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Fire history and postfire forest development in an upland watershed of interior Alaska

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[1] We reconstructed the history of wildfire in the study area of the 1999 FROSTFIRE experimental fire in interior Alaska using information from fire-scarred trees, fire-killed trees, tree recruitment dates, tree radial growth increases, and aerial photographs. This combination of methods resulted in more temporal and spatial precision than would have been possible with any subset. Stand-destroying wildfires affected 93% of the FROSTFIRE watershed and 47% of the control watershed between 1896 and 1925. We found no evidence for severe fires earlier in the 19th century or later in the 20th century, suggesting a temporal cluster of fires. The ignition of some of these fires may be associated with early 20th century mining activity near the study area. There is no evidence that any part of the study area has been burned by more than one severe fire in the past 200–250 years, suggesting fire frequencies lower than previously published estimates. Forests with prefire species composition developed within several decades following fire in birch forests and black spruce forests. South-facing birch forests show no evidence of succeeding to white spruce forests 200 years after fire. *INDEX TERMS:* 1851 Hydrology: Plant ecology; 4221 Oceanography: General: Dendrochronology; 1823 Hydrology: Frozen ground; 9315 Information Related to Geographic Region: Arctic region; 9350 Information Related to Geographic Region: North America; *KEYWORDS:* Alaska, dendrochronology, fire scars, boreal forest, spruce, wildfire

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1. Introduction

[2] In June 1999, the FROSTFIRE project administered an experimental fire in upland boreal forest within an 11 km^2 forested watershed near Fairbanks, Alaska. A primary objective of the FROSTFIRE experiment is to extrapolate results about boreal wildfire's effect on processes and feedbacks at ecosystem and landscape scales to the regional boreal forest. Secondary succession following fire is one of the primary processes contributing to variation in forest structure and composition in interior Alaska forests. Within a particular topographic position, a large proportion of observable variation in tree density, living biomass, soil thermal properties, and ecosystem pools and fluxes of carbon and nutrients can be attributed to the amount of time elapsed since the previous fire [*Van Cleve et al.*, 1983, 1991; *Viereck*, 1983]. Time since the previous fire also determines the flammability of the vegetation and the severity of fire it can sustain [*Viereck*, 1983; *Dyrness et al.*, 1986]. Consequently, meaningful extrapolation of FROSTFIRE results depends on quantifying the successional age and status of the experimentally burned forest stands and adjusting the application of results based on the distribution of stand ages in the broader target region.

[3] Large, stand-replacing fires are the typical mode of fire behavior in interior Alaska, but the frequency of natural fires in this region is poorly known [*Dyrness et al.*, 1986]. Published estimates fall within the range of 40–200 years between fires [*Heinselman*, 1981; *Yarie*, 1981; *Viereck*, 1983; *Dyrness et al.*, 1986; *Mann et al.*, 1995; *Mann and Plug*, 1999]. Most of these estimates explicitly incorporate information about 20th century fires, including any ignited by people. If early 20th century exploration and settlement by Europeans increased fire frequency in the area of these studies, the estimated fire frequencies could be higher than natural frequencies. Estimates of fire frequency from charcoal in lake sediments can avoid this problem by providing long records of fire occurrence prior to European arrival. We know of only one such study in interior Alaska, and it provides an estimate of 198 years between fires during the last 2400 years [*Lynch et al.*, 2002].

[4] The objectives of our study are to produce a spatially and temporally precise history of severe fire in the FROSTFIRE study area, and to describe the forest composition at the time of past fires and the nature of forest succession

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since then. The annual precision of fire dates based on fire scars, combined with historical documentation of anthropogenic use of the study region, allows us to evaluate the possibility that each past fire was ignited by people. This will facilitate the interpretation of other studies in the region which may be biased by anthropogenic fire. In addition to fire-scarred trees, we incorporate fire history information derived from fire-killed trees, postfire age structures, abrupt increases in tree radial growth, and interpretation of aerial photographs. The spatial precision made possible by combining these methods will allow our maps of stand age and successional status to be overlain on the spatial pattern of ecosystem parameters measured by other researchers before, during, and after the FROSTFIRE experimental fire.

2. Methods

2.1. Study Site

[5] The Caribou-Poker Creek Research Watershed (CPCRW, 65°10' N latitude and 147°30' W longitude) is located between the Tanana and Yukon Rivers in interior Alaska, in the dendritically incised bedrock uplands 50 km north of Fairbanks (Figure 1). Climate in Fairbanks is continental, with warm summers (17.1°C in July), cold winters (−24.4°C in January), and low precipitation (270 mm, of which 37% falls as snow) [*Slaughter and Viereck*, 1986]. The 104 km^2 CPCRW consists of 10 subbasins, and we report results from 3 of these and from the area near the confluence of Caribou and Poker Creeks (Figure 1). The studied subbasins are V-shaped valleys along singly curved streams, with large areas having either north- or south-facing aspect, and covering an altitudinal range of 280 m to 750 m above sea level. Aspect strongly influences soil-thermal regime and vegetation cover, with areas of permafrost common on north-facing slopes and absent on south-facing slopes [*Haugen et al.*, 1982]. Black spruce (*Picea mariana* (Mill.) B.S.P.) is the dominant tree on north-facing slopes, ridge tops, and the upper reaches of each subbasin. Paper birch (*Betula papyrifera* Marsh.) dominates the overstory on most south-facing slopes, where aspen (*Populus tremuloides* Michx.) and black spruce are also common. White spruce (*Picea glauca* (Moench) Voss) is a common dominant only near poorly vegetated ridge tops and in stringer forests [*Quirk and Sykes*, 1971] along drainage rills on generally south-facing slopes.

[6] We know of no historical records of early fires near the study site, but there is evidence of human activity in and near the site during the early 20th century mining era, which peaked between 1901 and 1940 [*Cole*, 1999]. The richest placer deposit in the Fairbanks mining district was 10 km from the study site along Cleary Creek [*Prindle*, 1913]. Hillside canals which carried water for placer operations are still evident adjacent to the study basins. The 145 km long Davidson Ditch was completed in 1928 [*Cole*, 1999] and passed within 2 km of the study site. Ruins of a log cabin in the center of the primary FROSTFIRE basin apparently date from the mining era. On the surrounding hillside, many hundreds of black spruce trees were cut with an axe prior to being charred by a 1924 fire (C. Fastie, unpublished data, 1999). This is evidence of human activity in and around the study basins at a time when wood fires were the primary means of cooking, heating, and thawing permafrost during excavations in placer deposits. Consequently, an anthropogenic origin for fires dated to this period is possible.

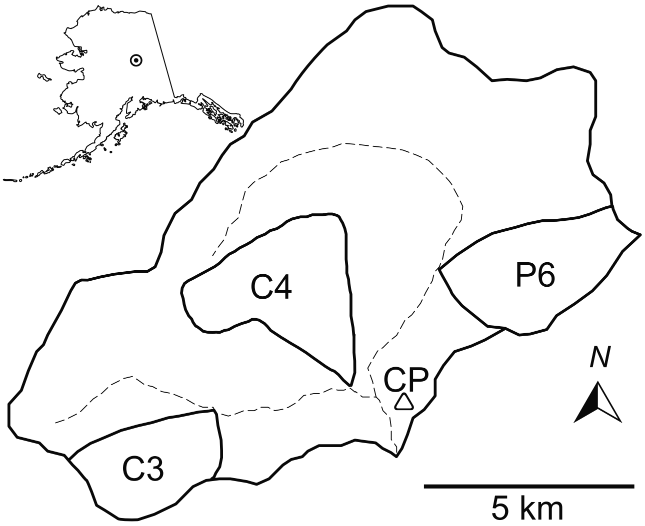

Figure 1. Location of the CPCRW in Alaska (inset), and the four sampling sites within the CPCRW. The watershed boundary of the CPCRW and the boundaries of three subbasins are shown (solid lines). Dashed lines are the primary creeks in the CPCRW. CP, the confluence of Caribou and Poker Creeks (sampling site is at triangle).

[7] We focused our sampling on the C4 subbasin (10.98 km^2) of CPCRW, the site of the 1999 FROSTFIRE experimental fire, and to a lesser degree on the P6 subbasin (7.17 km^2), designated as the FROSTFIRE control basin. We also sampled in two other sites in the CPCRW to determine if similar fire history patterns were present outside the two primary study basins. These areas are the C3 basin 2 km west of the C4 basin, and the confluence of Caribou and Poker Creeks 1 km south of the C4 basin.

2.2. Field Sampling

[8] To determine dates of past fires, we collected information from four sources: living trees scarred by fires, fire-killed trees, age distributions of trees that recruited in response to a fire, and abrupt increases in radial growth of trees that survived a fire.

[9] The study basins were searched for living black spruce trees with fire scars (basal scars caused when cambium on one side of the trunk was killed some time in the past [*Agee*, 1993; *Johnson and Gutsell*, 1994]). A complete cross-section through the scar was collected with a saw as close to the ground as possible. The location of these study sites is a function of our opportunistic encounters with scarred trees. These sites were also searched for black spruce trees killed by past fires. These distinctive dead trees are standing with no bark, no charring on the trunk, but branch stubs with charred tips. During a fire, moisture in live phloem and sapwood prevent charring of trunk wood, but branches and bark (which later falls to the ground and decomposes) are charred [*Johnson and Gutsell*, 1994]. Complete cross-sections were collected from these trees close to the ground, and if the outer surface was better preserved higher on the trunk, a second section was collected there.

Table 1. Aspect, Number of Fire-Scarred, Fire-Killed, and Live Trees Sampled, Sampling Method, and Date of the Last Severe Fire at Study Sites in Four Areas of CPCRW

		Trees sampled					
Site	Aspect	Fire-scarred black spruce. Date of scar and (number of trees)	Fire-killed black spruce	Living black spruce	Living white spruce, (birch) or [aspen]	Sampling method for live trees[a]	Year of last severe fire at the site
C4-A	E	1924(1)	0	0	0		1924
C4-B	VB	1924(2)	0	0	0		1924
C4-C	NE	1924(8)	6	8	0		1924
C4-D	N	1924(3), 1896(1)	0	0	0		1924
C4-I	S		0	11	19		1924
C4-J	S		0	0	(13)	1 plot, 5 m radius	1924
C4-K	S		0	0	(12)	1 plot, 5 m radius	1924
C4-L	S		0	0	(13)	1 plot, 8 × 11 m	1924
C4-M	S	1924(1)	0	18	27	4 plots, 4 × 100 m	1924
C4-N	RT		10	0	0		1924
C4-O	SW	1924(4)	0	0	0		1924
C4-P	SW		0	5	0		1924
C4-Q	RT	1924(1), 1909(6)	2	0	0		1909
C4-R	RT		4	35	0	1 plot, 17 × 43 m	1909
C4-S	RT	1924(1)	0	0	0		1896
C4-T	RT	1896(3)	2	0	0		1896
C4-U	RT	1896(3)	7	47	0	1 plot, 12 × 35 m	1896
C4-V	N	1896(1)	0	5	0		1896
C4-E	VB		2	0	0		1896
C4-F	E		2	0	0		1896
C4-G	E		1	0	0		1896
C4-H	E		2	0	0		1896
C4-W	S		0	1	3		<1750
C4-X	S		0	3	37		<1750
C4-Y	S		0	1	5		<1750
C4-Z	SW		0	0	(5)		<1750[b]
P6-A	S		0	13	(41), [3]	1 plot, 16 × 16 m	1925
P6-B	S	1925(4), 1935(2)	0	15	0	5 plots, 4 × 4 m	1925
P6-C	RT	1902(4)	0	6	0		1902
P6-D	RT		0	45	0	6 plots, 4 × 4 m	1902
P6-E	RT	1902(3)	0	0	0		1902
P6-F	RT	1902(1)	7	0	0		1902
P6-G	RT		1	0	0		1902
P6-H	N	1902(2), 1925(2)	0	19	0	3 plots, 4 × 4 m	<1800
P6-I	N	1935(1)	0	32	0	5 plots, 5 × 5 m	<1800
P6-J	S		0	20	8		<1800
P6-K	S		0	25	0	4 plots, 4 × 4 m	<1800
P6-L	NW	1924(4)	0	0	0		<1800
P6-M	SW		0	7	2		<1800
C3-A	SE	1905(1)	0	4	0		ND
C3-B	E	1905(7)	0	0	0		ND
C3-C	N	1911(2)	0	0	0		ND
Conf.	W	1901(3)	0	0	0		ND

VB, valley bottom; RT, ridge top; Conf., the confluence of Caribou and Poker Creeks; ND, not determined.

[a] Living trees not sampled in plots were the largest trees encountered at a site.

[b] Fire-scarred birch trees observed at site C4-Z suggest an early 20th century surface fire.

[10] At each of 21 sites in the two primary study basins, samples from 4–47 living trees were collected for growth records or age determination. These sites were selected subjectively to be representative of a larger area of the basin. At 11 sites (Table 1), trees were sampled systematically by establishing plots and sampling all trees (>3 cm basal diameter) to include the entire range of tree ages. At other sites, only the largest trees were selected to increase the probability of sampling the oldest trees (Table 1). At one site (Site C4-M), we also recorded the abundance of saplings (height >1.4 m and DBH < 2 cm) and seedlings (height < 1.4 m). Trees were sampled destructively to collect entire basal cross-sections at 7 sites (C4-C, J, R, U, V, P6-D, I), and increment cores were collected as close to the ground as possible at all other sites. Sampled trees included black spruce, white spruce, birch, and aspen. All increment cores were mounted on wooden strips and all cores and cross-sections were surfaced with progressively finer sandpaper and finished with 400 grit.

2.3. Tree Rings

[11] Annual rings from the oldest, living, non-scarred black spruce trees were cross-dated to produce a master chronology. Rings from these samples were measured to a precision of 0.001 mm on a sliding bench micrometer to produce a ring width chronology for cross-dating and quality control of undated samples [*Holmes*, 1983]. Dates of fire scars were determined by cross-dating ring widths before and after the scar year to ensure that no-rings were missing from the samples [*Madany et al.*, 1982]. Outer ring dates of fire-killed black spruce trees were determined by searching the entire outer circumference of all cross-sections

for the radius including the greatest number of rings and cross-dating the rings along that radius. Ring widths of most fire-scarred and fire-killed trees were measured and cross-dating was confirmed using the program COFECHA [*Holmes*, 1983].

[12] Recruitment dates of trees were estimated by making two corrections to the inner ring dates of samples. All cross-sections included the pith, but if the pith was not sampled by an increment core, a number of years was subtracted from the inner ring date based on the curvature and width of the inner most rings [*Duncan*, 1989]. The height of the sample above the root crown was used to estimate the age of the seedling when it reached the height of the sample. Age-height relationships from extensive sampling of Alaskan black spruce [*DeVolder*, 1999], white spruce (A.H. Lloyd and C.L. Fastie unpublished data, 2001), and birch (M. Gracz and E.E. Berg unpublished data, 1997) seedlings were used for these estimates.

[13] To determine if ring width patterns in trees not scarred by a fire recorded the presence of that fire, annual rings from trees near the edge of stringer forests (sites C4-W, X, Y) were measured and ring width series were searched for periods when radial growth increased by a factor of 2 from one 7 year period to the next.

2.4. Fire Margins

[14] Apparent fire margins, where younger vegetation bordered older vegetation, were noted in the field. These margins, and point locations of fire dates from tree ring analysis, were transferred to enlargements of black and white aerial photographs taken in June or July 1951. While viewing stereo pairs of these aerial photos, basin boundaries and all fire margins in the C4 and P6 basins were drawn. These margins were digitized onto rectified images of the 1951 aerial photos and the area of each basin and the area affected by each fire was measured.

3. Results

3.1. C4 Basin

[15] Fire scars from 35 black spruce trees in the C4 basin record fires in 1896, 1909, or 1924 (Table 1). Recruitment dates of trees in areas affected by these fires indicate a pulse of tree establishment that started immediately after each fire (Figure 2). Recruitment continued for 2–4 decades despite an apparent absence of further fires. On the south-facing slope where birch dominates today, a high density of black spruce seedlings and saplings suggests that black spruce recruitment continued for at least 6–7 decades after the 1924 fire, and has recruited more successfully than white spruce (Figure 2e and 2f). Large, systematic samples from plots provide information about the date of initiation of postfire recruitment that differs little from selections of the largest trees at a site (Figure 2, compare 2a, 2b, and within 2e, 2f).

[16] The outer ring dates of fire-killed trees are 1–20 years earlier than the date of the fire determined from fire scars (Figure 3). This range reflects the variable erosion of wood from the outer surface of the dead trunks. Seventy-two percent of the outer ring dates predate the fire by only 1–5 years, and at least one outer ring date in each sample was the year preceding the dated fire.

[17] The recruitment dates of these fire-killed trees are consistently earlier than recruitment dates of trees that were scarred by the same fires but were still alive when sampled (Figure 3), and the distributions are non-overlapping in the area of the 1896 fire (Figure 3a). These recruitment dates suggest that prior to the fires dated using fire scars, most of the C4 basin had not been affected by a stand-destroying fire since before 1750 (Figure 3).

[18] Old white and black spruce trees in stringer forests on the south-facing slope of the C4 basin record no sustained growth increases until the 20th century (Figure 4). Most of these trees record an abrupt growth release 1–4 years after the 1924 fire which destroyed the forest 5–15 m from these trees (Figure 4). However, 25% of the sampled trees record accelerating growth that started between 1911 and 1922 (Figure 4), probably the result of resources released after selective logging in the study stands between 1910 and 1924 (C. Fastie, unpublished data, 1999).

[19] The dated fires between 1896 and 1924 affected about 93% of the C4 basin (Table 2). The 1924 fire initiated recruitment in 78% of the basin (Table 2) including most of the north-facing slope dominated today by black spruce and the south-facing slope dominated by birch (Figure 5). The 1896 and 1909 fires were restricted in the C4 basin to ridge tops and areas high in the watershed, and affected a combined 15% of the basin (Figure 5, Table 2). Areas where a large proportion of trees survived all of the dated fires account for only about 7% of the basin (Table 2, Figure 5).

3.2. P6 Basin

[20] Fire scars from 23 black spruce trees in the P6 basin record fires in 1902, 1924, 1925, or 1935 (Table 1). Recruitment dates of trees in areas affected by the 1902 and 1925 fires indicate a pulse of tree establishment that started during the decade following the fire and was sustained for 1–4 decades after each fire (Figure 6). Although 7 trees scarred by the 1924 and 1935 fires were sampled (Table 1), we did not find postfire cohorts in the P6 basin initiated by these fires. The only year in which trees were scarred in both the C4 and P6 basins is 1924 (Table 1).

[21] The outer ring dates of trees killed by the 1902 fire are 1–5 years earlier than the date of the fire, and 6 of 8 outer ring dates are 1900 or 1901. The mean recruitment date of these fire-killed trees is 25 years earlier than the mean recruitment date of trees which were scarred by the same fire (Figure 7), a pattern less dramatic than in the larger samples from the C4 basin (Figure 3). An episode of recruitment apparently started at this site in approximately 1790, and started about 15 years later at another site of the 1902 fire (Figure 7a and 7b).

[22] Stands of black spruce on the north-facing slope of the P6 basin vary greatly in tree density and size, but closed-canopy forests of large trees have recruitment histories similar to low-density muskegs of small trees (Figure 7c). Tree ages in these stands suggest the beginning of a recruitment episode between 1780 and 1800, but record no recruitment associated with 20th century fires, indicating those fires missed these stands or caused little disturbance there (Figure 7c). In areas of the south-facing slope missed by the 20th century fires, black and white spruce establish-

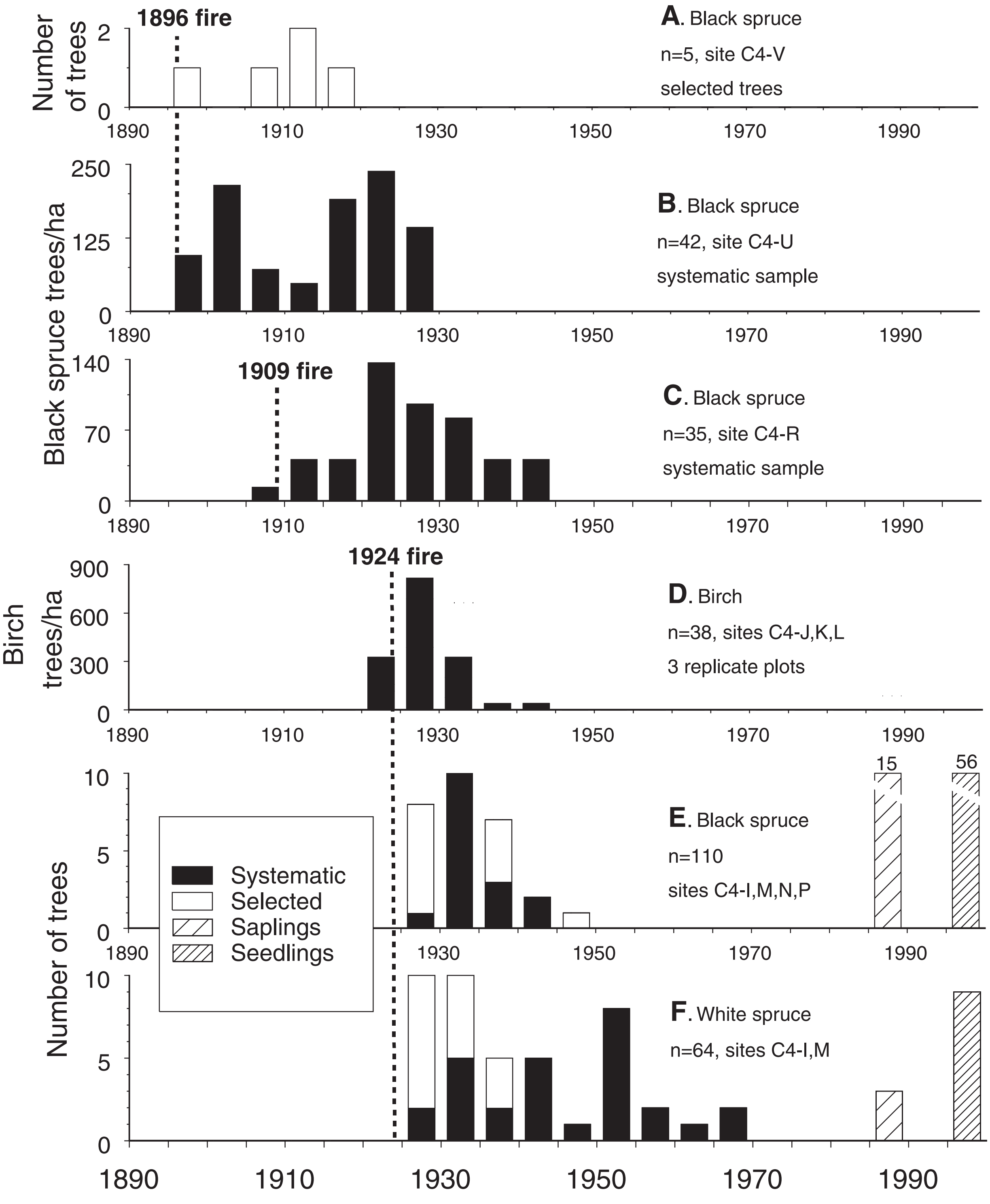

Figure 2. Frequency distributions of recruitment dates of trees establishing after the three most recent fires (dashed lines) in the C4 basin. Dates from systematic samples from plots (b–f) are distinguished from dates from selected large trees (a, e, f). Each panel includes trees from a different site or group of sites, or different species growing at the same sites. Note large differences in *y axis* scaling among panels. Legend is for all panels.

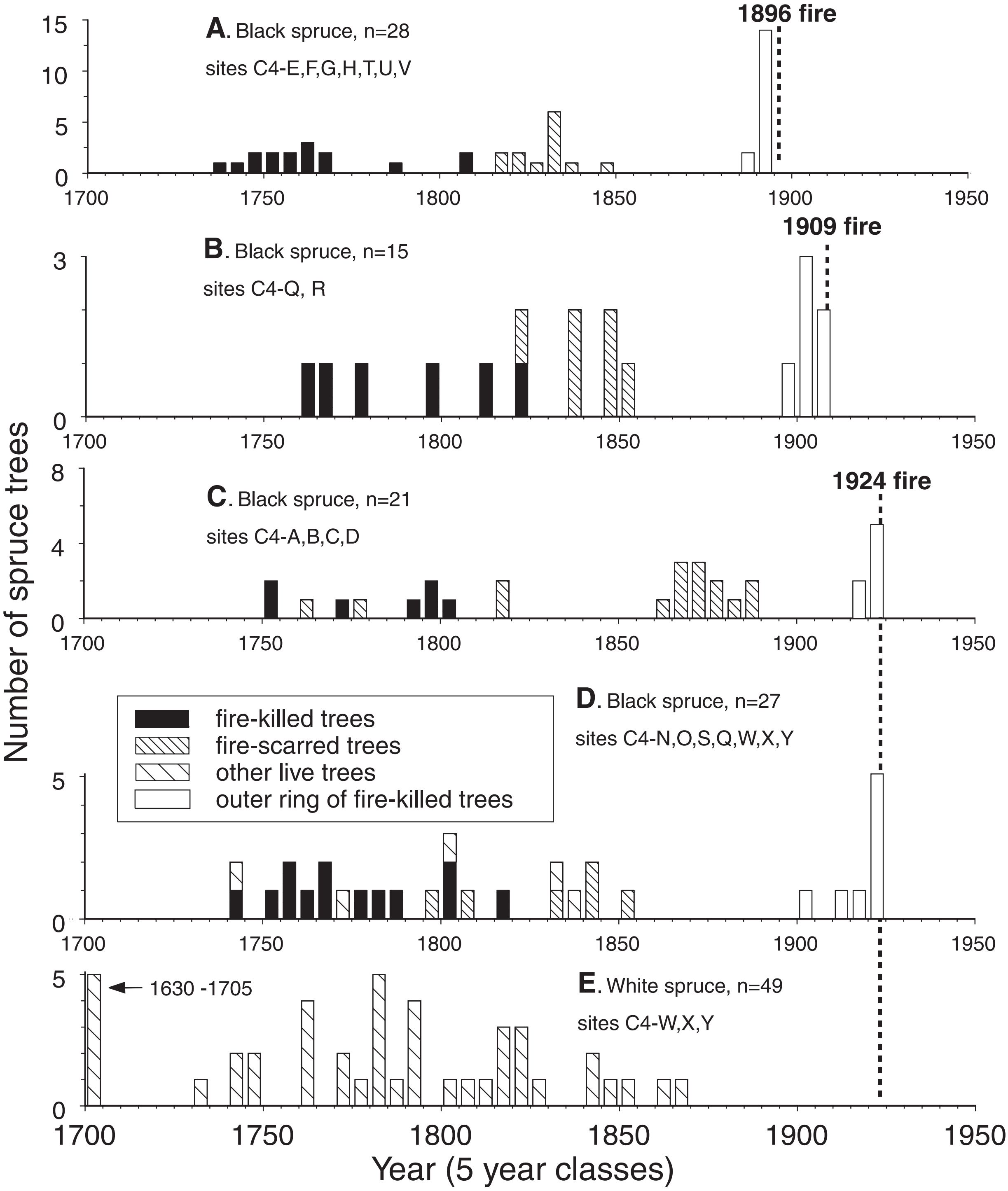

Figure 3. Frequency distributions of recruitment dates of trees in the areas of the three most recent fires (dashed lines) in the C4 basin, and recruitment and outer ring dates of trees killed by those fires (open bars). Recruitment dates of trees killed by fires, scarred by fires, and unscarred survivors are plotted separately. Both recruitment and outer ring dates of fire-killed trees are plotted, but the sample sizes (n) include those trees only once. Legend is for all panels.

ment dates suggest recruitment began between 1795 and 1810 (Figure 7d and 7e).

[23] The dated fires in 1902 and 1925 affected 47% of the P6 basin (Table 2, Figure 8). Like the 1896 and 1909 fires in the C4 basin, the 1902 fire was primarily restricted to ridge tops in the P6 basin (Figure 8), although trees scarred in 1902 (but no postfire cohort) were found near the valley bottom (site P6-H, Table 1). The 1925 fire was restricted in the P6 basin to the south-facing slope which today supports a young forest of birch and black spruce

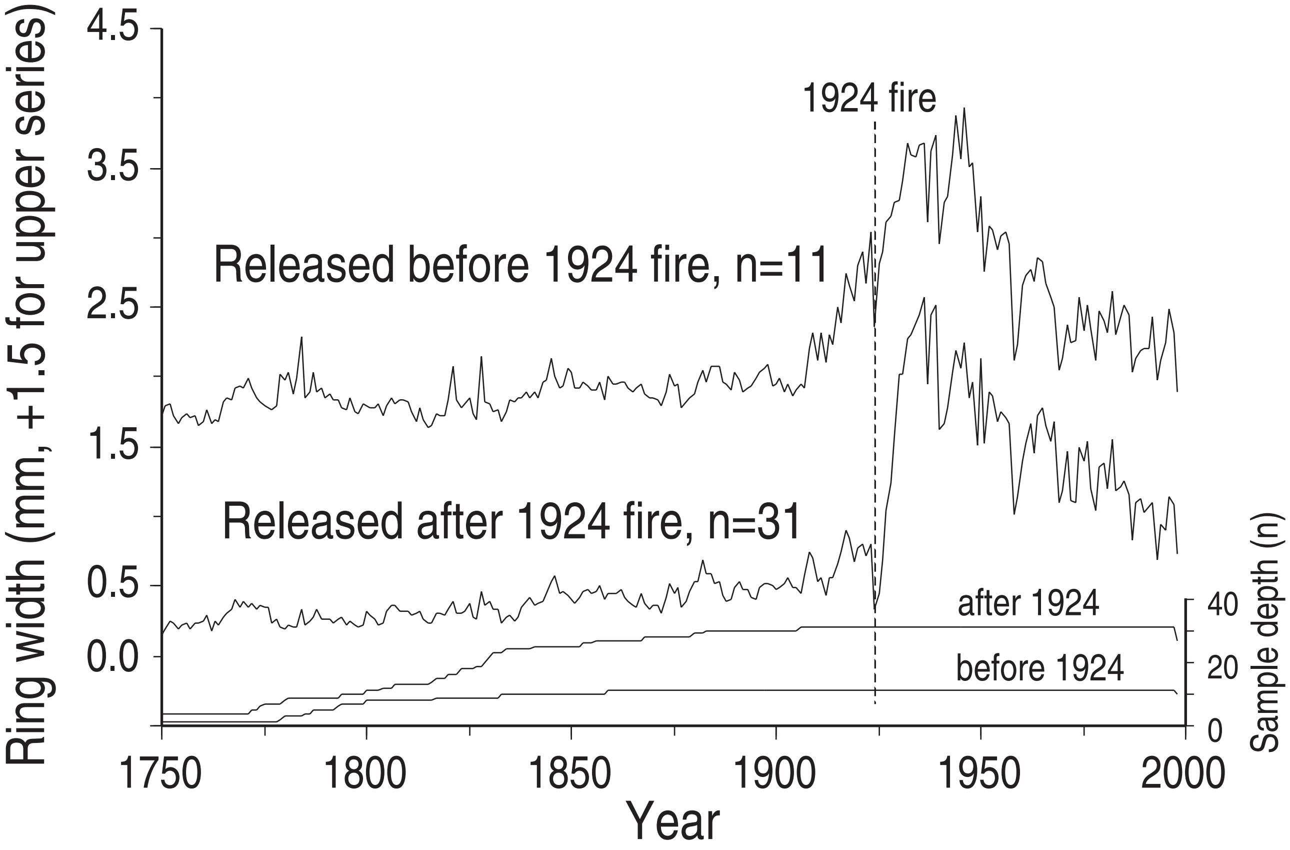

Figure 4. Mean ring widths of spruce trees recording a 2x growth release after the 1924 fire, and of trees initiating accelerated growth before 1924 at sites W, X, and Y (stringer forests) in the C4 basin. A constant of 1.5 mm was added to the upper series for clarity. The number of trees contributing to each mean (sample depth) is shown.

(Figure 8). We found no evidence in 53% of the P6 basin for the occurrence of stand-destroying fire since about 1800 (Table 2, Figure 8).

3.3. Sites Outside the C4 and P6 Basins

[24] Fire scars from 10 black spruce trees in the C3 basin record fires in 1905 and 1911, both years in which fires did not occur in the C4 or P6 basins (Table 1). The recruitment dates of fire-scarred and other live trees sampled in the C3 basin suggest a pulse of recruitment began before 1750 (Figure 7f). Fire scars from 3 black spruce trees at the confluence of Caribou and Poker Creeks record a fire in 1901, another unique fire year in our sampling within the CPCRW (Table 1).

4. Discussion

4.1. Fire History of the Study Area

[25] Substantial portions of the C4 and P6 basins (93% and 47% respectively) were affected by stand-destroying fires in the 30 year period from 1896 to 1925. We found no evidence of earlier fires during the 19th century, or severe fires later in the 20th century. The timing of this fire cluster overlaps the most active period of gold prospecting and mining in the Fairbanks area. The 1896 fire predates the documented arrival of the first two prospectors in 1901, and the 1901 and 1902 fires occurred when those were probably the only prospectors in the area [*Cole*, 1991]. Therefore, natural ignition is assumed for the 1896, 1901, and 1902 fires. Fires in 1909, 1924, and 1925 occurred during a period of intense mining activity and could have been ignited by humans.

[26] Although it is not possible to determine a natural fire frequency from our results, we can estimate the last, natural, fire-free interval for each study basin. We found no evidence of severe fire between 1750 and 1896 in the C4 basin, and none between 1800 and 1902 in the P6 basin. These intervals of 146 and 102 years, both in areas of black spruce forest, exceed the 50–100 year range of average fire intervals

Table 2. Area and Percent of the C4 and P6 Basins Burned in Each Dated Fire and in One or More Earlier Fires

Basin	Fire year	Area of basin burned (km^2)	% of basin burned
C4			
	<1750	0.72	6.6
	1896	1.29	11.7
	1909	0.41	3.7
	1924	8.57	78.0
	total	10.98	100
P6			
	<1800	3.83	53.4
	1902	2.08	29.1
	1925	1.26	17.5
	total	7.17	100

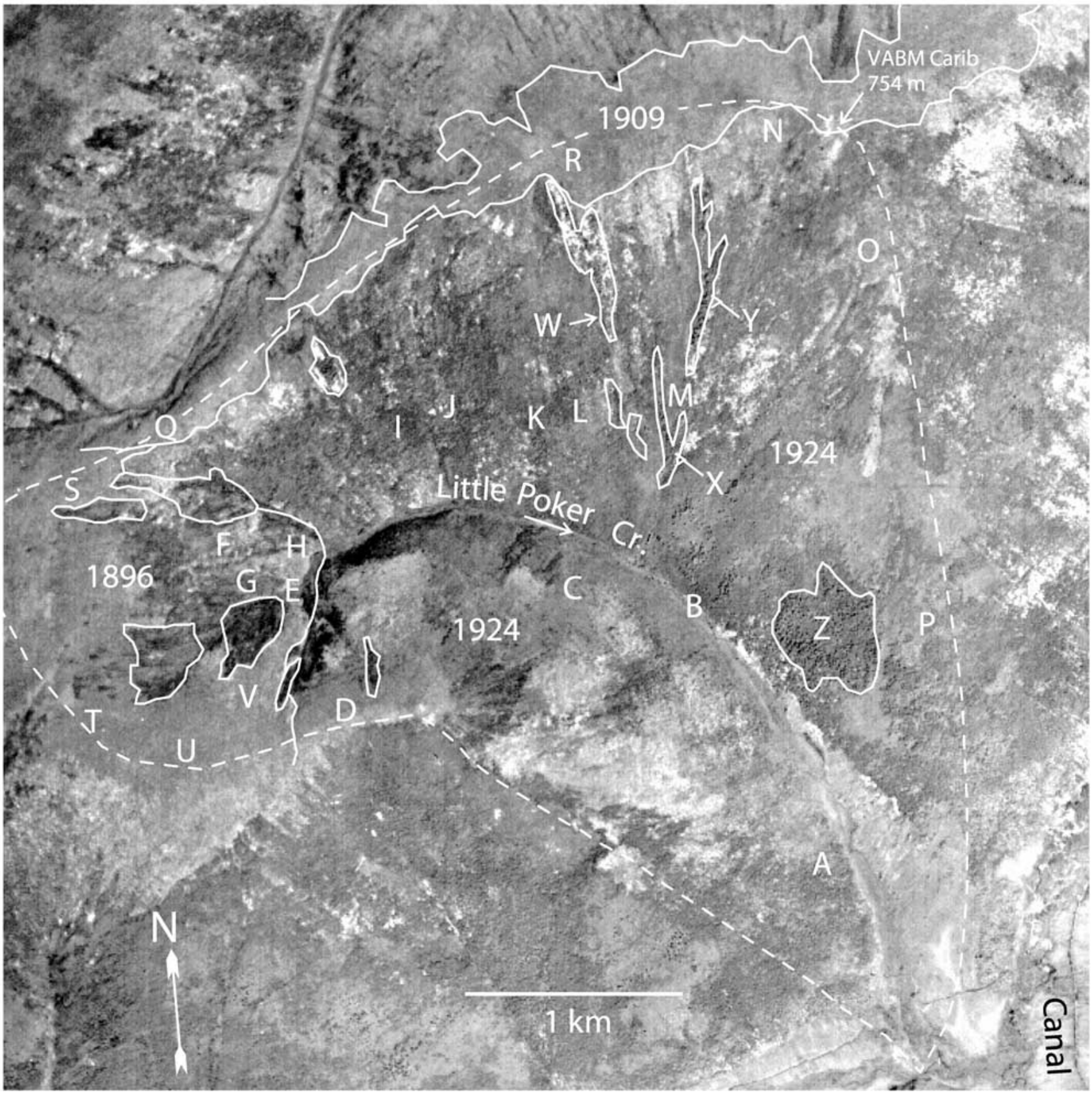

Figure 5. June 27, 1951 aerial photograph of the C4 basin. The basin boundary (dashed) and boundaries between areas burned (solid) by 3 known fires and 1 or more older fires are overlain. Polygons with no date include many overstory trees that survived the three dated fires. Letters are study sites.

estimated from age structure studies of black spruce forests in interior Alaska [*Viereck*, 1983]. In addition, the fire-free interval in small portions of the C4 basin extends from before 1750 to the present time, and the majority of the P6 basin may not have burned in the last 200 years, although these intervals might have been extended by fire suppression efforts in the late 20th century. These long fire-free intervals are consistent with the possibility that earlier studies may have overestimated natural fire frequencies by including data from early 20th century anthropogenic fires.

[27] Approximately 70% of the area burned in the 1999 FROSTFIRE experiment in the C4 basin had last burned in a severe fire in 1924, and most of the remaining area of the 1999 fire had previously burned in 1896. The ages of the stands affected by the FROSTFIRE burn are probably typical of upland stands in the region, which were also exposed to anthropogenic fire in the early 20th century. There is little information with which to estimate the proportion of interior Alaska that escaped anthropogenic fire early in the 20th century. Farther from the most active mining districts, average stand ages could be substantially greater than those in the C4 basin.

4.2. Fire Variability and Detectability

[28] The past fires identified and mapped in this study include only severe fires that killed trees and disturbed

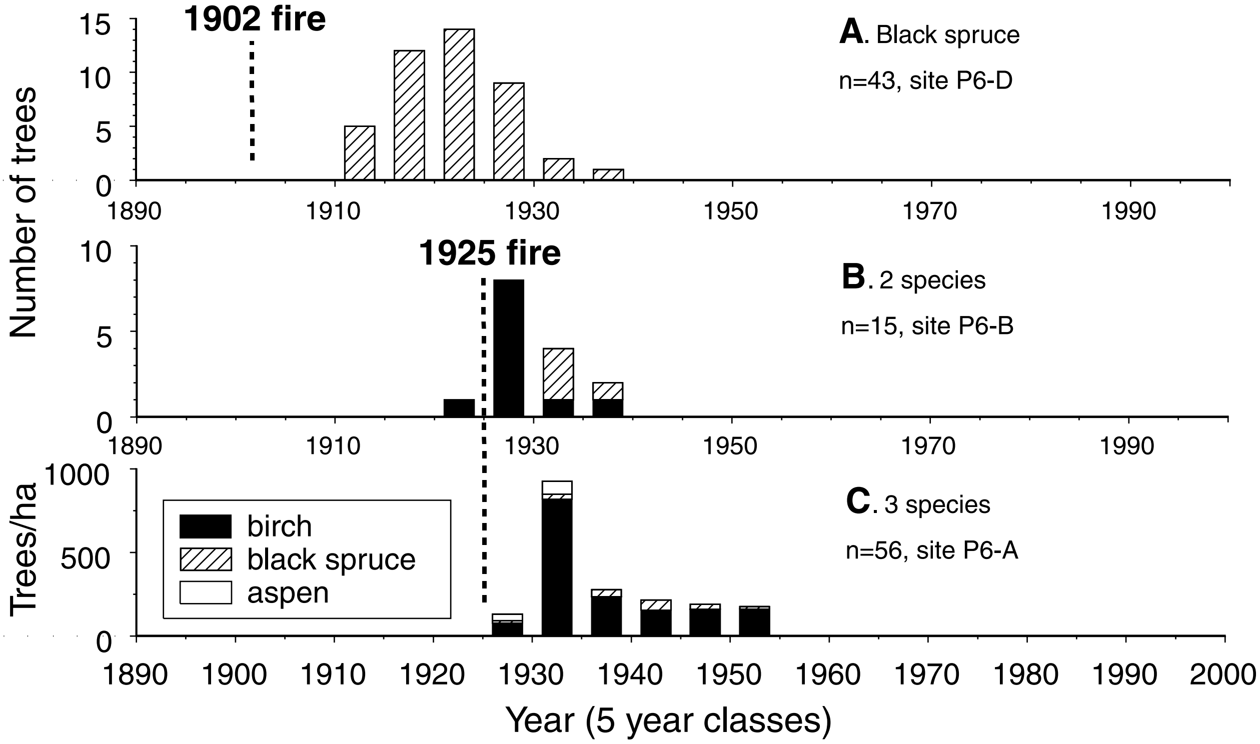

Figure 6. Frequency distributions of recruitment dates of trees establishing after the 2 most recent fires (dashed lines) in the P6 basin. Each panel includes trees from a systematic sample at a unique site. Legend is for all panels.

organic soil horizons sufficiently to promote tree recruitment. Most fires also spread to some extent as low intensity surface fires, and some fires may nowhere become sufficiently intense to kill or scar trees or create conditions for new recruitment. These fires leave little evidence of their occurrence, and our methods would not have detected most of them. Therefore, as in previous work on Alaskan fire regimes [*Heinselman*, 1981; *Yarie*, 1981; *Viereck*, 1983; *Dyrness et al.*, 1986; *Mann et al.*, 1995; *Mann and Plug*, 1999], our conclusions about fire frequency and fire-free intervals apply only to severe, stand-replacing fires. At several sampling areas in this study, trees scarred by fires were found where it appeared that most trees survived that fire and where no recruitment had been initiated (e.g., sites C4-D, S, P6-B, H, I, L). This suggests that low-intensity surface fires may be common and under-represented in our sample, making our estimates of fire-free intervals too high. However, fires which kill few trees and fail to disturb the forest floor have substantially less impact on forest communities than more severe fires. By focusing on severe fires, we maintain the ecological relevance of our results and the advantage of direct comparison with previous studies.

[29] As with all historical reconstructions, the record of interest fades with time, and the record of low-intensity fires fades substantially faster than that of more severe fires. Fire scars and fire-killed trees recording fires as early as 1896 were abundant and conspicuous throughout the study basins, but there was a complete absence of similar evidence for earlier fires. It is possible that other fires occurred earlier in the 19th century for which little evidence remains. Our conclusions assume that such fires were either low-intensity or affected relatively small areas and were therefore of lesser ecological importance.

[30] All dated fires in this study burned unknown areas outside of the study basins, so we learned little about the extent of these fires. However, in any given year, stand-destroying fires did not burn in more than one of the four nearby basins studied, suggesting that none of these fires was larger than about 20 km^2. These were therefore relatively small fires in a region where fire extent can be 250–500 km^2 [*Viereck*, 1983; *Dyrness et al.*, 1986].

[31] The three earliest fires dated in the C4 and P6 basins (1896, 1902, 1909) were restricted primarily to ridge top stands of black spruce. These sites have the best drainage and the greatest exposure to wind and lightning. The restriction of some fires to these settings suggests that ridge-top black spruce stands might support a distinct fire regime. Stringer forests of white spruce have apparently been fire-free for the last 250 years despite being surrounded by flammable forests. Another distinct fire regime, one of infrequent fires, may characterize these stands.

4.3. Postfire Vegetation Development

[32] The current composition of ridge-top and north-facing stands of black spruce that burned between 1896 and 1924 is similar to the prefire communities at these sites. Evidence for this includes many scattered black spruce trees that survived those fires, and many standing trunks of black spruce trees that were killed by those fires. The postfire development of these stands has followed a pathway of rapid self-replacement [*Viereck*, 1983] which depends on seeds held in the canopy in semi-serotinous cones.

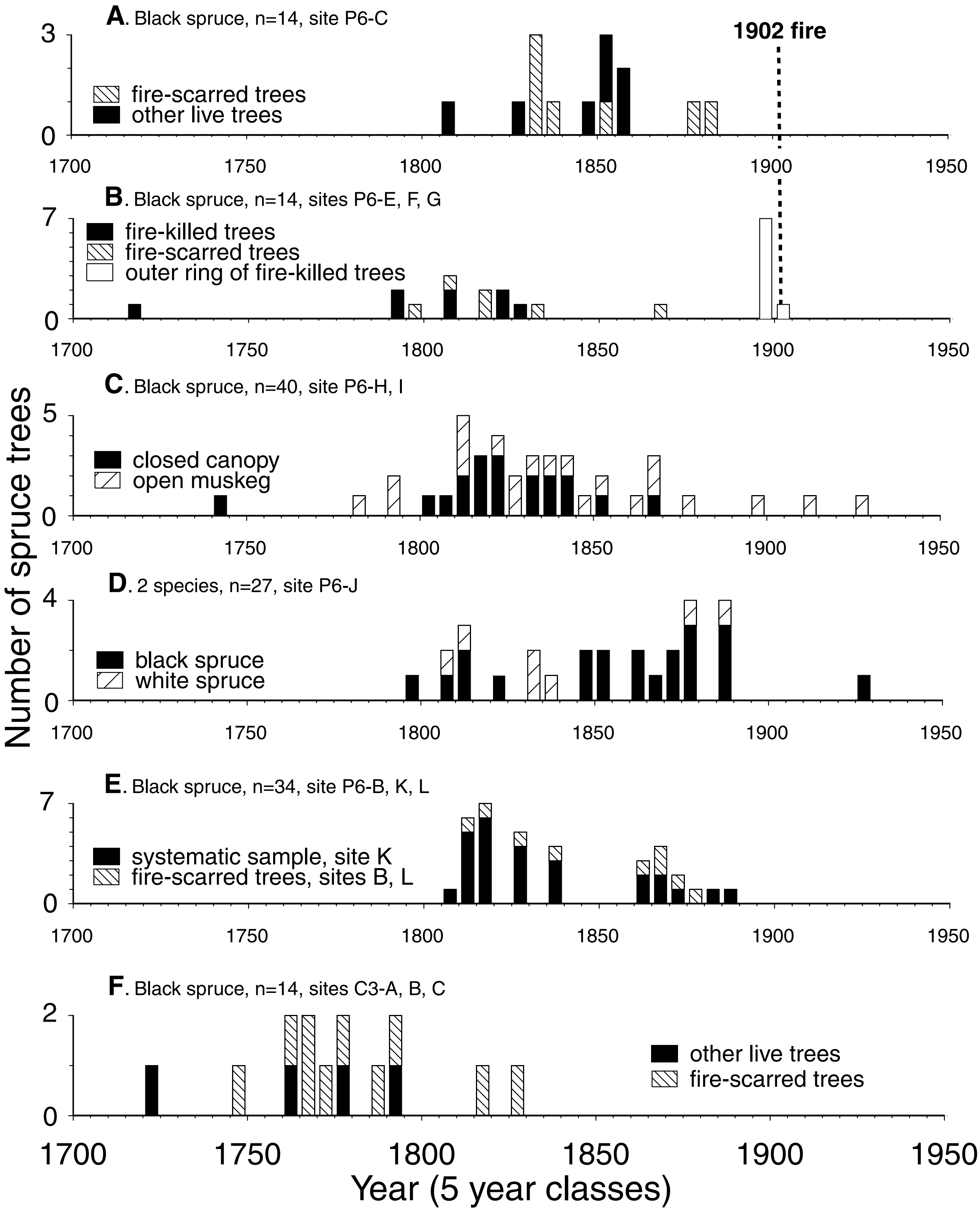

Figure 7. Frequency distributions of recruitment dates of trees in the area of the 1902 fire (a, b) and trees in areas apparently not burned since 1800 (c, d, e) in the P6 basin, and trees surviving 20th century fires in the C3 basin (f). Trees killed by fires, scarred by fires, and unscarred survivors are plotted separately. In panel B, both recruitment and outer ring dates of fire-killed trees are plotted, but the sample size (n) includes those trees only once. In panel E, fire-scarred trees were scarred in 1924, 1925, and 1935.

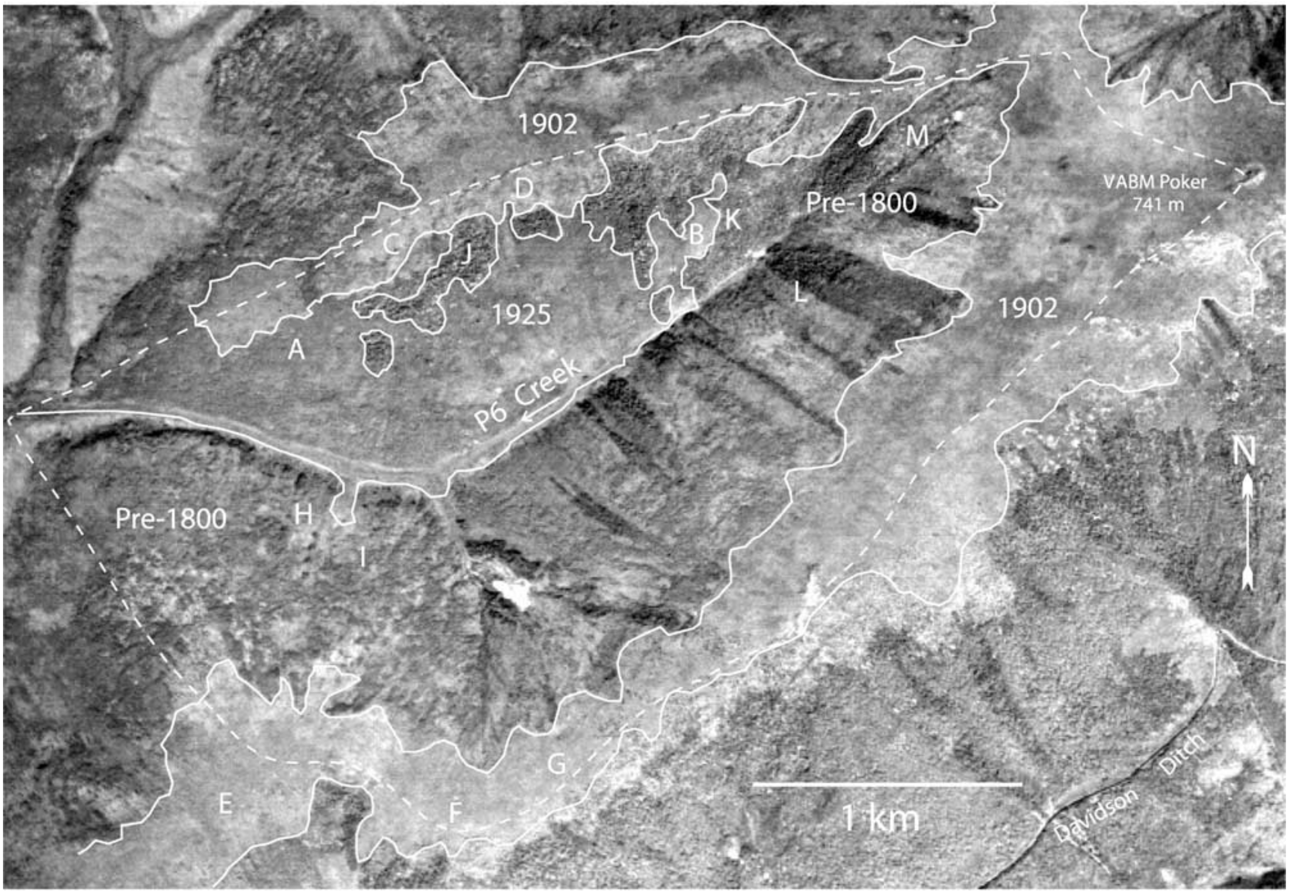

Figure 8. July 14, 1951 aerial photograph of the P6 basin. The basin boundary (dashed) and boundaries between areas burned (solid) by 2 known fires and 1 or more older fires are overlain. Polygons with no date include many trees that survived the two dated fires. Letters are study sites.

[33] South-facing slopes in both the C4 and P6 basins support closed-canopy birch forests that were established after fires in 1924 or 1925. The birch trees began recruiting from seed soon after the fires, and in some areas, trees with multiple trunks suggest birch also sprouted from root crowns that survived the fires. Although the expected successional pathway for upland, south-facing slopes is for early hardwood stands to be replaced by white spruce [*Dyrness et al.*, 1986; *Van Cleve et al.*, 1991], trees in the understory of these forests are primarily black spruce. Young white spruce are present throughout these slopes but are most abundant near remnant white spruce stringer forests not destroyed by 20th century fires (sites C4-W, X, Y, Figure 5). Although black and white spruce both began recruiting immediately after the fires (Figures 2e and 2f), black spruce is more abundant (data not shown) and better represented in the seedling and sapling classes (Figures 2e and 2f). This suggests that black spruce will remain the most important codominant with birch in these stands.

[34] Portions of these south-facing slopes escaped the 20th century fires and reveal the stand composition at the time of the fires. Site C4-Z (Figure 5) is dominated by birch trees that predate the 1924 fire (data not shown), and the understory includes very few spruce. Fire scars on many birch trees suggest that a low-intensity surface fire (possibly the 1924 fire—rotten heartwood prevents dating of most scars on birch) spread through this stand. Large areas on the south-facing slope of the P6 basin (e.g., sites P6-J, K) support large birch trees, aging clones of aspen, and scattered spruce in the overstory, subcanopy, and understory. Black and white spruce in these stands are of similar age, but black spruce greatly outnumber white spruce (e.g., Figure 7d). The early 19th century establishment dates of many spruce and the absence of 19th century fire scars suggest that these stands were not affected by stand-replacing fires after ca. 1800. At the time of the 1925 fire, the south-facing slope in P6 was apparently a 125 year-old birch and aspen forest with codominant black spruce and a less important component of white spruce. Most importantly, 75 years later, after 200 years of postfire succession, the remnant patches still have a similar composition.

[35] The expected successional pathway from early hardwood stands to late successional white spruce forests within about 150–200 years [*Dyrness et al.*, 1986; *Van Cleve et al.*, 1991] is not occurring on these slopes. These results extend a recent observation that Alaskan south-facing stands of aspen with codominant white spruce persist through multiple fire cycles without succession to white spruce forests [*Mann and Plug*, 1999]. In the C4 basin, a surface fire at site C4-Z might have destroyed spruce seedlings and saplings and strengthened the dominance of birch. In the P6 basin, we have documented a persistence of birch and black spruce which appears to have continued for two centuries in the absence of severe fire. Unlike the "fire-hardening"

hypothesis of *Mann and Plug* [1999], compositional persistence at these sites may not depend on frequent fires favoring species capable of resprouting after severe fire, but could be attributed to the long-term competitive superiority of hardwood trees compared to white or black spruce in these habitats. This result is similar to recent findings in boreal western Canada where hardwood stands persist in a state of gap-phase replacement without succession to spruce forest [*Cumming et al.*, 2000].

4.4. Multiple Sources of Fire History Information

[36] The most precise evidence for the timing and extent of past fires can be derived from fire-scarred trees and standing trunks of trees killed by fire. Spruce trees with fire scars are common in the study area and in other parts of interior Alaska [*Mann et al.*, 1995; *Mann and Plug*, 1999]. Fire scars record fire dates with annual precision, although we found that one or more rings immediately following the scar can be missing, so cross-dating is required. Fire-killed trees are also common in the study area, and outer ring dates of 6–14 trees killed by 20th century fires always included at least one date preceding the dated fire by one year. With substantial sample sizes, this method therefore has the potential to provide estimates of fire dates with annual or near-annual precision.

[37] Recruitment dates of trees surviving a fire or killed by that fire can suggest the dates of earlier severe fires which predate the beginning of the fire scar record. The earlier recruitment dates of fire-killed trees compared to trees that were scarred by the same fire suggests that fire-killed trees may be a more reliable source of information about the timing of earlier fires. The difference probably results from differential rates of mortality or scarring depending on tree-age at the time of the fire, or to differential rates of decomposition and loss from the record of the oldest fire-killed versus fire-scarred trees. In addition to being old trees, fire-killed trees were slow-growing and had a high proportion of rings with reaction wood, the high density of which probably increases the durability of the standing trunks compared to trees with little or no reaction wood.

[38] Obtaining a large sample of recruitment dates of living trees can confirm the timing of independently dated fires, but by itself, provides an estimated fire date only within a range of 5–10 years for early 20th century fires. Sources of error include determining the recruitment date of trees, and estimating the lag between the fire and the start of recruitment. The primary source of error in determining recruitment dates is estimating the number of years the tree grew before reaching the height of the sample. Samples collected close to the ground and the use of robust equations describing age-height relationships for each sampled tree species reduce this error. A large sample of black spruce trees at one of our sites (Figure 6a) indicates a pulse of recruitment starting 10 years after the dated fire. Based on observations of rapid postfire recruitment of black spruce in interior Alaska [*Viereck*, 1983; *Dyrness et al.*, 1986] we assume recruitment started earlier than the indicated time, and that the discrepancy is due to the equation overestimating the early height growth of trees at this site. In part because of these inherent sources of error, a small sample of recruitment dates from 5–16 of the largest trees at a site provided an estimate of the fire date similar to the estimate derived from a larger, systematic sample. Although these small-sample maxima of tree ages [*Cumming et al.*, 2000] are apparently good estimates of stand initiation dates following 20th century fires, obtaining estimates with similar precision for older fires probably requires larger samples.

[39] The above methods provide point samples of fire occurrence. To map the extent of past fires, high-quality aerial photographs, preferably stereo pairs, are required. Distinguishing fire margins from other ecotones in interior Alaskan taiga is complicated by variation in tree height and stand composition produced by strong gradients in soil thermal and hydrological properties. The availability of early aerial photographs offers a great advantage because it reduces the elapsed time between the fires and the record in the image. Although only 26 or 27 years had elapsed between the time of the last severe fires in the study basins and the 1951 aerial photographs used in this study, fire margins could be reconstructed only by synthesizing information from all of the above methods and from additional observations in the field.

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