Wrench Creek (WRC) Spruce Slope. The black line is the median of the normalized ring widths, with the count of cores arrayed along the bottom of the plot. The gray area portrays the range of 20th to 80th percentile values. Vertical lines show major volcanic eruptions (in red) and the four historical coldest summers in Kotzebue (blue).

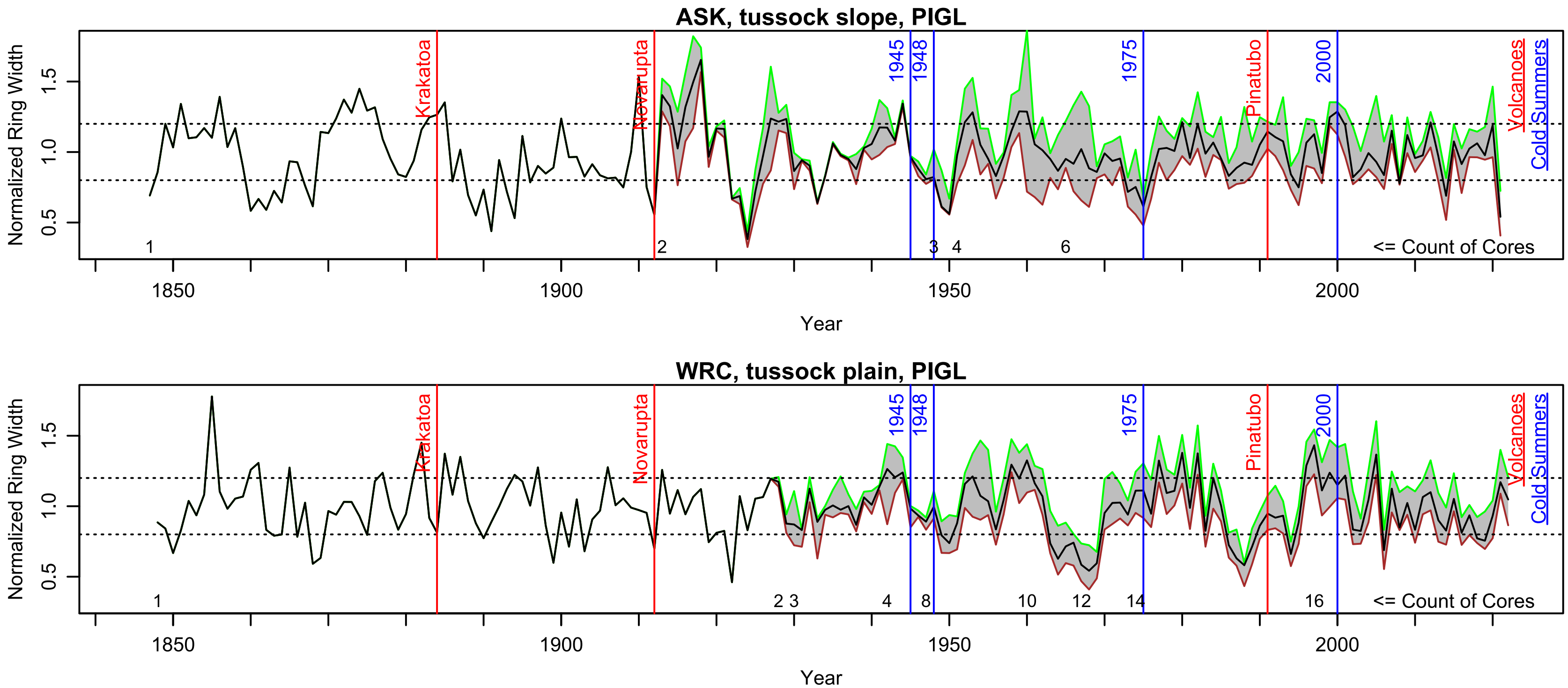

Figure 31. Normalized white spruce (PIGL) tree ring widths vs year on the tussock transects Asik (ASK) Tussock Slope and Wrench Creek (WRC) Tussock Plain. The black line is the median of the normalized ring widths, with the count of cores arrayed along the bottom of the plot. The gray area portrays the range of 20th to 80th percentile values. Vertical lines show major volcanic eruptions (in red) and the four historical coldest summers in Kotzebue (blue).

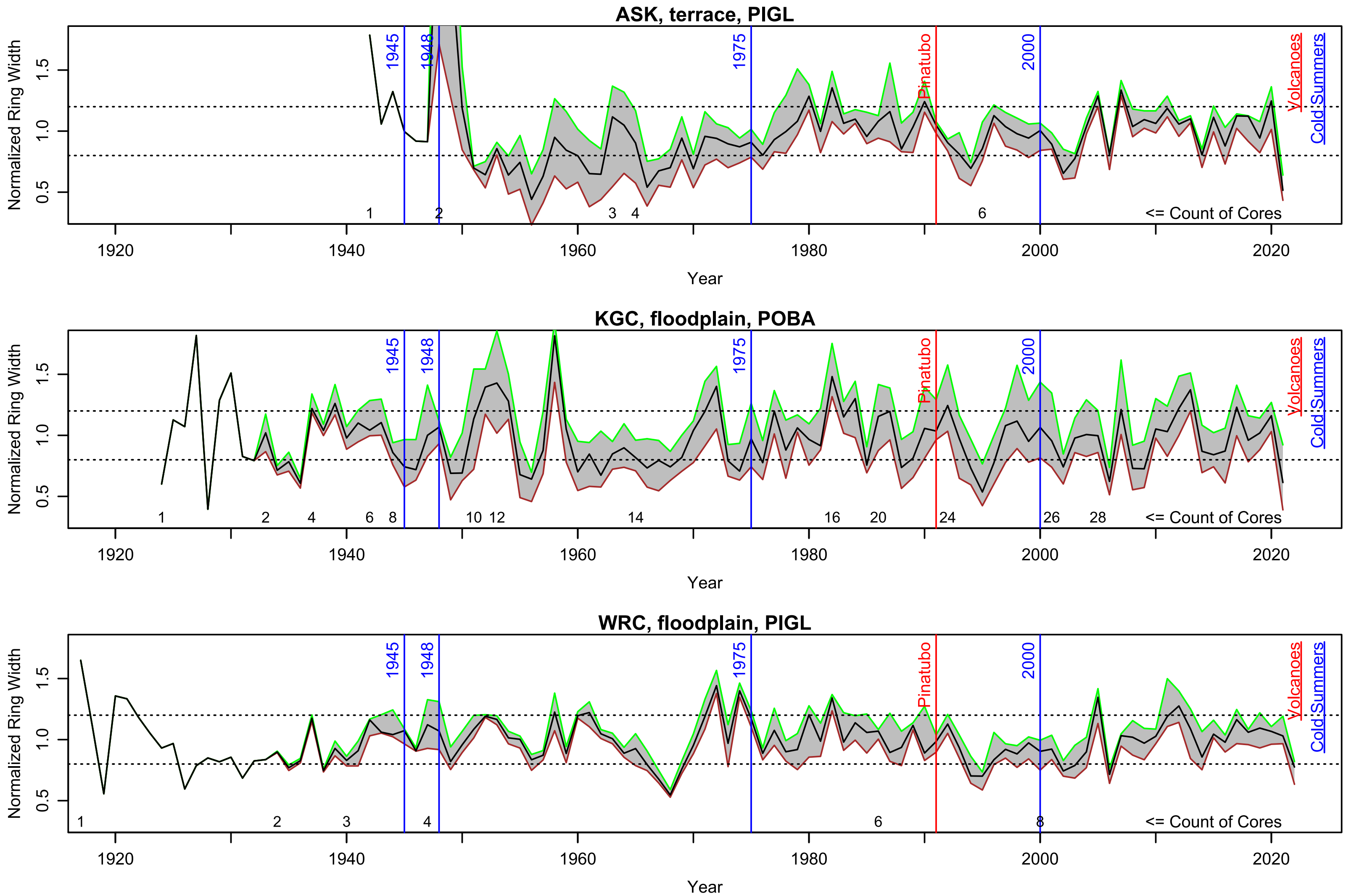

Figure 32. Normalized tree ring widths vs. year on the floodplain and terrace transects. White spruce (PIGL) at Asik (ASK) and Wrench Creek (WRC), balsam poplar (POBA) at Kagvik Creek (KGC). The black line is the median of the normalized ring widths, with the count of cores arrayed along the bottom of the plot. The gray area portrays the range of 20th to 80th percentile values. Vertical lines show major volcanic eruptions (in red) and the four historical coldest summers in Kotzebue (blue).

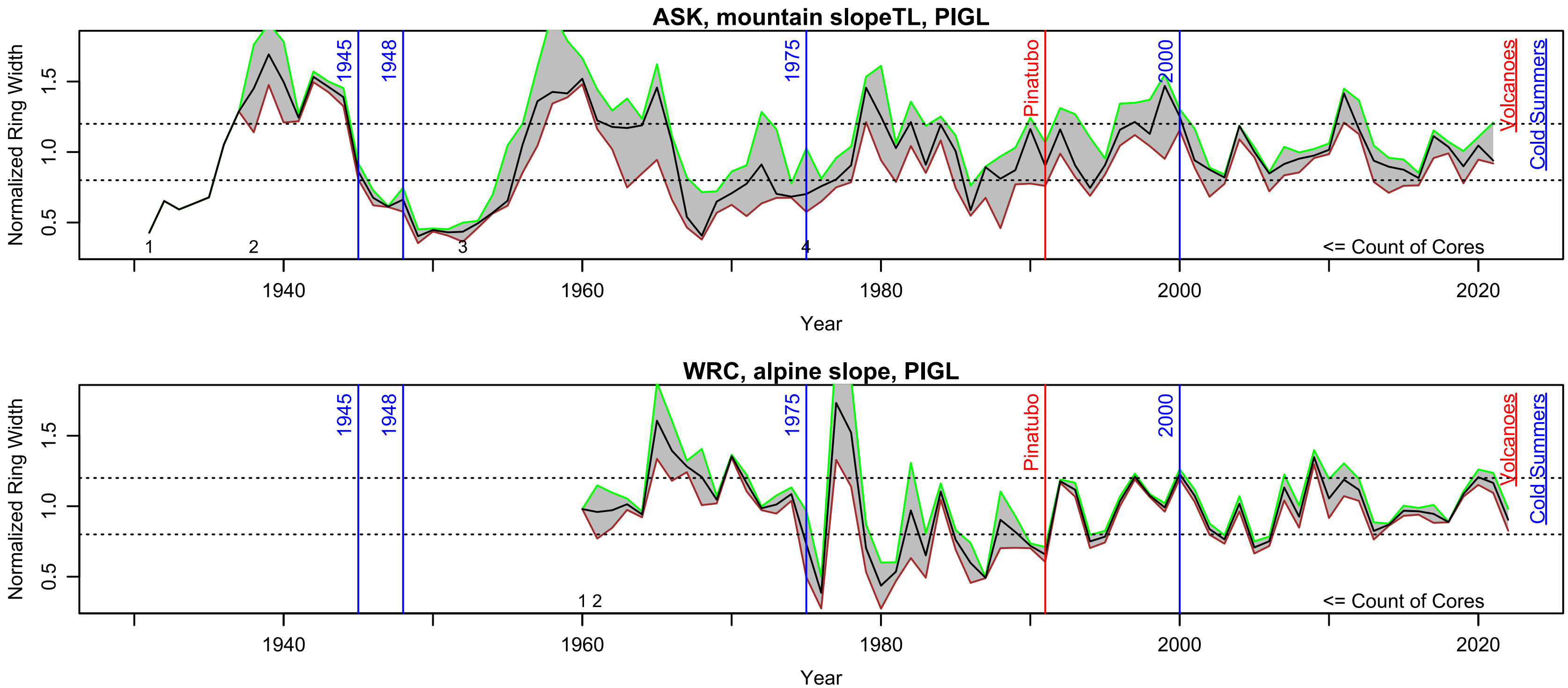

Figure 33. Normalized white spruce (PIGL) tree ring widths vs. year on the treeline plots: Asik (ASK) Mountain SlopeTL (plots 13 and 14) and the Wrench Creek (WRC) Alpine Slope Transect. The black line is the median of the normalized ring widths, with the count of cores arrayed along the bottom of the plot. The gray area portrays the range of 20th to 80th percentile values. Vertical lines show major volcanic eruptions (in red) and the four historical coldest summers in Kotzebue (blue).

Tree Rings and Summer Warmth

A comprehensive test of climate-tree ring relationships was beyond the scope of this investigation, but I tested one climatic relationship that was suggested by inspection of the ring width plots in the previous section: the relationship between summer warmth (as expressed by thaw degree-days) and ring width. Of special interest is the implication from inspection of the ring width time series that individual, isolated warm or cold summers do not matter greatly, but multi-year cold or warm spells may be important.

As was suggested by simple inspection of ring widths in the preceding section, ring width was indeed weakly correlated with summer warmth in the year the ring formed ("yr0" in Figure 34). In fact, nearly 40% of the trees had negative correlation with TDD in "yr0", meaning that those trees grew less during warm summers than cold summers. However, very few of those correlations, either positive or negative, were statistically highly significant.

Correlations of ring widths with the preceding year's summer warmth ("yr1" in Figure 34) were a little stronger, with about 70% of cores showing a positive response to TDD; however, only about 6% had highly significant positive correlations ($p < 0.05$). Tree ring width was related more strongly to summer warmth averaged over multiple preceding summers: correlations of ring width to weighted averages of TDD extending from the preceding year (year 1) out to years 3, 4, 5, and 6 showed positive relationships with 74 to 83% of all cores, and 28 to 32% of all correlations were both positive and highly significant at $p < 0.05$ (see the bars labeled "yr1-3", "yr1-4", etc. in Figure 34).

To investigate which trees had positive or negative relationships with temperature, I took the regressions for ring width vs. the weighted average of TDD from preceding years 1, 2 and 3 (the "yr1-3" case in Figure 34) and summarized them by landform/transect (Figure 35) and soil drainage class (Figure 36). Positive relationships with temperature still dominated these various subclasses. The strongest positive relationships with temperature were found at the Wrench Creek Spruce Slope and Tussock Plain Transects, where nearly half were significantly ($p < 0.05$) positive. Trees that had negative correlations with temperature were concentrated on the ASK Mountain Slope and KGC Floodplain Transects, and they were on drier sites (well to excessively drained, Figure 36).

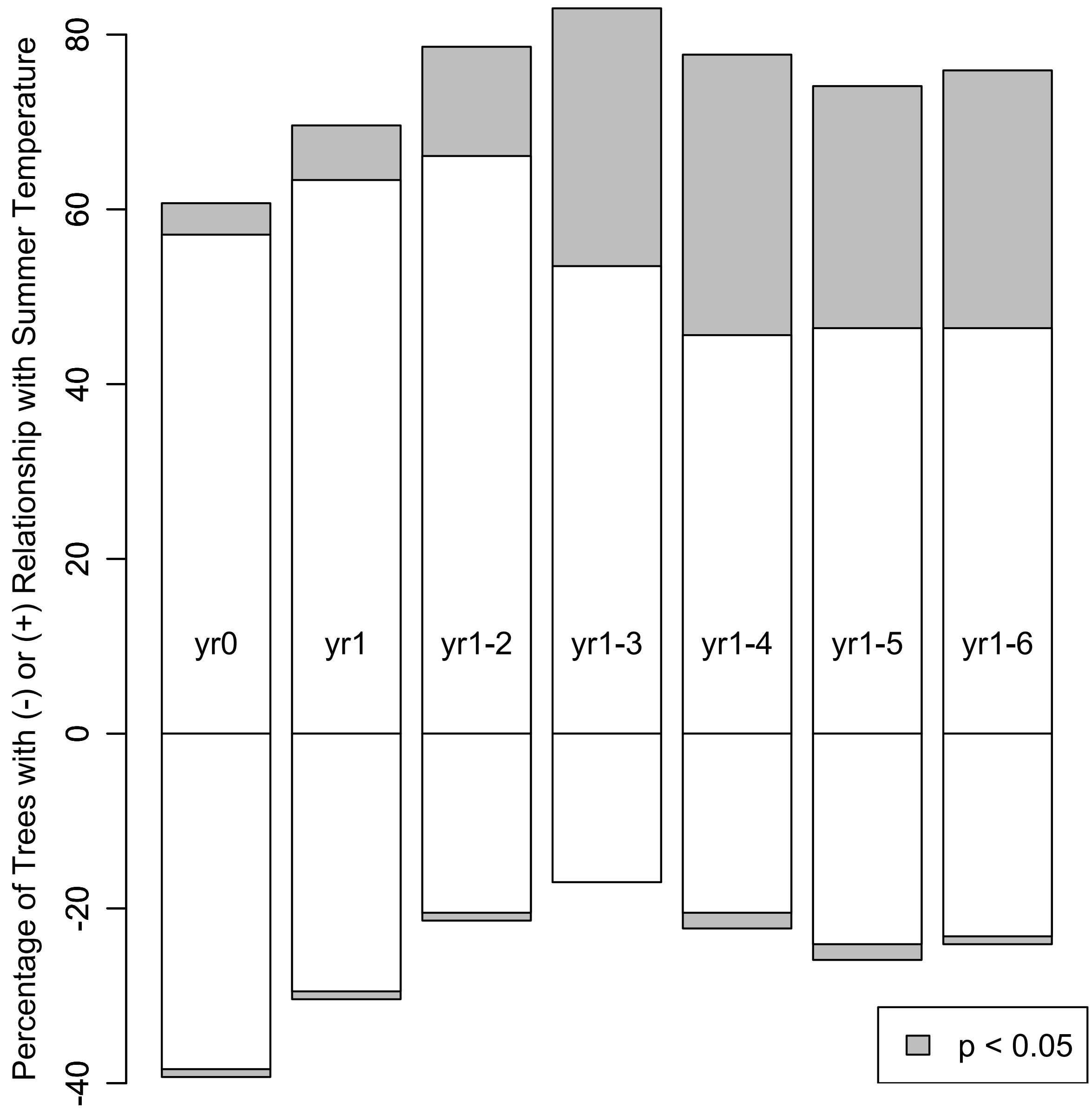

Figure 34. A test of the relationship between tree ring widths and summer temperatures as expressed by the annual sum of thaw degree-days at Kotzebue, for the years 1943 through 2022. The bars display the percentage of individual trees with positive (above the zero line) or negative (below the zero line) linear correlation with TDD. The shaded portions of the bars portray the percent of the regressions that were highly significant ($p < 0.05$). The bar label "yr0" indicate regressions of ring with vs. the current year sum of TDD, "yr1" is the preceding year's TDD. The other bars "yr1-2", "yr1-3", etc. summarize correlations of ring width with multi-year weighted average TDD. These averages began with year 1 (the preceding year) and out to the years indicated by the 2nd digit, e.g., "yr1-3" was years 1 through 3. The years were weighted using a Gaussian (normal) curve to one standard deviation, i.e., the most distant year received a weight proportional to the height of the Gaussian bell curve at one standard deviation from the peak.

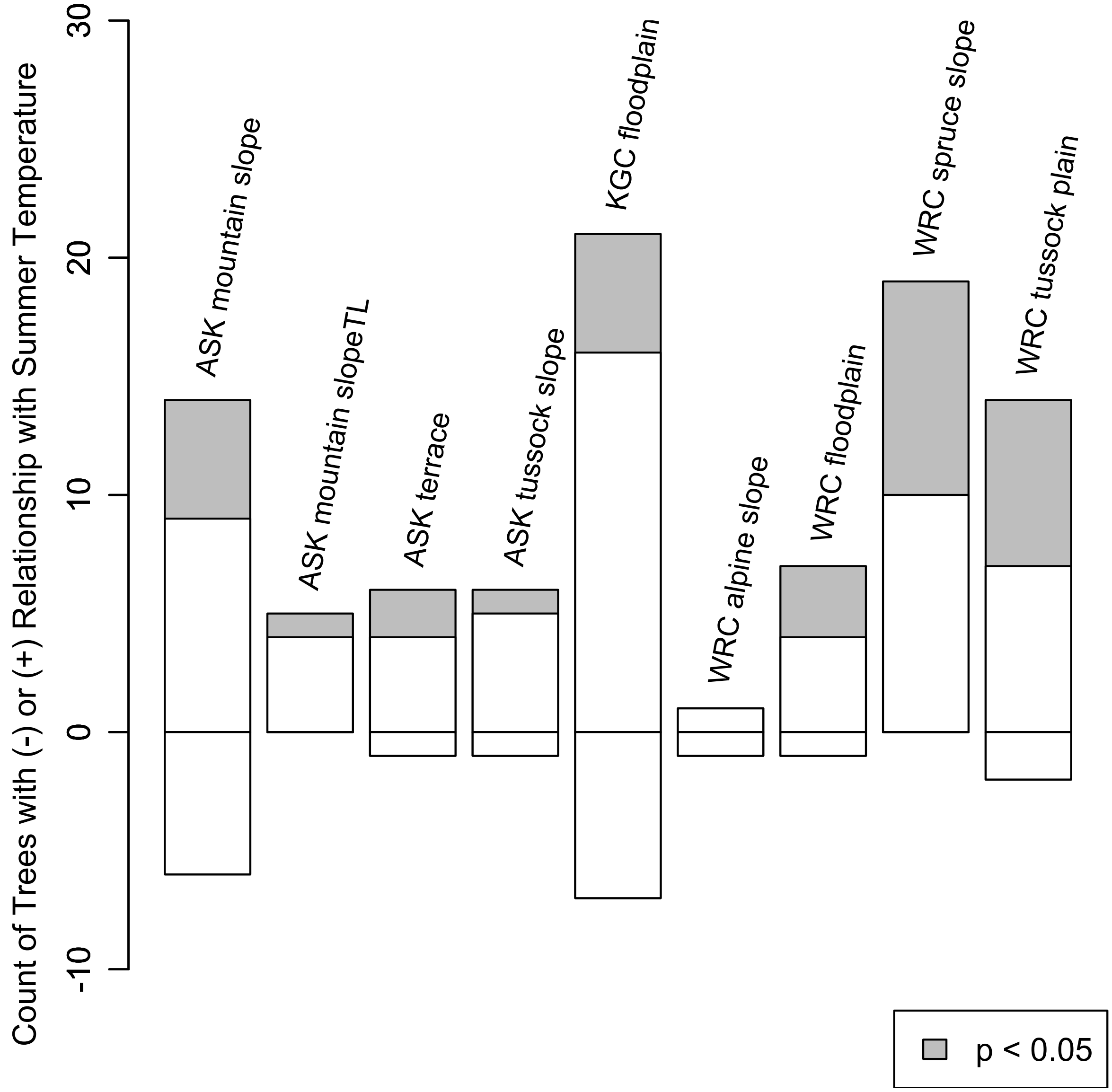

Figure 35. Relationship between tree ring width and summer warmth on individual landform-based transects. Normalized ring widths were regressed against the weighted average of TDD at Kotzebue for prior years 1, 2 and 3 ("yr1-3" in Figure 34, see it for further explanation).

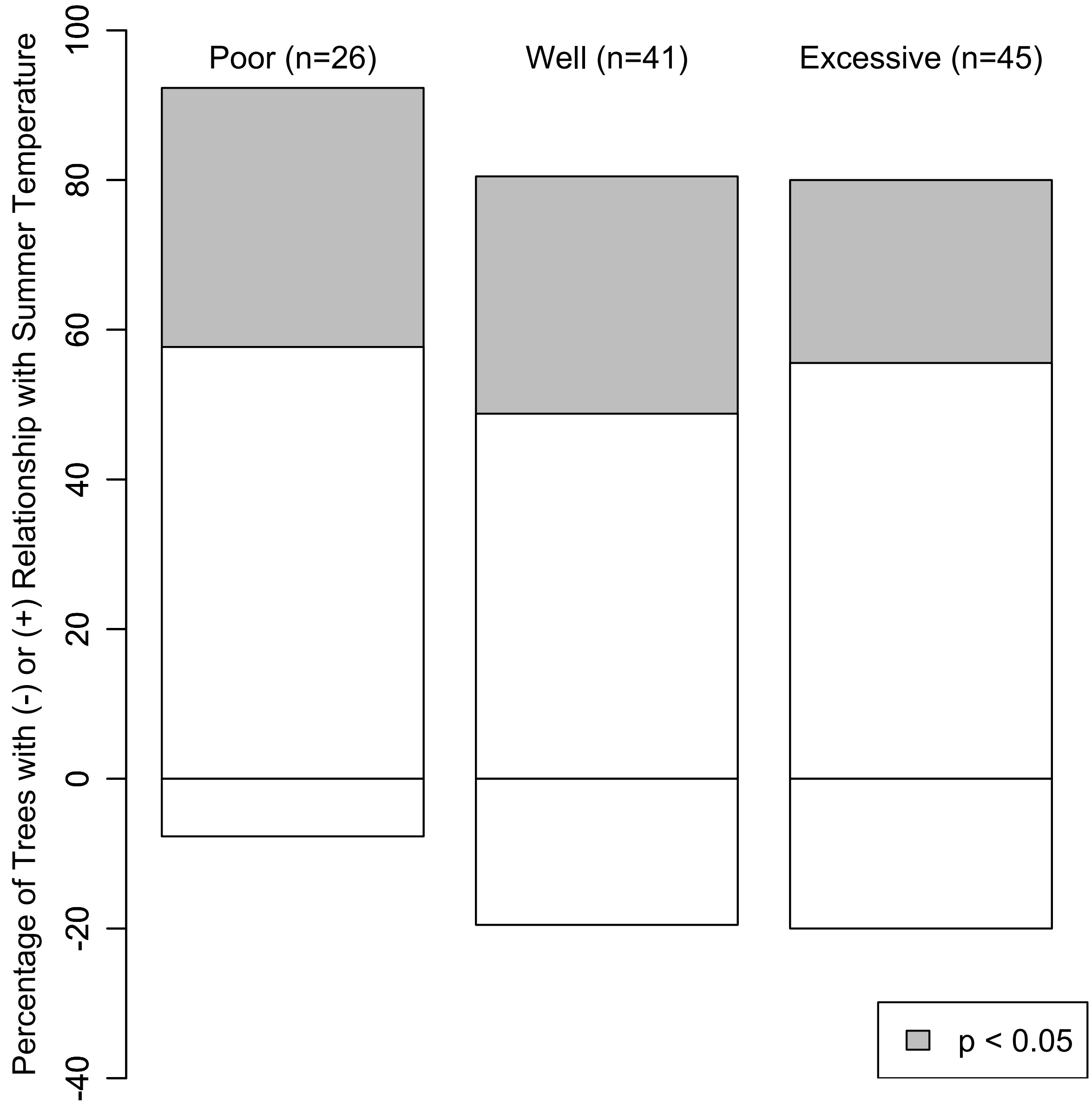

Figure 36. Relationship between tree ring width and summer warmth for different soil drainage classes. Normalized ring widths were regressed against the weighted average of TDD at Kotzebue for prior years 1, 2 and 3 ("yr13" in Figure 34, see it for further explanation). Soil drainage classes are *Poorly Drained* ("Poor"), *Moderately well to Well drained* ("Well"), and *Somewhat Excessively to Excessively Drained* ("Excessive"; Soil Survey Division Staff 1993 and Swanson 2015).

Discussion

Old Growth Forests

The hillslope white spruce at the Asik and Wrench Creek nodes easily meet the age definition of old growth white spruce established by the US Forest Service for the Chugach National Forest (150 years; USFS 2023). Rowland (1997) also found numerous trees in the Kelly River drainage (a few miles upstream of our Wrench Creek Node) and in the lower Kugururok River drainage (downstream of our Kagvik Creek node) that were over 200 years old. In her Kugururok study area, Rowland (1997) found 9 trees in excess of 300 years old, including two that were 400–410 years old. Suarez (1999) also found trees near our Asik node that were over 300 years old. Thus there are multiple stands of old-growth white spruce in the western Noatak National Preserve.

The cold climatic conditions of the study area clearly limit the size and growth rate of these trees, but not their longevity. Cold environments do not limit tree age: the oldest living trees in existence are bristlecone pines (*Pinus aristata*) that grow near treeline in California and Nevada (Ferguson 1969). White spruce in our environment lack one important limiting factors to their survival: competition from other trees. The only other tree species found here, balsam poplar, is not shade-tolerant, long-lived, or widespread in any environment except floodplains.

Disturbance prevents the development of old-growth forests in many environments, and in our study area river channel migration and wildfire are the most important disturbance processes. The age of white spruce forests is limited by river channel migration on floodplains, and hence the oldest trees we observed there were from the 1900s. Wildfire prevents old-growth forests from developing over much of Alaska, but not in our immediate study areas. This finding is interesting because wildfires have actually been quite common in the Noatak Valley during historic times (Figure 37) and over the past 2000 years (Higuera et al. 2011a, b). Higuera et al. (2011a, b) studied charcoal in lake cores in the Noatak Valley, including one location just 15 km southeast and another 25 km east of the Wrench Creek node. They found that over the past 2000 years the fire return interval ranged from 30 to 345 years, with a median of 150 years. Our tree-ring results show that there are places on the landscape where the vegetation and fuel conditions, microclimate, or presence of natural fire breaks have allowed old-growth forest to escape these rather frequent fires. Fires in the Noatak Valley are often light burns across tussock tundra, and the main fuels consumed are fine litter (Hudspith et al. 2017). Perhaps in our area weather conditions are typically sufficient to allow desiccation of these fine litter fuels to burnable levels, but not the shrub fuels that carry fires in our open forests.

The tree growth in the old-growth forests at Asik and Wrench Creek suggests that they are maintaining themselves and perhaps becoming more dense with time: both locations added basal area in the time between our visits in 2011 and 2021 or 2022, and there were many more seedlings than larger trees in the stands. Long-term monitoring will show whether increasing tree size and abundance is a long-term trend or a short-term one that will be interrupted by disturbance events such as windthrow, insects and disease, or fire.

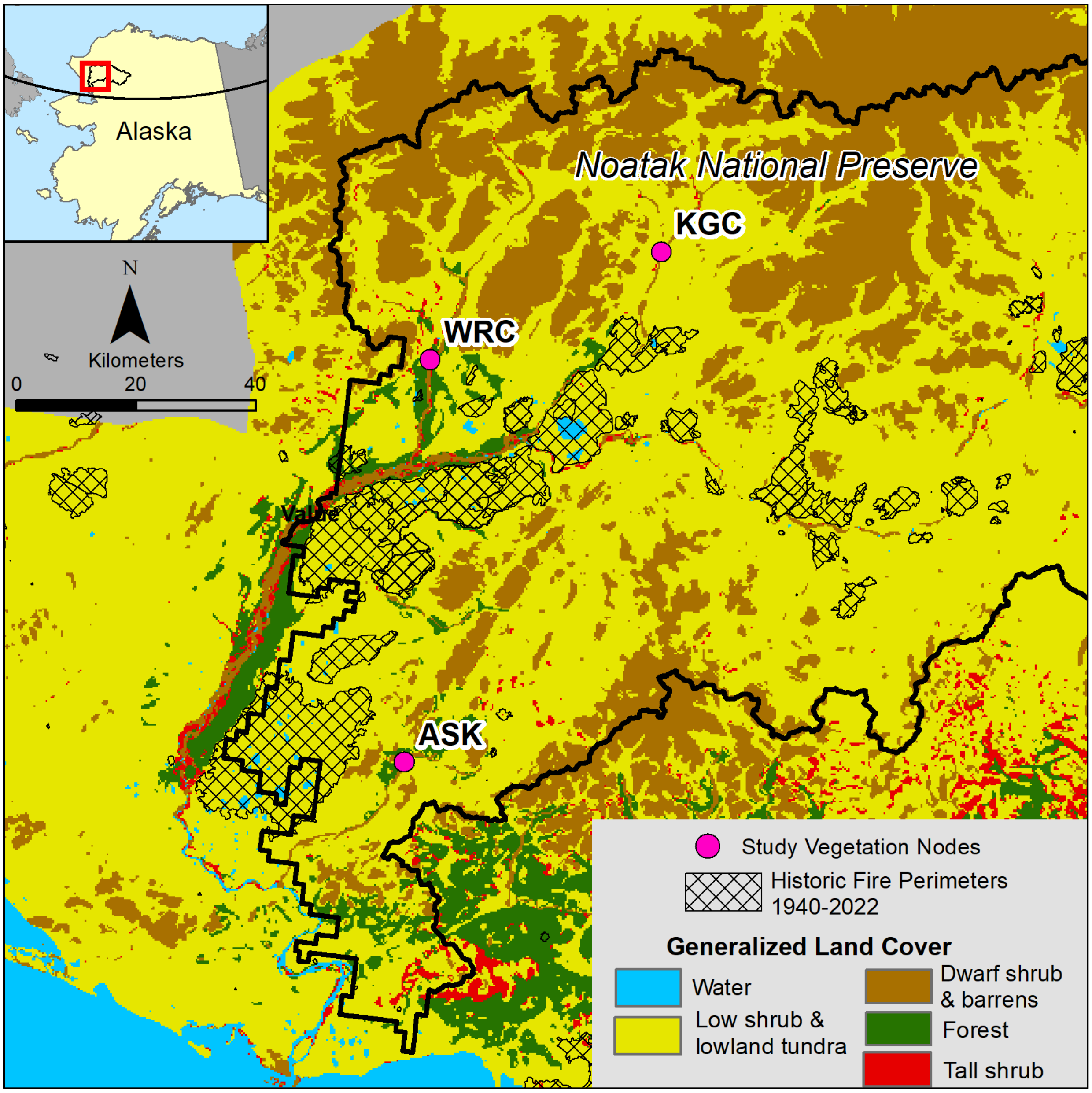

Figure 37. Historic wildfire perimeters in relation to forests in the Noatak National Preserve. The cross-hatched area shows the extent of wildfires in 1940 through 2022, from AICC (2023).

Expanding Forests

Younger forests occurred in our study areas on floodplains, at higher elevations near treeline on slopes, and locally on undulating tussock tundra.

New forests on floodplains and river terraces

Forests of varying ages on floodplains and river terraces are a normal consequence of river channel migration and tree colonization of new river bars (e.g., Viereck et al. 1993). Traditionally this was viewed as a dynamic equilibrium process, by which older forests are destroyed by river erosion at about that rate that new forests colonize and mature on new river bars. Our youthful floodplain forests thus could be mainly the result of dynamic equilibrium erosion-deposition-plant succession on river bars and not overall tree expansion. However, historical aerial photographs show that vegetation has expanded on river bars in Interior Alaska in recent decades (Frost et al. 2023), though in that study it was shrubs and not trees that expanded. My study of aerial photographs (Swanson 2013) in ARCN failed to detect net tree expansion on floodplains, but the sample size was too small to be conclusive. It is possible that forests are becoming more widespread or denser on floodplains as a result of warming, but the main reason that forests are relatively young on floodplains is still the youth of the surfaces that they are growing on. Seedling density and rates of growth in stand-wide basal area on floodplains show that the colonization and growth forests on floodplains is more rapid than any other environment in our area. The near lack of seedlings in the floodplain poplar forests at Kagvik Creek is probably the result of shading by the dense canopy of larger poplars and shrubs (i.e., normal stand development), and thus the result of normal stand development.

New groves in lowland tussock tundra

Suarez et al. (1999) studied 5 stands of white spruce within about 1 km of our nearest Asik plots. They ran transects from older stands resembling our Mountain Slope onto wetter tundra resembling our Tussock Slope Transect. They found old-growth trees on the drier sites like we did, some dating back to the late 1600s. Trees were progressively younger moving out onto the tundra, suggesting recent expansion. Tree ages in the expansion areas were mostly from the 1900s, with some trees proximal to the source area in the 1800s. These results match our tree ages from the Asik Tussock Slope Transect and Wrench Creek Tussock Plain Transect, and suggest recent expansion of trees onto these less favorable sites. While climate change is likely to be behind this expansion, succession after wildfires also could locally explain young tree ages on tussock-dominated landforms in the Noatak Valley.

New forests at altitudinal treeline

The youth of trees at altitudinal treeline suggest expansion there during the 1900s. Wildfire disturbance as an explanation for the youth of the trees near treeline is unlikely, owing to the proximity of unburned old-growth forest just below and the near absence of fuels in the alpine zone above. Rowland (1997) also found that most of the trees at higher elevations in her Kelly River and Kugururok River study areas became established in the 1900s. Lloyd and Fastie (2003) found altitudinal treeline advance of white spruce to be widespread in interior Alaska, beginning in the mid-1800s to mid 1900s. Climate warming is the obvious explanation for tree expansion into cold climates at high elevation. Seedling density was still quite low in these expanding forests, as was the observed rate of growth in stand-wide basal area. Tree expansion at treeline is striking, but still a much slower process than tree colonization and growth on floodplains.

Noatak forests past and future

During the previous interglacial period (roughly 100,000 years ago), white spruce were present further up the Noatak Valley than today, in the vicinity of the Anisak River (Figure 1; Edwards et al. 2003). A little further upstream, in the vicinity of the Cutler River, white spruce from the Kobuk River Valley have recently overcome the divide between the Noatak and Kobuk (Dial et al. 2022). Trees are expanding rapidly, over 4 km per decade, into the large basin there in the middle Noatak Valley, though trees remain scattered and small. White spruce are clearly on the move, and if the climate continues to warm, we can expect widespread spruce colonization along river valleys in the Noatak region. Dial et al. (2022) found juvenile spruce 9 to 23 km north of any seed-producing adults in the Cutler River area, while in 2023 I observed 2 small spruce growing near the Kelly River approximately 16 km upstream from the current spruce forest limit. This shows just how far spruce seeds can be carried by the wind, most likely across hard-packed snow in the winter. These unusual long-distance dispersal events can result in the establishment of scattered trees, while infilling of trees between these rare colonists to form genuine forests will take many decades. Most seeds disperse in the immediate vicinity of the parent tree, and it takes a few decades for spruce to grow to seed-producing age.

Expansion of poplar is likely to proceed faster, because it is already more widespread. However, our unpublished data show that poplars need near-neutral soils (soil pH of about 6.5 or higher), while spruce tolerates acid soils (soil pH as low as about 4.5). Given the rather limited extend of non-acidic soils in NOAT (Jorgenson et al. 2009, Swanson 2015), future poplar forest will be limited in extent to specific environments, notably floodplains and slopes where fresh non-acidic mineral substrate is exposed.

Tree Rings Through Time

We would expect tree growth to be aided by warm temperatures in the obviously cold-limited environment of the Noatak Valley. Our results suggest that the cumulative effects of multiple warm or cold years are more important than a single warm or cold year.

Warm Summers, Drought, and Nutrients

Multiple studies in Alaska have shown "divergence" in the relationship between the tree growth and temperatures, which means that not all trees show the expected positive relationship with temperature; drought stress in warm summers has been cited as the main reason (Jacoby and D'Arrigo 1995, Wilmking and Juday 2005, Porter and Pisaric 2011, Juday et al. 2015). The degree of drought stress varies between trees depending on location, soil conditions, competition (Porter and Pisaric 2011, Nicklen et al. 2016, 2019, 2021). Nicklen et al. (2021) found that white spruce in Interior Alaska was particularly sensitive to low precipitation on sites with shallow thaw. Wilmking et al. (2004) found that in a transect across the Brooks Range, the positive reaction of trees to warm temperatures was most consistent at their farthest west study site, which was on the Noatak River in NOAT: there 76% of trees responded positively to temperature in the year preceding the ring, a result quite similar to mine (Figure 34). This result suggests that any effect of drought is less pronounced in the western Brooks Range. Brownlee et al. (2016) studied tree physiology in addition to ring widths in Brooks Range white spruce, and found that drought stress did not explain "divergence". My results showed a high proportion of trees with positive response to warmth on all landforms and soil drainage classes, though trees that did not respond positively to warmth were slightly more common on dry sites. Thus the literature available to date and my results suggest that, while drought is clearly a factor limiting tree growth at some times and locations in Alaska, it is probably a minor factor in my study area.

The soil temperature regime in our area probably limits the benefit to trees of a single summer of warm air temperatures. Even in a warm summer the soil is frozen early in the season, and later in the summer the soil is still so cold that root activity and microbial release of nutrients are greatly inhibited. To illustrate, consider the two available years (2018 and 2019) of ground temperatures at the USDA-NRCS monitoring station "Snotel 1175 Kelly Station", which is in a white spruce forest 16 km south of the Wrench Creek node. These two years included the warmest summer on record at Kotzebue (2018) and a summer year near the long term average (2019), as measured by sum of thaw degree-days (Figure 5). In both years the temperature at 20 cm depth first went above freezing during the second week of June and reached a summer maximum of only 5°C to 6°C (USDA-NRCS WRCC 2023). In this environment, a series of several warm years is much more likely to be helpful to tree growth: if the surface layer that is hospitable to tree roots expands over multiple years, the trees can grow roots into it, and additional decomposition of organic matter due to warmer soils releases nutrients. Sullivan et al. (2015) observed that nutrient limitations may matter more to tree growth than direct temperature effects in our environment.

There are additional physiological reason why white spruce ring growth might respond to growing conditions of several previous years. Wood production depends on the prior development of foliage to support it. White spruce needles persist for four to six years (Kayama et al. 2007) and a series of good years allows a tree to build up a persistent foliage basis for photosynthesis and thus ring growth. Also, boreal spruce are able to store reserves that are utilized to maintain growth during unfavorable periods (Huang et al. 2021).

All of these mechanisms—warming or cooling soil, accumulation of new foliage, and storage—are likely explanations for why the cumulative effect of several years of warm or cold summer is more closely related to tree growth than the temperature in the current or previous year (Figure 34).

Cold Summers

Some of the isolated extremely cold summers, such as the 1815 "year without a summer" caused by the Tambora volcanic eruption and the massive Krakatoa eruption in 1883, are visible in the tree ring record, though the resulting narrow rings are no more extreme than were observed in some other years within a few decades of the eruptions. Some volcanic eruptions (e.g., Pinatubo in 1991), and also summers known to be cold based on historical climate records (e.g., 2000), had no visible effect. Our trees are very cold-adapted, and they apparently can store photosynthate for later use (Huang et al. 2021). Thus a single cold summer may not stand out in the ring record, unless it is quite extreme. However, as just described, a series of cold summers is likely to be more of a problem because this will exhaust the trees' temporary storage reserves, force tree roots into an ever-shallower surface layer that is becoming progressively starved of nutrients due to restricted decomposition, and also restrict foliage growth. The late 1940s (with exceptionally cold summers in 1945 and 1948) are a good example: many trees showed declining ring growth during the late 40s that bottomed out in 1949–1950.

Other Factors

There still is a lot we don't understand about what drives tree ring growth. A good example is the years 1994–1995, which had poor ring growth years across our study area and elsewhere in the western Noatak Valley (Brownlee et al. 2016). Except for the cold spring of 1992 (due to the Mt. Pinatubo eruption), the early 1990s had normal to slightly above-normal temperatures at Kotzebue.

And precipitation was unexceptional, except for very wet July and August of 1994. Apparently some other factor, perhaps not weather-related, was responsible for the poor tree growth years of 1994–1995.

While my study has emphasized climate effects on tree growth, other factors not directly related to climate can also be important. White spruce periodically produce large numbers of seeds, and ring widths are greatly reduced in large seed-production years (Juday et al. 2003, Nicklen et al. 2018). Insect and disease outbreaks can be significant also (Holsten et al. 2008). We observed Spruce Needle Rust (*Chrysomyxa ledicola*) in trees on plots during both of our visits to Wrench Creek (2011 and 2022).

Conclusions

Old-growth white spruce forests occur on well-drained hillslopes near the northern limit of trees in the Noatak National Preserve. They consist of open stands that are mostly less than 10 m tall, with some trees more than 300 years old. Stands of younger trees that became established in the 1900s are present near elevational treeline, and in small groves of trees on tussock tundra. These are interpreted primarily as forest expansion due to climate warming, though re-establishment of trees after wildfire is also possible in the tussock tundra. On river floodplains and terraces the stands of both white spruce and balsam poplar also consist of trees that began life in the 1900s, but here the main cause was probably colonization of new areas exposed by river channel migration. Trees in all environments added basal area between our visits in 2011 and 2021 or 2022, with floodplain environments showing the greatest tree growth.

Tree rings dating as far back as the late 1600s showed much year-to-year variation in width, but the effect of individual cold summers was surprisingly weak. Some of the major global climate perturbations due to volcanic eruptions were visible in the tree ring record, but the resulting ring growth was generally no worse than other bad growth years within a few decades of the volcanic event. Tree ring width was statistically correlated more closely with the average warmth of several preceding growing seasons (as expressed by the sum of thaw degree-days) than with the current year's warmth or the previous year's growth alone. This is probably due to the cumulative effect of several years' warmth (or cold) on the conditions in the tree rooting zone, on the amount of foliage available to support photosynthesis, and the level of stored reserves in the tree.

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Appendix A: Tree Data Summary Tables

Table A1. Heights, Diameters, and Ages of Cored Trees, Summarized by Plot.

Node	Transect Name	Species [A]	Plot	Height min (m)	Height max (m)	DBH min (cm)	DBH max (cm)	Pith Year (min)	Pith Year (max)	N
ASK	Terrace	PIGL	2	7.1	7.1	8.6	8.6	1990	1990	1
ASK	Terrace	PIGL	3	5.2	6.9	10.2	14.3	1944	1960	2
ASK	Terrace	PIGL	5	3.2	3.2	6.4	6.4	1995	1995	1
ASK	Terrace	PIGL	6	3.8	6	7.4	19.8	1940	1982	3
ASK	mountain slope	PIGL	7	6.4	8.3	13.1	19.8	1721	1827	4
ASK	mountain slope	PIGL	8	5.5	7.1	9.1	17.7	1686	1867	4
ASK	mountain slope	PIGL	9	6.9	10.1	17.6	22.4	1807	1867	4
ASK	mountain slope	PIGL	10	7	12.6	14.5	30	1695	1857	4
ASK	mountain slope	PIGL	11	5.4	6.3	12.4	14.8	1703	1863	4
ASK	mountain slopeTL	PIGL	13	3.2	4.5	6.9	10	1929	1977	4
ASK	mountain slopeTL	PIGL	14	4.2	4.2	12	12	1935	1935	1
ASK	tussock slope	PIGL	17	4.5	4.5	7.1	7.1	1995	1995	1
ASK	tussock slope	PIGL	19	3.3	6.6	5.7	7.2	1949	1952	2
ASK	tussock slope	PIGL	21	5.5	8.1	12.8	20	1910	1946	4
KGC	floodplain	POBA	1	4.9	9.3	6.4	8.9	1981	1984	4
KGC	floodplain	POBA	2	4.4	7.8	8.4	31.8	1916	1989	4
KGC	floodplain	POBA	4	4.1	8	6.7	21.7	1984	1998	4
KGC	floodplain	POBA	5	5.4	8.7	12.6	18	1933	1939	4
KGC	floodplain	POBA	6	5	5.9	8	8.9	1977	1985	4
KGC	floodplain	POBA	7	4.5	6.6	5.8	22.3	1981	1990	4
KGC	floodplain	POBA	8	5.2	8	8	20.8	1931	1942	4
WRC	tussock plain	PIGL	1	6.7	9	11.4	17.1	1942	1965	3
WRC	tussock plain	PIGL	2	6.3	8.9	20.2	25.6	1922	1957	4
WRC	tussock plain	PIGL	3	6.1	8	10.9	16.6	1959	1983	4
WRC	tussock plain	PIGL	4	6	10.1	14	34.5	1835	1957	4
WRC	tussock plain	PIGL	7	6.4	6.4	12.6	12.6	1993	1993	1
WRC	spruce slope	PIGL	8	4.5	5.3	12.9	15.2	1941	1956	4
WRC	spruce slope	PIGL	9	5.4	9.9	24.2	33.4	1734	1849	4
WRC	spruce slope	PIGL	10	7.1	10.3	15.5	31.2	1814	1941	4
WRC	spruce slope	PIGL	11	7.4	8.1	16.8	28.1	1792	1878	4
WRC	spruce slope	PIGL	13	7.9	8.6	23.9	29.3	1883	1915	3
WRC	alpine slope	PIGL	14	6.3	8	11.2	12.5	1955	1958	2

[A] PIGL – *Picea glauca* white spruce, POBA – *Populus balsamifera* (balsam poplar)

Table A1 (continued). Heights, Diameters, and Ages of Cored Trees, Summarized by Plot.

Node	Transect Name	Species [A]	Plot	Height min (m)	Height max (m)	DBH min (cm)	DBH max (cm)	Pith Year (min)	Pith Year (max)	N
WRC	floodplain	PIGL	18	3.9	4.9	6.6	11.5	1985	1997	3
WRC	floodplain	PIGL	20	7.6	9	17.5	22.6	1910	1939	5

[A] PIGL – *Picea glauca* white spruce, POBA – *Populus balsamifera* (balsam poplar)

Table A2. Tree Cover, Basal Area, Density, and Cover Summary by Plot [A].

Node	Transect	Plot	Species [B]	Basal Area (m^2 ha^{-1})		Seedling Density (count ha^{-1}) [C]		Tree Density (count ha^{-1}) [C]		Canopy cover (%)	
				Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2
ASK	mountain slope	7	PIGL	9.5	10	8750	5000	795.8	689.7	8	11
ASK	mountain slope	8	PIGL	4.8	4.5	14375	7500	901.9	1008	8	7
ASK	mountain slope	9	PIGL	13.7	12.8	2500	625	1591.5	1485.4	3	13
ASK	mountain slope	10	PIGL	6.5	7.7	1875	5000	901.9	795.8	8	3
ASK	mountain slope	11	PIGL	4.3	5.4	9375	1875	1114.1	1326.3	7	4
ASK	mountain slope	12	PIGL	0	0.1	5000	3750	0	212.2	6	12
ASK	mountain slope TL	13	PIGL	0.3	0.3	1875	2500	212.2	265.3	2	1
ASK	mountain slope TL	14	PIGL	0.1	0.3	1250	0	106.1	424.4	4	7
ASK	terrace	1	PIGL	0	0	0	0	0	0	0	0
ASK	terrace	2	PIGL	0	0	0	0	0	0	0	0
ASK	terrace	3	PIGL	0	0	0	0	0	0	0	0
ASK	terrace	4	PIGL	1	1.4	3750	3125	212.2	318.3	0	0
ASK	terrace	5	PIGL	0	0	0	0	0	0	0	0
ASK	terrace	6	PIGL	3.3	3.9	11250	5625	53.1	212.2	13	15
ASK	tussock slope	15	PIGL	0.3	0.8	625	0	212.2	265.3	5	9
ASK	tussock slope	16	PIGL	0	0	0	625	0	0	0	1
ASK	tussock slope	17	PIGL	0	0.2	0	1250	0	106.1	0	0
ASK	tussock slope	18	PIGL	0.5	0.7	0	1875	159.2	265.3	0	5
ASK	tussock slope	19	PIGL	0.1	0.1	1250	1250	53.1	106.1	3	5

[A] Tree data from within the 8-m radius monitoring plot (cored trees are outside of this plot; see Methods).

[B] PIGL – *Picea glauca* white spruce, POBA – *Populus balsamifera* (balsam poplar).

[C] "Seedlings" are trees less than 1.37 m tall; "Trees" are greater than 1.37 m tall.

Table A2 (continued). Tree Cover, Basal Area, Density, and Cover Summary by Plot [A].

Node	Transect	Plot	Species [B]	Basal Area (m^2 ha^{-1})		Seedling Density (count ha^{-1}) [C]		Tree Density (count ha^{-1}) [C]		Canopy cover (%)	
				Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2
ASK	tussock slope	20	PIGL	0	0	0	0	0	0	0	0
ASK	tussock slope	21	PIGL	7.3	10	3750	1250	2069	1962.9	18	18
KGC	floodplain	1	POBA	0.2	1.1	1250	2500	636.6	1273.2	12	32
KGC	floodplain	2	POBA	0.6	3.2	1250	1875	1273.2	1962.9	15	37
KGC	floodplain	3	POBA	0	0	0	0	0	0	0	0
KGC	floodplain	4	POBA	19.5	23.1	2500	0	848.8	1167.1	47	43
KGC	floodplain	5	POBA	6.3	8.5	625	0	848.8	901.9	16	13
KGC	floodplain	6	POBA	0.1	0.9	3125	0	106.1	1114.1	2	10
KGC	floodplain	7	POBA	1.9	3.6	5625	1875	954.9	2069	14	20
KGC	floodplain	8	POBA	4.3	7.7	0	625	2281.2	2758.6	61	37
KGC	tundra lowlands	9	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	10	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	11	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	12	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	13	POBA	0.2	1	625	2500	106.1	1008	0	3
KGC	tundra lowlands	14	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	15	POBA	0	0	0	0	0	0	0	0
KGC	tundra lowlands	16	POBA	0	0	0	0	0	0	0	0
WRC	alpine slope	14	PIGL	0.1	0.4	0	0	53.1	53.1	4	0
WRC	alpine slope	15	PIGL	0	0	0	0	0	0	0	0
WRC	alpine slope	16	PIGL	0	0	0	0	0	0	0	0

[A] Tree data from within the 8-m radius monitoring plot (cored trees are outside of this plot; see Methods).

[B] PIGL – *Picea glauca* white spruce, POBA – *Populus balsamifera* (balsam poplar).

[C] "Seedlings" are trees less than 1.37 m tall; "Trees" are greater than 1.37 m tall.

Table A2 (continued). Tree Cover, Basal Area, Density, and Cover Summary by Plot [A].

Node	Transect	Plot	Species [B]	Basal Area (m^2 ha^{-1})		Seedling Density (count ha^{-1}) [C]		Tree Density (count ha^{-1}) [C]		Canopy cover (%)	
				Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2	Episode 1	Episode 2
WRC	alpine slope	17	PIGL	0	0	0	0	0	0	0	0
WRC	floodplain	18	PIGL	0.1	1.3	19375	16250	477.5	1538.5	11	23
WRC	floodplain	18	POBA	0	0.3	2500	2500	106.1	583.6	3	4
WRC	floodplain	19	PIGL	0	0.2	55000	28750	0	689.7	0	7
WRC	floodplain	19	POBA	0.3	0.9	6250	4375	901.9	1538.5	9	12
WRC	floodplain	20	PIGL	12.1	18.3	0	0	1220.2	1432.4	21	17
WRC	floodplain	20	POBA	0.9	0.1	7500	3125	159.2	583.6	10	3
WRC	spruce slope	8	PIGL	3.5	8.2	11875	11250	1114.1	1644.6	24	22
WRC	spruce slope	9	PIGL	5.8	10.2	8750	3125	583.6	742.7	16	26
WRC	spruce slope	10	PIGL	8.9	10.2	1875	625	795.8	795.8	1	3
WRC	spruce slope	11	PIGL	8.2	8.4	3125	2500	583.6	795.8	18	24
WRC	spruce slope	12	PIGL	0	0	625	3750	0	53.1	0	0
WRC	spruce slope	13	PIGL	13.8	15	1250	625	689.7	583.6	7	15
WRC	tussock plain	1	PIGL	0.2	1.6	625	4375	106.1	265.3	0	5
WRC	tussock plain	2	PIGL	1.5	2.3	625	1250	795.8	954.9	8	12
WRC	tussock plain	3	PIGL	1	1.6	1250	625	212.2	318.3	0	3
WRC	tussock plain	4	PIGL	3.7	4.5	0	0	212.2	265.3	9	13
WRC	tussock plain	5	PIGL	0	0	1250	1250	0	0	0	0
WRC	tussock plain	6	PIGL	0	0	0	0	0	0	0	0
WRC	tussock plain	7	PIGL	0	0	0	0	0	0	0	0
WRC	tussock plain	21	PIGL	0	0.1	0	0	0	53.1	0	0

[A] Tree data from within the 8-m radius monitoring plot (cored trees are outside of this plot; see Methods).

[B] PIGL – *Picea glauca* white spruce, POBA – *Populus balsamifera* (balsam poplar).

[C] "Seedlings" are trees less than 1.37 m tall; "Trees" are greater than 1.37 m tall.

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