FIRE AND CLIMATE HISTORY OF LOWLAND BLACK SPRUCE FORESTS, KENAI NATIONAL WILDLIFE REFUGE, ALASKA

by Andrew De Volder

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Approved:

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R. Scott Anderson, Ph.D., chair

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Joy Nystrom Mast, Ph.D.

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James I. Mead, Ph.D.

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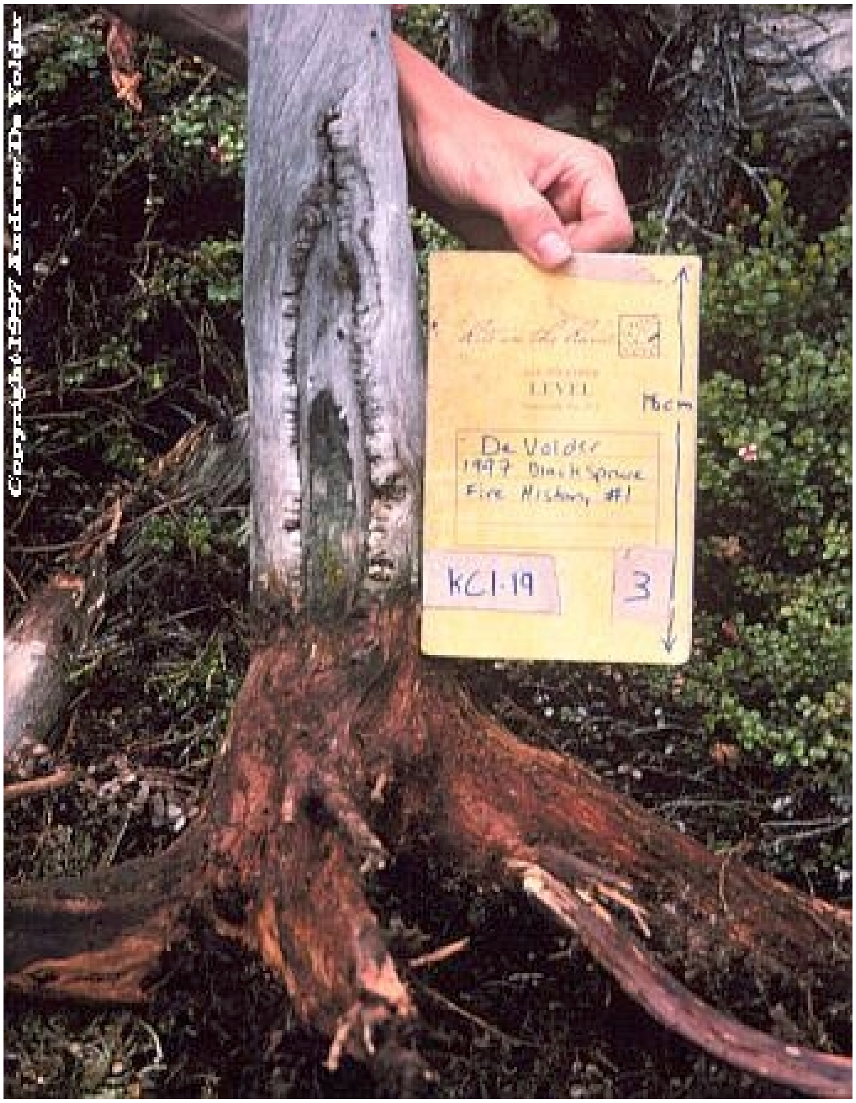
Thomas W. Swetnam, Ph.D.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Abstract

FIRE AND CLIMATE HISTORY OF LOWLAND BLACK SPRUCE FORESTS, KENAI NATIONAL WILDLIFE REFUGE, ALASKA

Andrew De Volder

In order to define the fire regime in Kenai NWR black spruce forests, a detailed fire and climate history study was undertaken. Utilizing techniques of dendrochronology I dated fire scars, and dated the outer-rings of fire-killed trees (burn poles) within areas of unknown fire history, and I analyzed the age-classes of living and dead trees. From a total of 1,022 cross-sections and 771 increment cores twelve fires were dated, the earliest of which occurred in 1708. Fire return intervals for the entire study area range from 25 to 185 years with an average of 89 years (S.D.= 43 years). The fire cycle of lowland black spruce forests was between 42 and 56 years. Analysis of the temporal pattern of fire events revealed a gap in fire occurrence between 1762 and 1828. Nine of the 12 fires occurred between 1828 and 1898, which was coincident with European settlement of the Kenai Peninsula.

The gap in fire occurrence is proposed to have coincided with the onset of the coldest time period of Little Ice Age (the 19^{th} century cold period). This also corresponds to a period of very low fire activity in western Canada, the western and southwestern United States, northern Quebec, and Sweden. This may be an indication of some larger Northern Hemispheric climatic shift at this time. The increase in number and frequency of fires after 1828 is attributed to, in part, an increase in human presence on the Kenai Peninsula and to more favorable climatic conditions.

Acknowledgements

Many people have helped me make this study a fantastic success. First I would like to thank my parents Betty and David for their continued support throughout this phase of my academic career. I thank God for spiritual support through the tough times.

By far the largest contribution to this study came in the form of a grant to R. Scott Anderson (PI) and Andrew De Volder (co-PI) for two years of financial assistance from the United States Fish and Wildlife Service, Region 7. I thank Region 7 Fire Management Officer Larry VanderLinden for arranging this funding. I would also like to thank the Center for Environmental Sciences Education for providing me with a teaching assistantship for my first year at NAU. I cannot thank Sally Evans enough for her cheerful support and management of project workings at NAU. Thanks Sally.

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During the fall semester of 1998 I studied at the Laboratory of Tree Ring Research at the University of Arizona. Thanks to Rex Adams, Chris Baisan, Kurt Kipfmueller, Matt Rollins, and Dan Ryerson, and Tom Swetnam for discussions on many topics related to dendrochronology. Thanks to Ron Towner for reviewing a portion of this document. I also thank everyone else at LTRR for providing me with a fantastic learning experience during the Fall of 1998.

Thanks to the Ecology Lab in the College of Ecosystem Science and Management for allowing me to use their tree-ring measuring system. Thanks also go to Steve Andariese for granting me computer and ARC/INFO access in the Geography Department of the Southwest Forest Science Complex, without which I could not have produced the fire maps used in this study.

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This is Laboratory of Paleoecology contribution number 69.

Table of Contents

List of Tables

List of Figures

Chapter One: Introduction

"Our woodlots, of course, have a history, and we may often recover it for a hundred years back, though we do not. Yet if we attended more to the history of our woodlots, we should manage them more wisely." *Henry David Thoreau*, Faith in a Seed.

FIRE HISTORY

Wildfire is considered to be the most important disturbance mechanism in the boreal forest (Lutz, 1956; Viereck, 1973; Wright & Heinselman, 1973; Rowe & Scotter, 1973; Goldammer & Furyaev, 1996). Numerous studies detailing the fire history of eastern North American boreal forests (Heinselman, 1973; Cogbill, 1985; Payette *et al.*, 1989; Bergeron, 1991; Desponts & Payette, 1992) and western North American boreal forests (Johnson, 1979; Johnson & Strang, 1982; Larsen, 1996; Larsen, 1997) have been completed. However, relatively few fire history studies have been completed in Alaska (Yarie, 1981; Gabriel & Tande, 1983). From these studies, depending on the geographic location and type of forest under study, researchers report fire return intervals of 40-150 years.

Typically, studies of fire history in boreal forests begin with defining homogeneous vegetation polygons determined from air photos. These homogenous vegetation patches, or stands, are inferred to be even-aged forest stands originating after a fire or other disturbance event. Investigations in the field usually involve taking increment cores from canopy dominant living trees within stands to obtain a minimum age of the fire event from a cluster of tree ages. However, in areas where 20th century fires have burned over older fires and the ages of living trees are known, this approach cannot be applied. The use of dead forest remains, therefore, is a very important tool for extending the chronology of fire and other disturbance events back in time (cf. Henry & Swan, 1974; Payette *et al.*, 1989; Mann *et al.*, 1994). Additionally, fire scars on living and dead trees can be used to accurately determine the date of a particular fire (Arno & Sneck, 1977; Dieterich & Swetnam, 1984), but have the disadvantage of being difficult to find, especially in forest types subject to high intensity stand-replacing fires such as in the boreal forest (Yarie, 1981). However, this limitation does not make the use of fire scars impractical, rather their use is of great importance when reconstructing fire histories using both fire scars and age-class data (Tande, 1979; Romme, 1982; Payette *et al.*, 1989; Bergeron, 1991; Bergeron & Brisson, 1990; Desponts & Payette, 1992). Well-dated fire scars used in conjunction with age-class data from trees (living or dead) in the same stand can verify the dates of fire occurrence and provide information about fire intensity. Analysis of fire scars using techniques of dendrochronology can achieve annual, and seasonal resolution of fires that burned on the landscape (Dieterich & Swetnam, 1984; Baisan & Swetnam, 1990).

DENDROCLIMATOLOGY

Tree-ring records can provide high resolution annual estimates of temperature extending back in time for centuries when no instrumental records exist. These high resolution proxy records are of great value to researchers concerned with changes in the climate system over long time periods (Jacoby & Cook, 1981; Jacoby *et al.*, 1988; Briffa *et al.*, 1990; Briffa *et al.*, 1995; Luckman *et al.*, 1997; Overpeck *et al.*, 1997; Wiles *et al.*, 1998; Mann *et al.*, 1998). In southcentral Alaska, the longest instrumental weather station record is from Seward, beginning in 1908. While over 90 years in length, questions concerning the long-term climate variability in this region cannot be addressed with such a short record. Forest disturbance agents such as insects and fire are important mechanisms of ecosystem change in boreal forests (Lutz, 1956; Viereck, 1973; Wright & Heinselman, 1973; Rowe & Scotter, 1973; Goldammer & Furyaev, 1996). In Alaska, both of these disturbance mechanisms have linkages to climate during the growing season. Therefore, a climate record longer than instrumental observations is needed to assess the uniqueness of the present climate. With the use of tree-ring reconstructed temperature changes over long time periods when no instrumental records exist, one can begin to address such questions as whether or not the recent warming observed in the instrumental record is unusual, or if warm summer temperatures occurred during reconstructed fire years or during periods of insect outbreaks.

Site and tree selection is critical in dendroclimatology and involves sampling trees that are limited (or stressed) in their growth by some component of the climate system. If one wishes to retrodict temperature from tree-rings, one would sample trees growing at tree line, where growing season temperature is often most limiting (Fritts, 1976). Implicit in this example is the assumption that the year-to-year ring-width variation observed in samples obtained from these trees is due to limiting climate factors at these sites, and that the limiting factor is primarily temperature and not precipitation. Careful sampling within a site is essential to maximize the climate signal of interest, and to minimize non-climatic factors, such as competition with neighboring trees and individual tree damage, which can effect ring-width patterns (Cook, 1987).

Once trees are sampled and ring-widths measured, correlation of climate variables with ring-widths is done to determine the best set of climate variables that can explain the variance observed in the ring-widths. This is done with weather station records in the area of study, contemporaneous to the tree-ring record. Once a relationship has been established, tested, and verified, one can use a linear model to retrodict climate parameters over time periods when only tree-ring records exist (Fritts, 1976).

ANECDOTAL EVIDENCE FOR FIRE ON THE KENAI PENINSULA

Little information about the occurrence of fire on the Kenai Peninsula prior to 1940 exists. The information that does exist is mostly found in anecdotal accounts of “extensively burned forests,” or reports of “rarely traveling more than two miles without entering a burned area” (Whitney, 1921). The earliest documented account of a fire on the Kenai Peninsula comes from the journal of Peter Doroshin, a Russian prospector working near the east end of Skilak Lake in the summer of 1851. Doroshin reports being unable to work for a period of several days due to a forest fire in this area (Lutz, 1960). Unfortunately the exact location of Doroshin’s mining site remains unknown, however, an old burned area south of Skilak Lake needs to be examined.

Approximately fifty years later, W.A. Langille on a survey trip across the Kenai Peninsula, described general areas where fires had burned on the landscape (Langille, 1904). He mentioned that much of the plateau region was burned, especially along both sides of the Kenai River. However, the Kenai River runs for approximately 100 kilometers through the mountains and the lowlands. Since Langille (1904) made the distinction between the mountains and the plateau, one can assume that this account refers to what is known today as the Kenai lowland region. Unfortunately, Langille did not name specific locations, or give specific dates of fires.

Palmer (1938) quotes Andrew Berg, a homesteader and trapper who arrived on the Kenai Peninsula in 1890, as saying, “there were three fires , this first occurring in 1871, the second in 1891, and the third in 1910”. These fires reportedly burned over the benchlands area between Skilak and Tustumena Lakes. In a review of the early occurrence of moose on the Kenai Peninsula, Lutz (1960) provided an extensive review of the anecdotal evidence for the occurrence of fire on the Kenai Peninsula.

KENAI PENINSULA RESEARCH

Very little research concerning fire history of Kenai Peninsula forests has been done. Lutz (1956) conducted field studies during the summers of 1949 through 1952 in an attempt to describe ecological effects of forest fires in Alaska. He was especially interested in the large 1947 fire which burned over 110,000 ha of black spruce forests in the center of what is now the Kenai National Wildlife Refuge (Kenai NWR). Although he did not set out to describe fire history, Lutz provided some indications as to the age of some of the 1947 pre-fire forest stands. However, as with Langille, Lutz provided only general descriptions of the areas where he did his studies. Given this limitation, only broad generalizations can be made from his work.

Gracz *et al.* (unpubl.) describe the disturbance history of the Kenai NWR white spruce (*Picea glauca* [Moench] Voss), birch (*Betula papyrifera* L.), and aspen (*Populus tremuloides* L.) forests. Their study provides an approximate 5-10 year resolution for the occurrence of fires and other disturbances in the mature white spruce forest type of the Kenai NWR. Although no direct evidence for fire in black spruce forests is presented, generalizations may be drawn between fires in white spruce and black spruce forests. Two upland white spruce sites in the northern lowlands region investigated by Gracz *et al.* (unpubl.) are surrounded by black spruce forests. Fires were found to have burned at these sites prior to 1870 as determined from age-class analysis. It is conceivable that these fires not only burned the white spruce forest, but also burned the surrounding black spruce forest.

Therefore, given the general nature of Lutz's (1956) study and the specificity of Gracz *et al.* (unpubl.) to white spruce forests, very little is known of the fire history of black spruce forests on the Kenai NWR.

ALASKA FIRE HISTORY STUDIES

Two fire history studies done in Alaska may provide useful comparisons to the fire history of Kenai NWR black spruce forests. Yarie (1981) used age-class analysis to calculate the fire cycles and fire frequencies of an approximately 100,000 km^2 western interior Alaska forest along the Porcupine River. This area included white spruce, black spruce, and hardwood forest types. Yarie (1981) was able to calculate the fire cycle for the past 200 years for each of the stand types. He found that white spruce forests burn approximately every 100 years and black spruce forests burn approximately every 40 years. These estimations were based on three to five tree ages per stand from 371 stands. Using this small number of age determinations for each stand and then assuming those trees accurately represent stand age structure is a questionable assumption. Regeneration of black spruce tends to occur over one to two decades after a fire event (Black & Bliss, 1980; Sirois & Payette, 1989; Gagnon & Morin, 1990). Sampling three or five trees in a post-fire stand is insufficient to represent the range of variability in tree ages one would find in most even-aged post-fire forest stand. Therefore, a likely error in the study would be the underestimation of maximum tree ages leading to the calculation of higher fire frequencies and perhaps shorter fire cycles.

Gabriel and Tande (1983) attempt to describe the fire history of individual physiographic regions of Alaska by using fire statistical data. Fires were mapped in individual geographic units using lightning fire location data for a period of 23 years, from which fire size per year, per geographic unit was determined. They determined a fire cycle of over 2,000 years for the Porcupine Plateau, where Yarie (1981) calculated a fire cycle of 26 years for the same area. The authors also calculated a fire cycle of greater than 10,000 years for the Kenai Peninsula. The use of reported fire data is extremely biased towards fire detection, and the use of only lightning fire data is biased towards areas where lightning fires are more common (i.e. interior Alaska). Using data for only 26 years during a period of active fire suppression also introduces a bias towards smaller fires and longer fire cycles. Describing fire history for large areas (53 units averaging 7 million acres each) cannot be done reliably using only fire statistics since different forest types will burn with different frequencies. Given these limitations, Gabriel and Tande's (1983) attempt at a broad-brush treatment of the fire history of Alaska is of limited usefulness.

DENDROCLIMATOLOGY

There have been numerous studies which detail tree-ring reconstructed temperature in high latitude regions (Jacoby & Cook, 1981; Fritts & Lough, 1985; Jacoby *et al.*, 1988; Jacoby & D'Arrigo, 1989; Briffa *et al.*, 1990; Briffa & Schweingruber, 1992; D'Arrigo & Jacoby, 1992; Schweingruber *et al.*, 1993; Briffa *et al.*, 1994; Earle *et al.*, 1994; Gostev *et al.*, 1996; Luckman *et al.*, 1997; Overpeck *et al.*, 1997; MacDonald *et al.*, 1998; Mann *et al.*, 1998). Most relevant to the current study are three investigations: Jacoby and D'Arrigo (1989), Briffa *et al.* (1992), and Mann *et al.* (1998).

Jacoby and D'Arrigo (1989) reconstructed northern North American annual temperature from a tree-ring network extending along the boreal forest latitudinal tree line from northwestern Alaska to northeastern Canada. Based on eleven tree-ring width chronologies, they were able to reconstruct 302 years (1671-1973) of annual temperature. Of interest in this reconstruction is the dramatic and sustained warming trend as recorded by tree-rings beginning around 1850 and continuing through the 1940s. During this period of time, reconstructed annual temperatures increased more than 2.0 ^{o}C.

Mann *et al.* (1998) reconstructed Northern Hemisphere temperature trends using proxy indicators of temperature including ice core, ice melt, coral, and tree-ring data, along with gridded (5^o x 5^o grid) annual temperature anomalies from meteorological station data. Their reconstruction does not show the dramatic, sustained post-1850 increase in temperature that Jacoby & D'Arrigo (1989) show. Instead, Mann *et al.* (1998) show a dramatic post-1900 warming trend which terminates in the 1940s. Since Jacoby and D'Arrigo (1989) reconstructed Northern Hemisphere temperatures and Mann *et al*. (1998) reconstructed temperatures from a much more broad area with much more data, the results are different.

Briffa *et al.* (1992) reconstructed coastal Pacific northwest and Alaska summer temperatures from a network of tree-ring density chronologies from this region. The Briffa *et al.* (1992) reconstruction shows a sustained increase in temperature beginning around 1900 and lasting until around 1940. However, it does not show evidence of a warming trend beginning around 1850 as Jacoby & D'Arrigo (1989) show. Rather, a dramatic cold period is seen beginning around 1800, lasting for approximately 25 years.

Temperature reconstructions are often spatially explicit, only representing a small area around the study site. Therefore, comparison of a coastal area temperature reconstruction with one done in the interior of Alaska or above the Arctic circle may not reveal similar patterns of temperature change over time.

Chapter Two: General Setting of the Kenai National Wildlife Refuge

"The mountainous portion is the greater, made up of a range of extremely rugged mountains, from 3,000 to 6,000 feet in altitude, the valleys for the most part ice-filled to a general elevation of 2,000 to 4,000 feet, the ice uniting in a compact body, with its tentable [tentacle]-like arms spreading in every direction…" *W.A. Langille,* on the physiography of the Kenai Peninsula, 1904.

PHYSIOGRAPHY AND GEOLOGY

The Kenai Peninsula is located in southcentral Alaska and extends from 59^{o} to 61^{o} N latitude and 148^{o} to 152^{o} W longitude (Figure 1). Two physiographic provinces dominate the peninsula; the Kenai lowlands in the west and the Kenai Mountains in the east (Figure 2). Forming the eastern spine of the peninsula, the Kenai Mountains rise to elevations in excess of 1,900 meters and contain the Harding Icefield along with many tidewater and land-terminating glaciers. The Kenai lowlands extend from the base of the Kenai Mountains, west to the shores of Cook Inlet. Elevations in the lowlands rarely exceed 550 meters and are generally below 300 meters.

The Kenai River flows westward from the mountains through the middle of the Kenai Peninsula, dividing the lowland region into a northern area (the northern Kenai lowlands) and a southern area which can be described as the central Kenai lowlands. My study areas are in the northern Kenai lowlands and are bounded by the area burned in 1947 ("Forty-Seven Burn", FSB) and an adjacent area known as the Pipeline Road Study (PRS) area (Figure 3).

Modern Kenai lowland physiography is a result of repeated advances and retreats of alpine and valley glaciers from the Kenai Mountains and Cook Inlet, respectively. Four stades in the Naptowne late Pleistocene glaciation are recognized, the earliest being

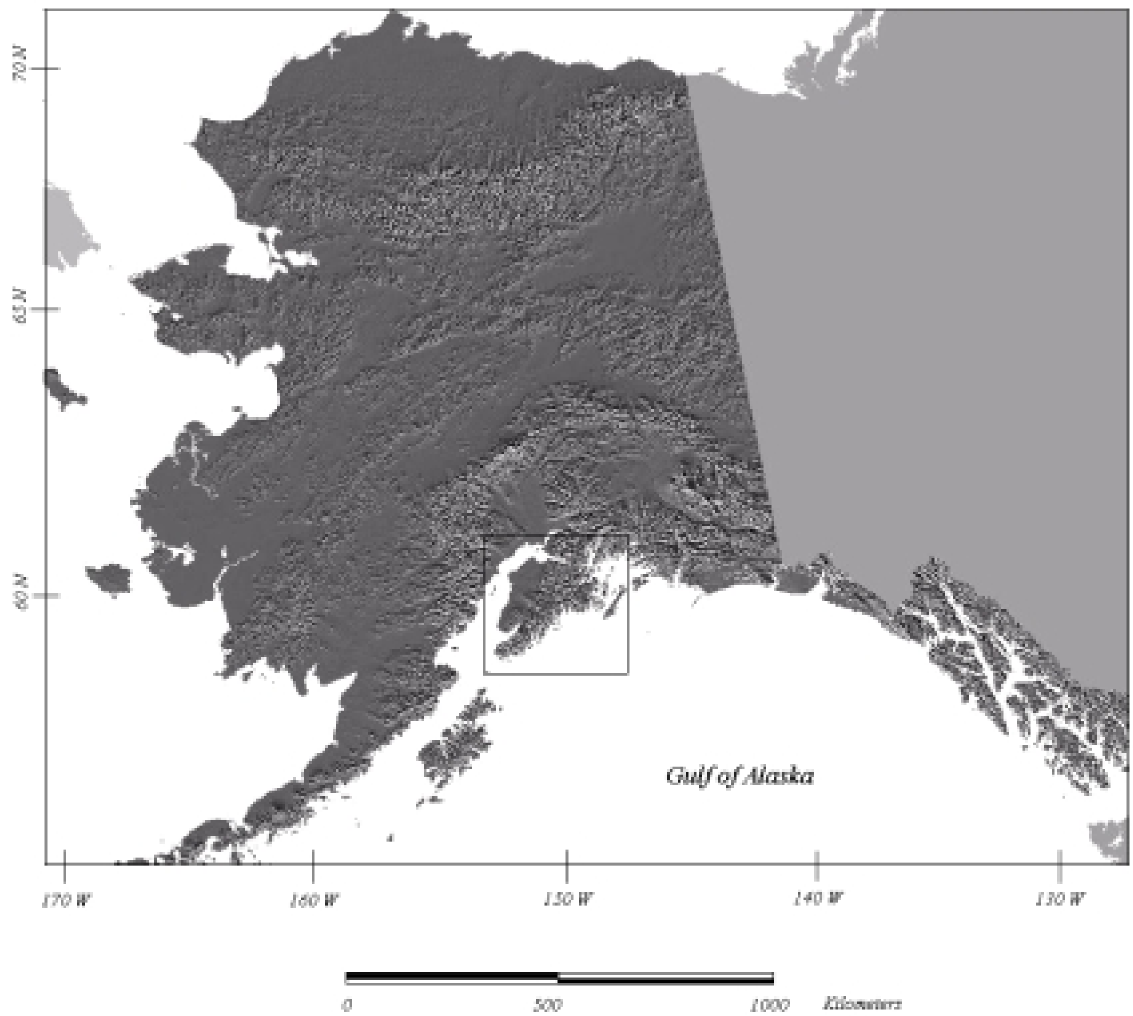

FIGURE 1. Location of the Kenai Peninsula, Alaska.

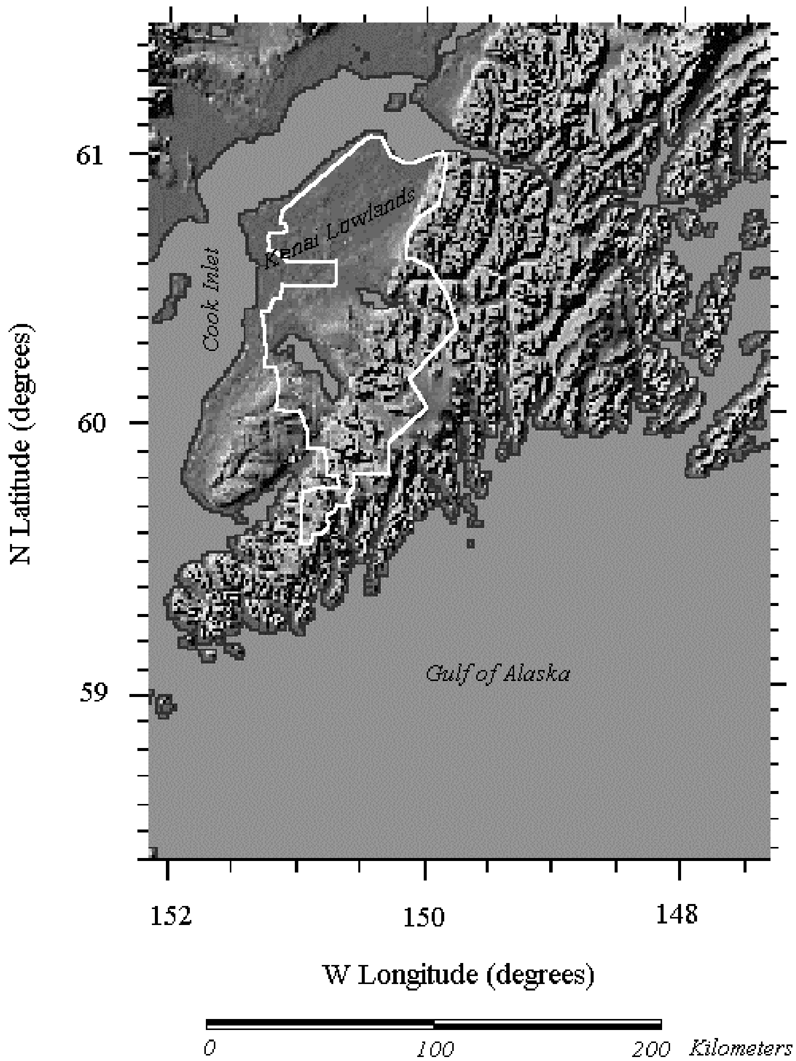

FIGURE 2. Physiographic provinces of the Kenai Peninsula and location of the Kenai National Wildlife Refuge.

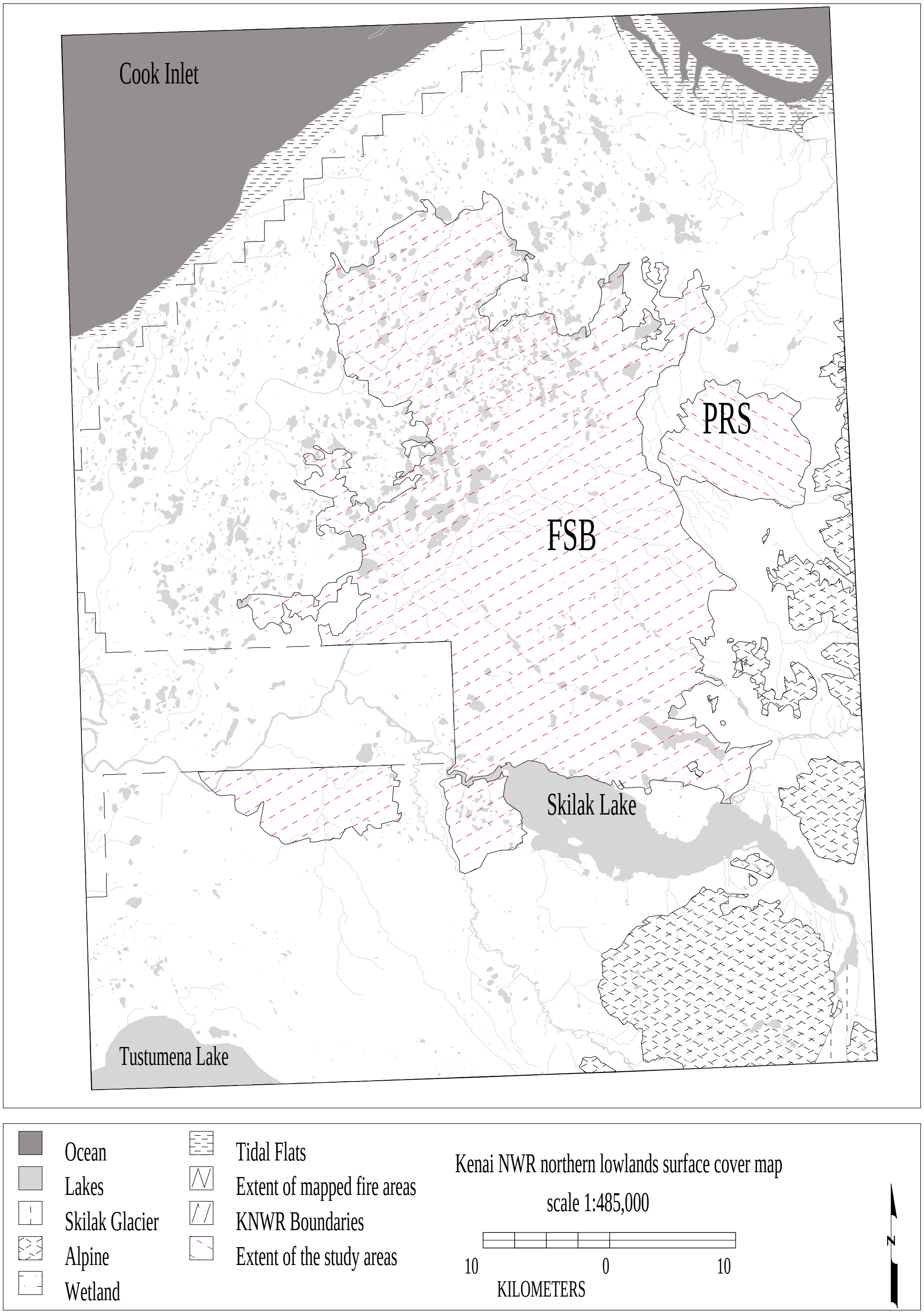

FIGURE 3. Locations and extents of the Forty-Seven-Burn (FSB) and the Pipeline Road Study (PRS) areas.

the Moosehorn dated at approximately 25,000 years BP to 16,000 years BP, and the final Elmendorf stade which is dated to approximately 10,000 years BP (Reger & Pinney, 1997).

The northern lowlands can be further sub-divided into two physiographic regions; the poorly-drained northwestern area dotted by hundreds of small kettle hole lakes and the glacial outwash plain in the southeastern region which has few lakes and little topographic relief (Figure 3). However, moraine deposits can be found throughout the entire northern lowland area.

The northern Kenai lowland region is covered with glacial till, volcanic ash, and deep layers of loess blown in from glacial deposits, all of which cover a thick layer of Tertiary sediments called the Kenai group (Karlstrom, 1964). Many different forest soil types which developed from different parent materials are found in the northern lowlands. The Naptowne soil type underlies most of the area burned in 1947 and is developed from fine textured silty material derived from loess and underlain by a gravely or cobble substratum. This soil type is largely found in areas of moderate to steep rolling hills and flat to gently sloping terrain (Rieger *et al.*, 1962).

LANDUSE

Native Alaskans, the Dena'ina (an Athabascan tribe), subsisted off the land for hundreds of years prior to the Russian influence of the mid-to late 18th century. When Captain Cook traveled to this region in 1778, Russian traders had established a permanent trading post on Kodiak Island, 160 kilometers to the south of the Kenai Peninsula (Whitney, 1921) . Archibald Menzies reported a Russian settlement at the mouth of the Kenai River occupied for nearly 12 years by the time he arrived in 1794. He also indicated that Russians were engaged in "commercial pursuits" (namely the fur trade) at this time around the Kenai Peninsula and in

Prince William Sound (Olson, 1993). Further commercialization took place near the end of the 18th century when the first ship was launched from a shipyard established on Resurrection Bay on the eastern coast of the Kenai Peninsula in 1795 (Whitney, 1921).

After the sale of Alaska from Russia to the United States in 1867, curiosity about the Great Land grew and during the mid-to-late 19th century, many hunters, trappers, and miners traveled to the Kenai Peninsula in search of wealth and adventure. Eventually permanent towns were settled and today three major towns are located in the Kenai lowlands, Sterling, Soldotna, and Kenai (Figure 4).

Established by President Franklin D. Roosevelt in 1941, the Kenai National Moose Range was intended to preserve the habitat of the giant Kenai moose. In 1980, with the Alaska National Interest Lands Conservation Act (ANILCA), the Moose Range name was changed to Kenai National Wildlife Refuge and more land area was acquired. Today, the Kenai NWR spans both the northern lowlands, the central lowlands, and the benchlands. Total land area of Kenai NWR exceeds 30% of the Kenai Peninsula land area (ca. 690,000 ha) (Figure 2). Major industries on the Peninsula include gas and oil exploration, timber harvesting on private land, and tourism. During the spring, summer and fall months hunting and fishing, along with other recreational activities, attract many thousands of people to Kenai NWR.

CLIMATE

The climate of the Kenai Peninsula can be characterized as boreal-maritime. A drier continental climate influences the central Peninsula, with a cool moderating oceanic influence along coastal areas. Storms typically track into the Gulf of Alaska and can produce locally heavy precipitation over much of the Peninsula. However, to the northwest of the Kenai

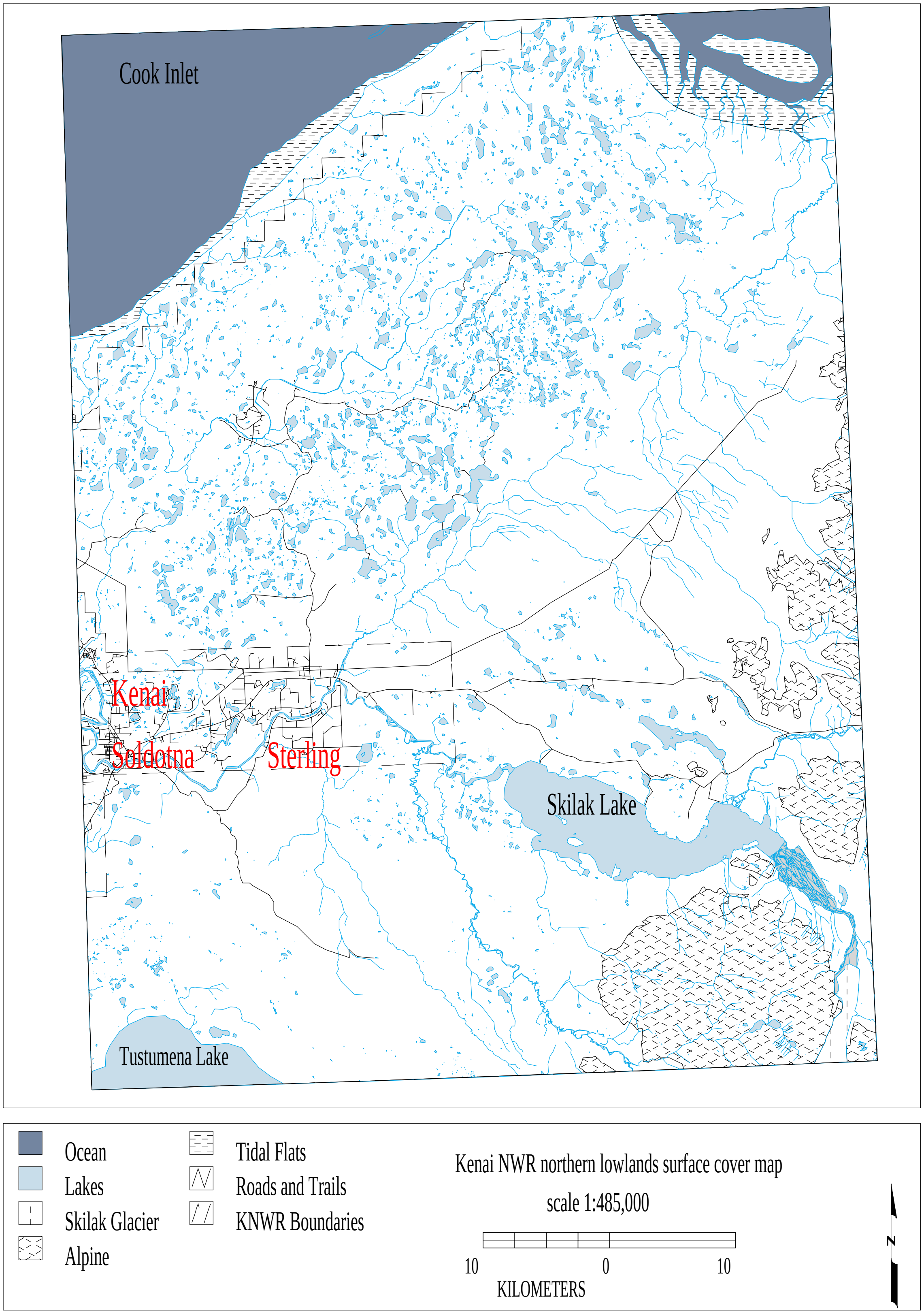

FIGURE 4. Location of Sterling, Soldotna,and Kenai in the Kenai lowlands.

Mountains a rainshadow effect extends for a distance of approximately 15 to 20 kilometers into the northern lowlands. This rainshadow greatly reduces the amount of precipitation this area receives, resulting in substantially drier conditions than the rest of the Peninsula for the summer months (De Volder, *personal observations*).

Mean temperatures at Kenai range from -11^{o}C in January to 12^{o}C in July. Lightning is infrequent over the Kenai Peninsula, but it can occur throughout the summer months associated with convective thunderstorms. During warm early spring conditions, trees may become water-stressed due to warm temperatures and frozen soils (Fritts, 1976). Fire weather tends to be severe under these conditions, and fire spread is rapid, usually resulting in severe stand-replacing fires (De Volder, *personal observations*). Annual precipitation at Kenai averages 484 mm with approximately one-third falling as rain from May to August (NCDC-USHCN, 1998). Fall rains commence in September with an average of 85 mm of precipitation falling during this month. The snow-free season begins in late-April to mid-May and ends in late-September to early-October.

VEGETATION

The dominant tree species in the northern lowlands is black spruce (*Picea mariana* [Mill] B.S.P.) (nomenclature follows (Hultén, 1968). It is found equally on well-drained and poorly-drained soils. On well-drained sites, the black spruce forest type typically has understory components of feather mosses (*Pleurozium*, *Ptilium*, and *Hylocomium* spp.), lichens (*Cladonia* and *Cladina* spp.), lingonberry (*Vaccinium vitis-idea* L.), and Labrador tea (*Ledum palustre* L., *Ledum palustre var decumbens* (Ait.) Hult.). On poorly drained sites understory vegetation is usually restricted to mosses, lingonberry, and Labrador tea. Well-drained, hilly moraine deposits are found throughout the study area and support mixed conifer stands of white spruce (*Picea glauca* [Moench] Voss), paper birch (*Betula papyrifera* Marsh.), quaking aspen (*Populus tremuloides* L.), and balsam poplar (*Populus balsamifera* L.). These species are also found scattered throughout the northern lowlands with black spruce, mostly on well-drained sites.

20TH CENTURY FIRES

Since fire records have been kept (ca. 1940), four large fires have burned in the northern Kenai lowlands. In 1947 a large fire occurred in the northern lowland region, burning approximately 110,000 hectares of black spruce forests (Figure 5). Current regeneration in this area is comprised primarily of black spruce and scattered birch and aspen trees that are 50 years of age, or younger. Three other fires burned approximately 32,000 hectares, 1,500 hectares, and 1,970 hectares in 1969, 1974, and 1996, respectively (Figure 5). Similar vegetation composition to that of the 1947 burn occurs in the 1969 and 1974 burns, while white spruce was a significant component of the area burned in 1996. Within the historically documented burns exist unburned vegetation islands that represent fragments of previous post-fire forests. Trees within these islands may be 100 to 200 years of age. Isolated and protected stands containing living black spruce trees over 230 and up to 360 years of age have been located in the northern lowlands (De Volder, unpubl.).

Several other fires have burned within the Kenai NWR since fire records have been kept. In July of 1963, a small fire burned approximately 160 hectares of black spruce forests around Engineer Lake in the northern lowlands. This fire burned over an area that had burned in 1947, only 16 years previous. In 1994 a fire (Windy Point burn) was started by a campfire of a hunting

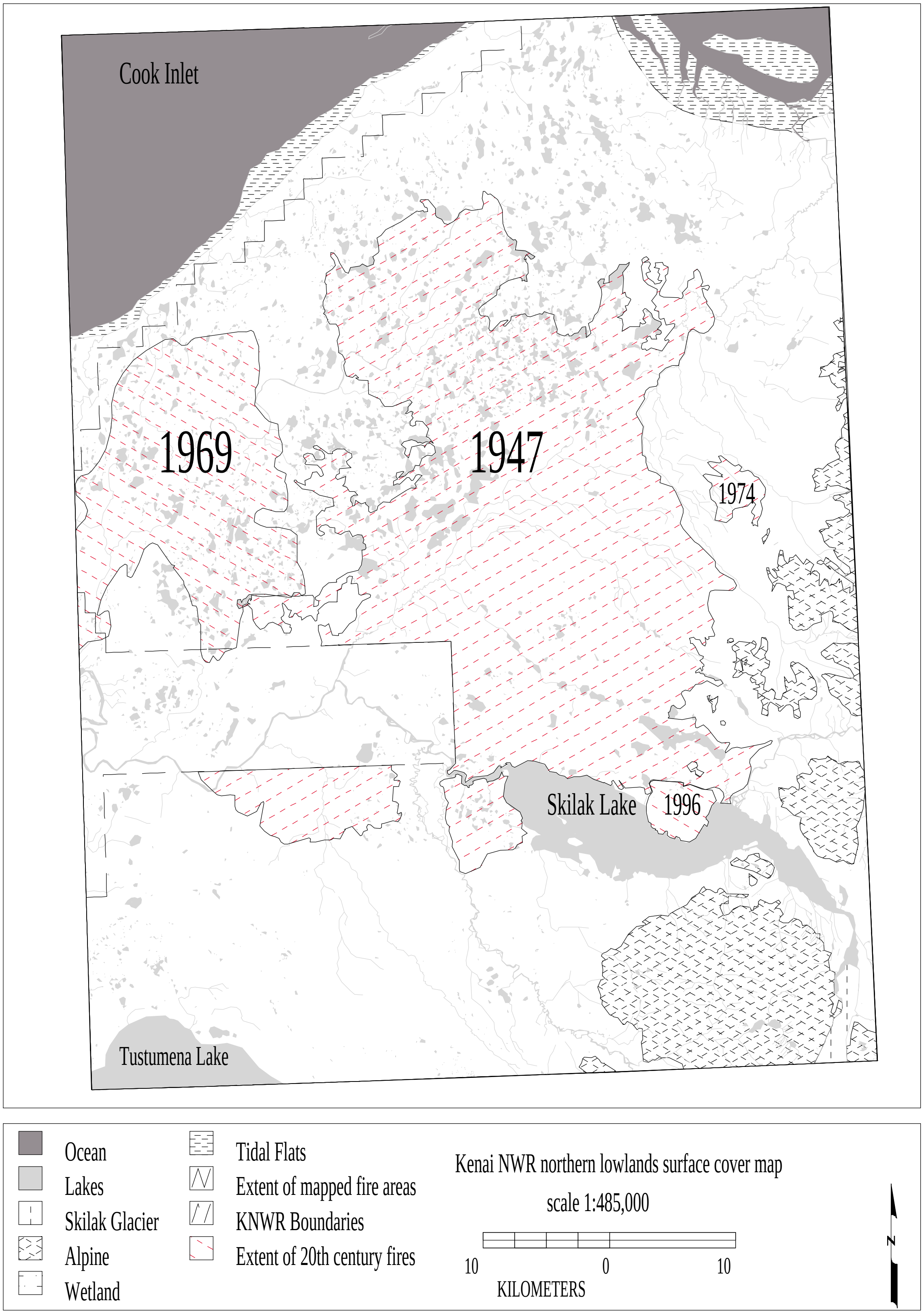

FIGURE 5. Locations of the 1947, 1969, 1974, and 1996 burns in the Kenai lowlands.

party on the southern shore of Tustumena Lake in the benchlands area. This fire began in August and burned over 1,100 hectares of mature black spruce forests, however it did not spread significantly into the surrounding white spruce forest type. This fire burned through September and was extinguished by the fall rains. In early June of 1996 a large fire occurred in the white spruce forest type in the uplands southwest of Tustumena Lake. Named the Crooked Creek fire, this fire began as an accidental ignition in a wood chip pile on private land, and eventually burned more than 7,000 hectares of private and Kenai NWR land.

Chapter Three: Fire History of Lowland Black Spruce Forests on the Kenai National Wildlife Refuge

"On all trips made on Kenai Peninsula we rarely traveled a distance of more than 2 miles without entering a burned area. These fires have been very destructive to timber. In most cases nearly every tree of any size was killed, and 90 per cent or more of them fell, upturning their roots." *Milton Whitney*, commenting on forest conditions on the Kenai Peninsula in 1916, from Field Operations of the Bureau of Soils, 1916 (Whitney, 1921).

METHODS

FIRE HISTORY SAMPLING

A unique situation exists within the FSB study area. Many still standing, fire-killed trees (burn poles) exist within this area. Weathered gray and without bark, these burn poles are easy to locate among the green foliage of living post-1947 black spruce trees. Since they were killed in 1947, their growth was stopped and any fire scars (from previous fires) on these trees are readily visible, even when completely healed. Due to their slow rate of growth, 100 year old black spruce trees killed in 1947 rarely exceed 10 cm in diameter. Therefore recovering information about past fire events using cross-sections is more efficient than sampling in living forests of over 100 years of age.

Since fire-scarred trees are not randomly distributed on the landscape (McBride, 1983), I used a sampling scheme that employed a 'maximum likelihood of occurrence' strategy. That is, I searched for fire scars in areas where they were most likely to be found. Such areas included (1) hillsides, or any significant change in slope, (2) margins of lakes and wetlands, and (3) old fire boundaries as determined from aerial photographs in areas unburned in the 20th century record. I focused primarily on locating and sampling fire-scarred burn poles. Upon locating a still standing scarred burn pole, I up-rooted it and removed a full basal cross-section with a hand saw. Height above root crown in centimeters, total height in meters, and diameter at breast height in centimeters were recorded for each burn pole sampled. Location of collection was marked on topographic maps using landmark locations such as lakes and wetlands for reference. Upon locating a single scarred burn pole, I searched the immediate area for additional scarred burn poles. Given that fire-scarred burn poles may have different healing forms due to amount of time between the scaring event and death, all scars encountered were collected regardless of healing form in order not to bias the sample. Within the FSB area, where no scarred burn poles could be located, I sampled unscarred burn poles for stand initiation dates. At each sampling location, I collected a total of 30 burn pole cross-sections from apparently canopy dominant individuals using the methods described above.

Vegetation islands exist within the FSB area. These are patches of living trees that were not killed in 1947, and likely represent a fragment of some older post-fire forest stand. Within these islands I cored 30 living trees to determine stand age. Trees were chosen throughout the stand, with preference given to canopy dominant or co-dominant trees as these trees were likely to have germinated after a fire event. Total height and diameter at breast height were recorded for each tree sampled. Location of collection was marked on topographic maps with the aid of aerial photographs. Black spruce trees, at a certain age, begin to reproduce vegetatively. The mode of regeneration is termed layering, and it occurs when low-hanging branch tips are covered by moist mosses. These branches eventually produce roots and begin to grow upright, and in the absence of disturbance black spruce layers could gain dominance in the canopy. These layer-derived trees are not of interest in a fire history investigation involving stand initiation dates (thus, the reasoning for sampling only canopy dominant trees).

DATING OF FIRES BY OUTER-RING ANALYSIS

Death dates of trees have been used widely in the southwestern United States in archaeological contexts for determining the construction dates of kivas, pithouses, and pueblos (Dean, 1978). Numerous other authors in other regions of the United States and Canada have used dead trees to extend disturbance histories back in time (Oliver & Stephens, 1977; Henry & Swan, 1974; Loope, 1991; Mann *et al.*, 1994) and to investigate tree demographics along with mortality and recruitment patterns through time (Johnson & Fryer, 1989; Johnson *et al.*, 1994; Mast & Veblen, 1994; Swetnam & Betancourt, 1998).

Outer-ring analysis can be used to determine whether episodic or continuous mortality of trees has occurred at a given site (Mast and Veblen, 1994). Payette *et al.* (1989) used outer-rings of fire-killed black spruce krumholtz to date fires in the northern boreal forest of Quebec when fire scars were not available. They assert "accurate fire dating with this technique may be achieved only with undecomposed stems that have retained their bark until the last fire," however, trees without bark can be used to date fires if their outer-rings are not eroded by weathering processes or decomposition. Fire dates obtained from this technique are often within a few years of the true fire date (Payette *et al.*, 1989).

The outer-ring dating technique that I present here is an expansion and refinement of the techniques used by the above authors and modified for the dating of fires in forests subject to high intensity, stand-replacing fires. For one to use this technique successfully, the use of uncharred burn poles is of great importance because charred burn poles can weather rapidly producing a sculpted surface, resulting in the loss of many, often narrow outer-rings. Furthermore, charred burn poles are assumed to have been dead at the time of the fire, therefore outer-rings of these burn poles can predate the most recent fire event by many years. My method assumes that un-charred and un-sculpted burn poles were killed by fire and subsequent outer-ring loss by physical weathering is minimal. One must use care in sampling burn poles for outer-ring dating. Standing burn poles typically have the least weathered outer-rings on surfaces that are not fully exposed to weathering elements. Therefore, if a pole is leaning, one should note the direction of lean on the cross-section, indicating the least weathered, most protected portion of the sample. Burn pole stumps, or logs, preserved under living trees are another valuable resource. Protected from excessive weathering, outer-rings on the under side (the side towards the ground) are often complete and un-weathered. A brown patena, or bark flakes often indicate an un-weathered surface, and can persist on protected burn poles and stumps for more than 100 years after death (De Volder, *personal observation*). Burn poles with excessive checking and cracking should not be sampled for outer-ring dating, although these poles can be used in age-class analysis.

In the laboratory two additional levels of detail critical to the success of this technique are (1) to note the type of outer-most ring on each specimen sampled and (2) to search the entire circuit of the sample for the most complete record of outer-rings. Since trees do not weather uniformly around their circumference, one must search the entire outer circuit of the sample to locate the outer-most rings. If latewood is present on the outer-most ring, this may indicate death late in the growing season, or early in the next year, with some subsequent weathering loss of the early formed wood cells. With this additional level of detail, it may be possible to determine the season in which the fire burned. However, in general, the loss of just a few wood cells on the outer-ring can change the interpretation of seasonality and therefore seasonal dating of fire occurrence by outer-ring analysis is equivocal. By plotting the outer-ring dates for a group of trees from a stand, one is be able to determine if all died in the same year, within a few years (suggesting a fire event), or if there is a wide range of dates that may suggest substantial outer-ring loss or death by some other process. One should strive to recover a sample of 20 or more burn poles for this technique to be used properly and fires to be dated accurately.

In the current study, I collected un-charred burn poles from areas that had an unknown 20th century fire history (i.e. vegetation islands within known burns or forest stands adjacent to dated burns) in order to obtain death dates for these individuals (Johnson & Fryer, 1989; Mast & Veblen, 1994). Increment cores of living trees were also taken from these stands of unknown fire history in order to obtain a minimum fire date bracketed between the inner-ring date from the oldest living tree(s) in the stand and the cluster of outer-ring dates of any burn poles recovered from the same site.

DENDROCHRONOLOGICAL ANALYSIS

Increment cores were mounted on individual wooden strips following the methods of Stokes & Smiley (1968) and were surfaced with increasingly finer grades of sandpaper until individual tracheids were visible under 40x or greater magnification. Each increment core was then visually cross-dated which involves recognizing and matching patterns of narrow and wide rings, or single narrow rings of a known date common among trees (Fritts & Swetnam, 1989). Other tree ring characteristics from a given area that can aide in cross-dating include: frost rings (inter-annular ring damage associated with sub-freezing temperatures during the growing season (Glerum & Farrar, 1966), traumatic resin ducts (resin pockets within an individual annual ring related to environmental stress or to a fire occurrence (Brown and Swetnam, 1994)), and light rings (fewer than normal thick-walled late-season growth cells within an annual ring). These easily recognizable tree-ring patterns or features are called "pointer years" (Kaennel &

Schweingruber, 1996). Once pointer years were identified, I used those years as a beginning date and counted rings to the next pointer year. If the next pointer year was dated correctly, the preceding segment was tentatively considered to be dated correctly. However, if a discrepancy in a ring count between pointer years was found, the source of the problem was located and corrected.

Once visually cross-dated, increment core ring-widths were measured to the nearest 0.01mm on a sliding micrometer bench. The computer program COFECHA was used (Holmes, 1983) to check the accuracy of visual cross-dating by dividing tree ring series into segments of 40 years in length with an overlap of 20 years, and to compare these segments with a temporary master chronology constructed with the remaining series from that site, or with an independently constructed chronology. COFECHA determines the best fit for each of these segments based on the highest correlation coefficients, and returns suggested beginning year values for each segment. Computation of series intercorrelation is also preformed by COFECHA and is a measure of the mean correlation among all tree-ring series from a single site. A high series intercorrelation indicates good agreement among the growth of trees from a particular site or area. Dating errors are indicated by locally low segment correlations. COFECHA suggests positions where the segment(s) has a higher correlation, however it is incumbent upon the investigator to check this possible source of dating error on the wood sample.

To aid in dating burn pole samples, a master tree-ring width chronology was developed by using cross-dated increment cores from living black spruce trees from the northern lowlands region. As more burn pole samples were dated the master chronology was supplemented by adding accurately dated un-scarred burn poles, this allowed me to construct a 300 year long chronology; longer than was possible by using living trees alone.

The seasonal occurrence of scars was estimated by determining the position of the scar within the annual ring. I defined four categories of seasonality: EE, early-earlywood (first third of annual ring); ME, middle-earlywood (second third of annual ring); LE, late early wood (last third of annual ring); and LW, latewood (within latewood band of the annual ring) (cf. Baisan & Swetnam, 1990). For this study: EE was interpreted as May to early June; ME as mid-June to mid July; LE mid-July to mid-August; and LW as mid-August to mid-September. Once visually cross-dated, as a check of my visual cross-dating, I measured ring-widths of a sample of approximately 40% of the total number of cross-sections collected in this study. Measured ring widths were then checked against the master ring-width chronology using COFECHA as described above. For those cross-sections that could not be visually cross-dated (due to short ring series or insufficient ring-width variability), I measured the ring widths of these cross-sections first, then used the suggested dates from the COFECHA analysis as a starting place. Then based on matching of the master ring-width chronology and pointer years, and in a graphical analysis of line graphs and the wood specimens I accepted or rejected this suggested date.

HEIGHT-AGE EQUATION

Age-class analysis of living and dead trees can be used to provide a minimum date for fires. However, this is limited by bias in the dates derived from cross-dated increment cores or cross-sections taken at some height above root crown. If one wishes to accurately date a fire event using age-class analysis, one needs to correct for these systematic biases, which are on the order of several years (Gagnon & Morin, 1990; DesRochers & Gagnon, 1997). The root crown (or root collar) is the zone of differentiation between the bole and the roots of a tree or shrub and has the most complete record of annual rings. At a certain height above the root crown a tree will be a certain age, and will have a predictable number of annual rings. The rate at which a tree grows in height will determine this number of annual rings. The number of rings missed by sampling at a certain height above root crown can be estimated by the use of a linear correction factor.

In this study, the fire-scar record was relatively short, and I wanted to extend the fire history record by using age-class data of fire-scarred burn pole sections and increment cores from living trees. In order to more accurately interpret these age-class data, I developed a height-age prediction equation to account for sample height above root crown. Two recently burned areas within Kenai NWR were selected where a total of 100 black spruce seedlings and saplings were harvested (Figure 6). A random point was selected within the 1974 burn (EAST) and the 1969 burn (WEST) intensive sample sites where a 100 meter transect of variable width was established. Every two meters along the transect, on the right or the left side as determined by a coin toss, the closest tree was sampled. Each tree was uprooted, excess root mass removed, and a 40-50 cm long stump section (including the root crown) was taken. In the laboratory, trees from each site were prepared separately. Each tree was cut into 1-2 cm thick cross-sections (15-20 sections per tree) and each was sanded on the bottom side with increasingly finer grades of sandpaper until individual tracheids were visible under 40x or greater magnification. Ring counts were made on the bottom of each cross-section in a random fashion (not in sequential order from each tree) so as to provide a check for ring counts on adjacent sections (Harrington & Deal, 1982). After all cross-sections were aged, each stem was then reconstructed, discrepancies in ring counts were located and corrected, and height growth in centimeters per year was measured. I measured height growth per year on each stem by using the age of sections

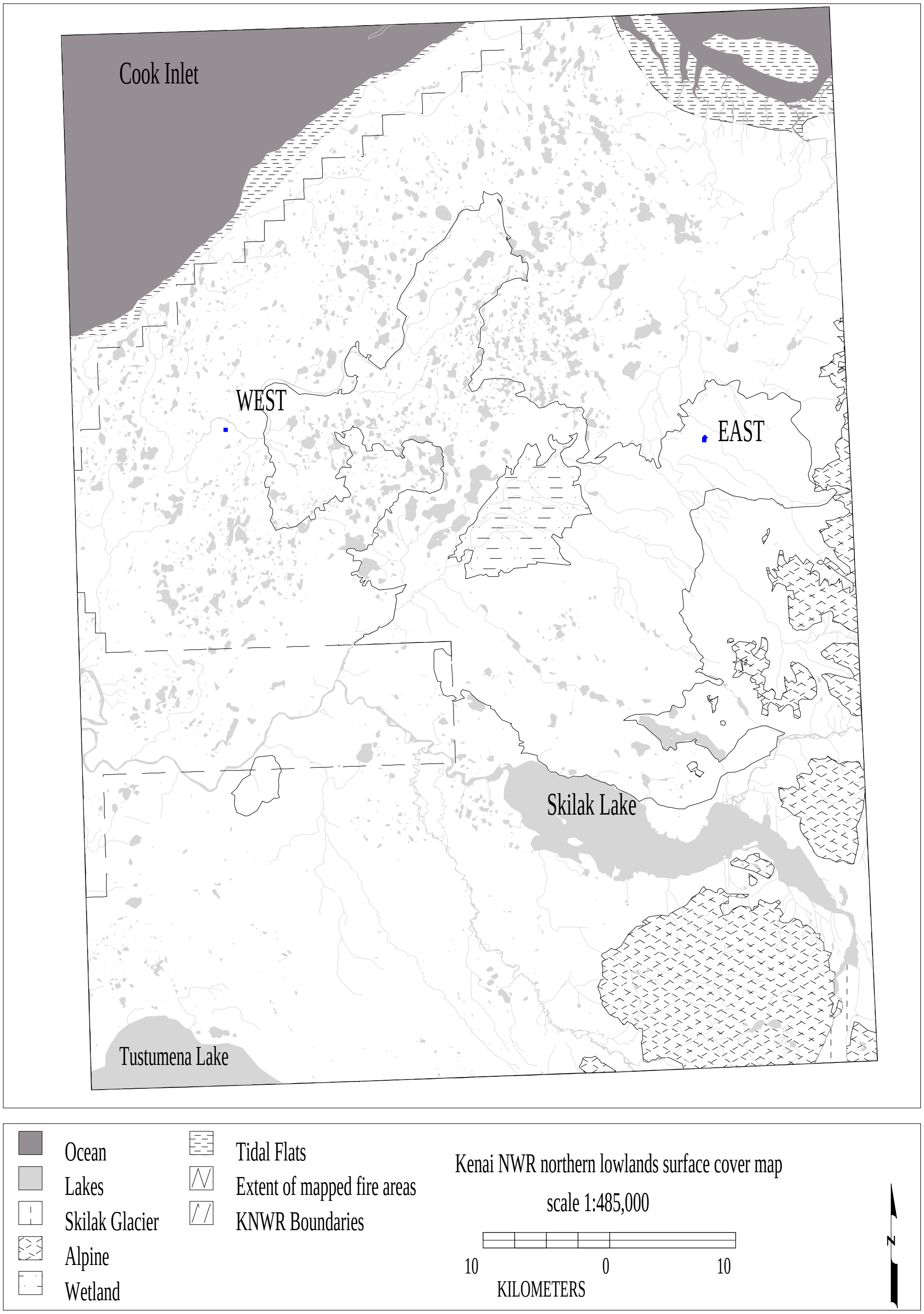

FIGURE 6. Locations of the WEST and EAST intensive sample sites.

coupled with apical bud scars which remain visible on the bark for up to 20 years (De Volder, *personal observation*). In instances where apical bud scars could not be seen, and where two adjacent sections differed in age by one year, I interpolated height growth to the midpoint of the two sections. For those seedlings that could not be sectioned, height growth was measured between apical bud scars. To overcome difficulties in determining accurate height growth in the first few years after germination, I collected, aged, and measured the height growth of 265 seedlings. Because apical bud scars are difficult to see on lower portions of a mature stem, using seedlings to determine immediate (< 4 years) post fire growth is a way to accurately determine immediate post-fire growth.

Height growth per year was standardized between trees of different ages by setting the germination year of each individual tree equal to each other regardless of calendar year. That is, for two trees that germinated in 1974 and 1980, the first year of height growth after germination would be equal to each other. Separate linear regression equations were developed based on height growth of trees from each area sampled.

FIRE MAPPING

Contiguous fire polygons were mapped using fire occurrence data obtained from fire scars, age-class of dead and living trees, and outer-ring dates of fire-killed burn poles. Fire boundaries were mapped using natural features such as lakes, wetlands, and river margins as fire breaks. Topography also aided in determining fire boundaries. In some locations, the 1947 burn stopped at elevations of approximately 75 to 90 meters (De Volder, *personal observation*). This represents a boundary between black and white spruce, or some other vegetational or fuel moisture change that limited the spread of the fire. Therefore, in some instances I used lines of topography and inferred vegetation changes as a boundary to fire spread. When mapping the edges of fire polygons, and no obvious boundary could be determined, a buffer of one kilometer was used around the outside of a sample point. Evidence from this study suggests that re-burning of any forested area does not occur in forests less than 25 years of age. Where two adjacent sample points differed in fire dates by less than 25 years, I assumed that the younger fire did not overburn the older fire area, and considered the older fire area a distinct boundary to fire spread. With the exception of one fire polygon, all mapped fire polygons are considered to be minimum estimates of true fire area.

FIRE RETURN INTERVALS AND THE FIRE CYCLE

Fire return intervals and fire cycles were calculated using all fire occurrence data including fire scars, age-class, and outer-rings dates. Fire return intervals were calculated as the time between two successive fires at one point, or stand on the landscape. For this study, fire return intervals were calculated based on re-burning of forest stands.

A second fire history statistic is the “fire cycle” which is a measure of the length of time required to burn an area equal in size to that under study. Not all of the forested areas within the study area need to burn, just an equivalent area to that under study (Van Wagner, 1978; Johnson, 1992; Johnson & Gutsell, 1994) . One of the measures utilized in calculating the fire cycle is a time-since-fire or survivorship distribution, A(*t*), which describes the cumulative proportion of the landscape surviving longer that time *t* (Johnson & Gutsell, 1994). A semi-log plot of cumulative area burned data is used to evaluate fire frequency changes. The simplest time-since-fire distribution can be described by either a negative exponential or Weibull distribution (Van Wagner, 1978; Johnson and Gutsel, 1994). Theoretically, changes of slope in either the negative exponential or Weibull plots indicates a change in fire frequency, or fire hazard, but certain biases exist in these estimation techniques (Finney, 1995).

RESULTS

HEIGHT-AGE EQUATION

I tested for a difference in the two slope coefficients of the EAST and WEST regressions (Zar, 1999). I rejected the null hypothesis ($H_o : \beta_1 = \beta_2$) that the regression coefficients were the same. This indicates that the slopes are significantly different ($P < 0.001$) and the data sets should not be combined. Therefore I used the regression equations from each area separately. Figure 7 shows the regression equations developed from each data set. Trees from the EAST site exhibit slower height growth (greater line slope) as compared to those from the WEST site. Note that each exhibits a strong linear growth trend for at least the first 10 years.

In order to evaluate the usefulness of these linear prediction equations, each was used to correct a sample data set of 62 post-1834 fire burn pole pith dates. The date of 1834 for the fire is obtained from more than 20 fire scars from the surrounding area. Figure 8 shows the uncorrected ages of the sample data set, as well as the corrected ages derived from the WEST (Figure 8b) and EAST (Figure 8c) height-age equations. Uncorrected burn pole ages are erroneously displaced to the right, as expected (Gagnon & Morin, 1990), from sampling at a height above the root crowns (Figure 8*a*). Applying the corrections shifts the age structure to the left as expected, but the EAST height-age equation clearly shifts the ages too far and thus overestimates burn pole ages (Figure 8*c*).

The EAST corrected data set suggests the fire occurred prior to 1834, which is not the case. The WEST corrected data set predicts four trees to have germinated in 1834, and therefore does not significantly overestimate germination dates of these trees (Figure 8*b*).

One could argue that the EAST correction equation should be used to correct tree-ages from the eastern portions of the study area, and the WEST correction equation should be used to correct tree-ages from the western portion of the study area. However, using the EAST height-age equation to correct living tree ages from the PRS area (in the eastern portion of the study area) provided unsatisfactory results (not shown) where I had an absolute date of a fire occurrence. Also, the EAST site appeared to be a poor site for tree growth with the average height of trees being 0.66 meters as compared to an average height of 1.79 meters of trees from the WEST site. Therefore, all age-class data and other inner-ring dates will be corrected using the WEST height-age equation. These corrected dates will be considered to be estimated germination dates.

DATING OF FIRES BY OUTER-RING ANALYSIS

Figure 9 shows an outer-ring date distribution of 463 uncharred burn poles killed by fire in 1947. About six-percent of the burn poles have outer-ring dates of 1947, over 50% have outer-ring dates of 1946, and over 84% have outer-ring dates within five years of the fire occurrence (1942-1946) (Figure 9). The 1947 burn began in early June and burned through August. Therefore, trees killed by fire in 1947 should have begun growing in June, having produced few earlywood cells, and those trees killed in August would have put on a nearly complete ring. Therefore loss of outer-rings by physical weathering explains the few burn poles with outer-ring dates of 1947. These burn poles were not collected specifically for outer-ring dating of the 1947 burn, rather these samples were from burn poles used for age-class analysis

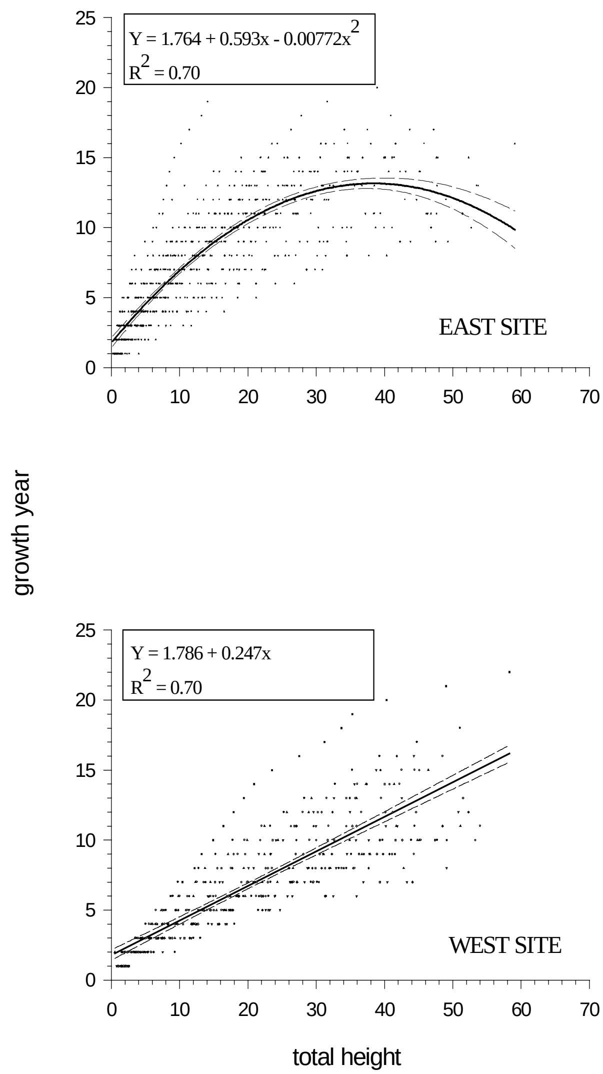

FIGURE 7. Height-age regression plots developed from trees in the EAST and the WEST intensive sampling sites; where *x* equals the height above root crown in centimeters and *Y* equals the number of years missed by sampling at height *x*. Dashed lines are 95% confidence limits.

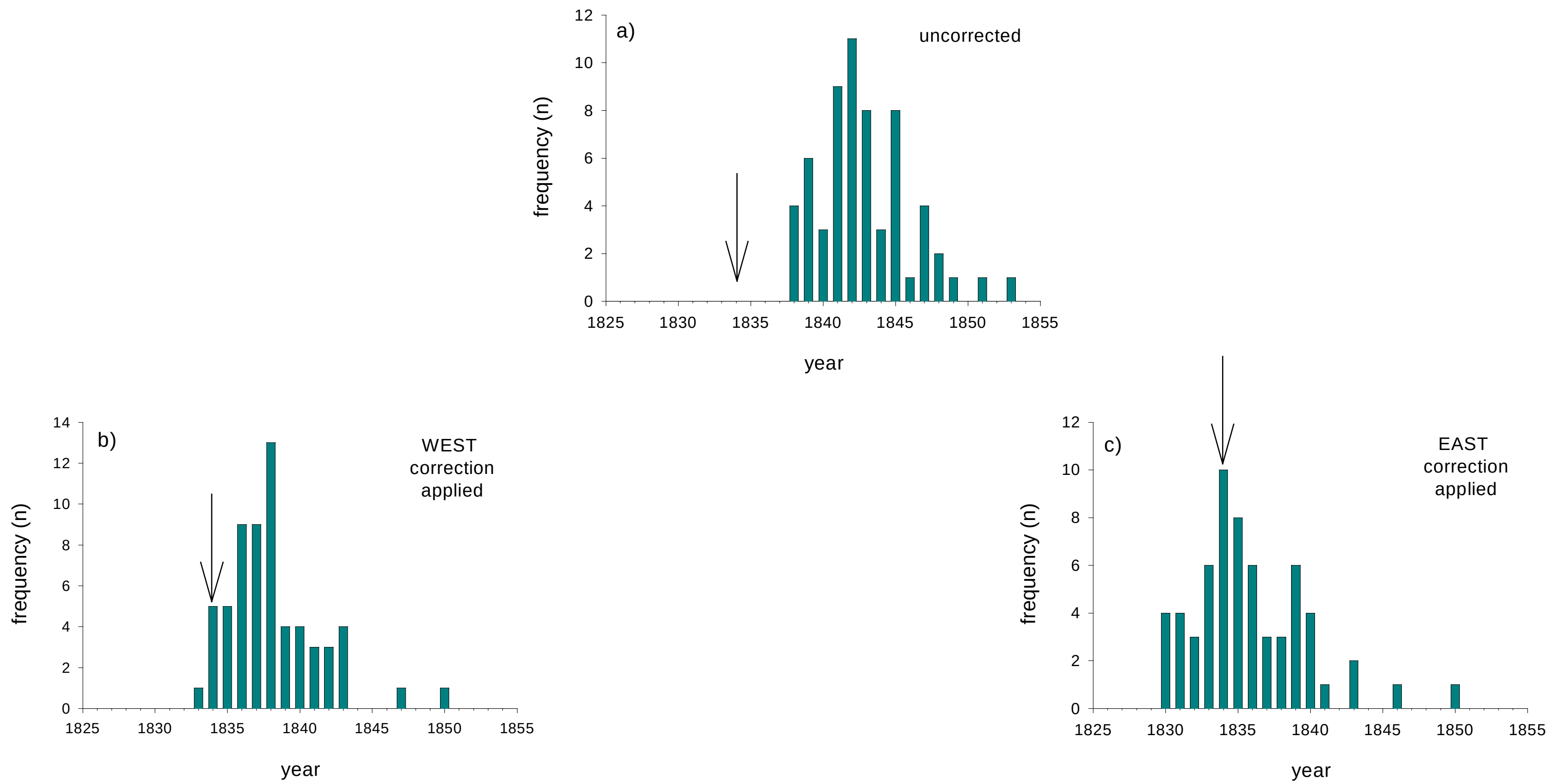

FIGURE 8. Uncorrected (a) and corrected ages of 62 post-1834 fire burn poles using the WEST regression equation (b) and the EAST regression equation (c). Uncorrected ages show a systematic shift to the right of the 1834 fire due to sample height above root crown. Note the shape of the estimated germination date distribution produced by the WEST regression equation as compared to the shape of the estimated germination date distribution produced by the EAST regression equation. Arrow is 1834.

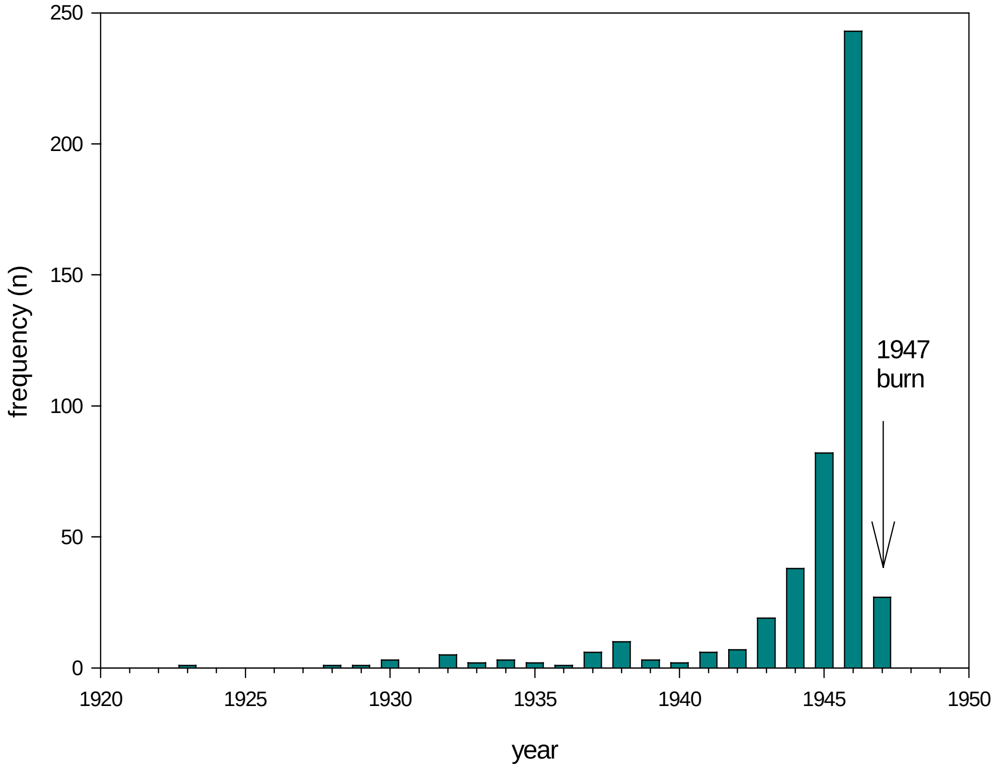

FIGURE 9. Outer-ring dates of 463 un-charred burn poles collected from within the 1947 burn. Of the total, 52% have outer-ring dates (death dates) of 1946, while 84% have outer-ring dates within 5 years (1942-1946) of the fire occurrence. One burn pole had an outer-ring date of 1956 (not shown). The left-skewed distribution is due to outer-ring loss from weathering processes, and possibly due to death of some trees prior to 1947.

and for fire-scar dating. Therefore the outer-ring date distribution presented in Figure 9 is compiled form trees not sampled for the best preservation of outer-rings. However, these outer-ring dates do provide a well-replicated control for the evaluation of other outer-ring date distributions from areas of unknown fire history.

TEMPORAL AND SPATIAL CHARACTERISTICS OF DATED FIRES

I collected samples from 90,000 hectares of the 110,000 hectare FSB and the 8,200 hectare PRS areas (Figure 10). Within this area, a total 171 sampling locations were visited during the summers of 1997 and 1998 (Figure 11). From these locations I collected 1,022 basal cross-sections and 771 increment cores. Of the total number of cross-sections, I successfully cross-dated 912 (89%). Of these, 447 cross-sections exhibited some form of scarring (44%), however only 189 of the 447 (42%) scarred cross-sections were scarred by fire. Of the 771 increment cores I successfully cross-dated a total of 730 (95%). Cross-sections and increment cores that were not datable had insufficient ring-width variability to be confidently dated. It is also conceivable that some of the undated cross-sections were older than the master chronology that I had available.

A total of 12 fire dates were determined from fire scars, age-class analysis, and outer-ring analysis. Table I shows the temporal (annual and seasonal) and spatial characteristics of each of these fires. Slightly more than 50 percent of these fires, including the 20th century fires, occurred entirely within or began early in the growing season, which is interpreted to be May to early or mid-June. The remaining half of the dated fires burned in the middle to late portions of the growing season, which corresponds to July through August, and perhaps into early-September. The individual fire sizes ranged from less than one hectare to over 36,000 hectares (Table I).

FIGURE 10. Extent of the area sampled in this study. Note the difference in area between the 1947 burn and the area sampled.

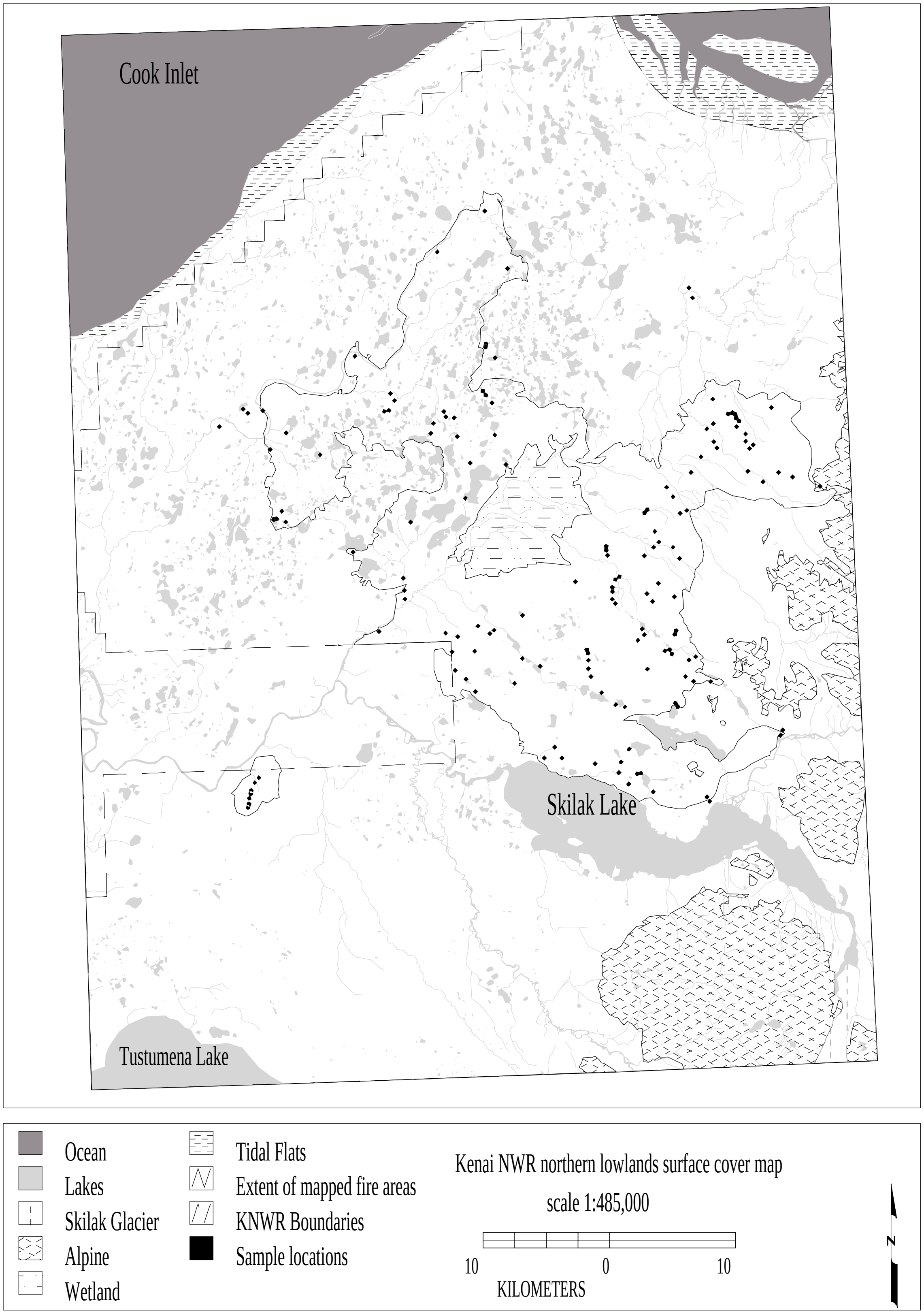

FIGURE 11. Location of all sample points from the 1997 and 1998 field seasons.

TABLE I. Temporal and spatial characteristics of Kenai NWR lowland fires. Percent of study area is based on 90,000 hectares, the sampled area in this study. Areas are minimum estimates.

Year	Season	Month(s)	Area (hectares)	Percent of Study Area
Tree-ring Based				
1708[a]	EE	June	7,119	7.9
1762[a,b]	EE	June	26,174	29.1
1801[b]	EE	June	point	NA
1828[b]	EE	June	4,887	5.4
1833[b]	EE/LW	June-August	4,101	4.6
1834[b]	EE-ME	June-mid-August	16,455	18.3
1849[a,b]	ME-LW	July-late-August	36,692	40.8
1867[a]	?	UNKNOWN	8,251	9.2
1874[b]	LE-LW	late-July-late-August	35	NA
1884[b]	?	POORLY DEFINED	?	NA
1888[b]	ME-LE	July-mid-August	20,038	22.3
1898[a]	ME-LW	July-August	1,681	1.9
1898[b]	LE-LW	late-July-late-August	1,326	1.5
20th Century Fires				
1947	EE-LE	June-August	109,836	
1969	LE	August	31,690	
1974	LE	August	1,487	
1994	LE	August	1,133	
1996	EE	early May	1,969	
1996	EE	early June	7,086	

[a]fire occurred in the PRS area

[b]fire occurred in the FSB study area

Figure 12 shows the distribution of estimated fire sizes through time, with no noticeable trend in fire size through time. However a noticeable increase in fire occurrence is observed beginning after 1830.

FIRE RETURN INTERVALS AND FIRE CYCLES

Fire return intervals were calculated for combinations of fire occurrence within the FSB and PRS areas. The range of fire return intervals is 25 to 185 years, with a mean and standard deviation of 89 and 43 years, respectively (Figure 13a, Table II, Table III). I partitioned all fire return intervals into logical physiographic categories of Mountains, Rainshadow, and Lakes (Table II). The Mountains category contains sites that are very near or in the foothills of the Kenai Mountains. Three fire return intervals in this category have a range of 71 to 163 years, with a mean and standard deviation of 132 and 52 years, respectively (Figure 13b, Table II). The Rainshadow category is defined from sites within a 25 kilometer zone from the Kenai Mountains (trending in a northeast, southwest direction) that encompasses very level terrain with few lakes and rivers. This category contains 17 fire return intervals with a range of 31 to 185 years, and a mean and standard deviation of 88 and 41 years, respectively (Figure 13c, Table II). The Lakes category is defined as those sites outside of the rainshadow, and also roughly corresponds to the divide between the glacial plain and the lakes region of the northern lowlands. This category contains 6 fire return intervals with a range of 25 to 119 years, and a mean and standard deviation of 69 and 36 years, respectively (Figure 13d, Table II).

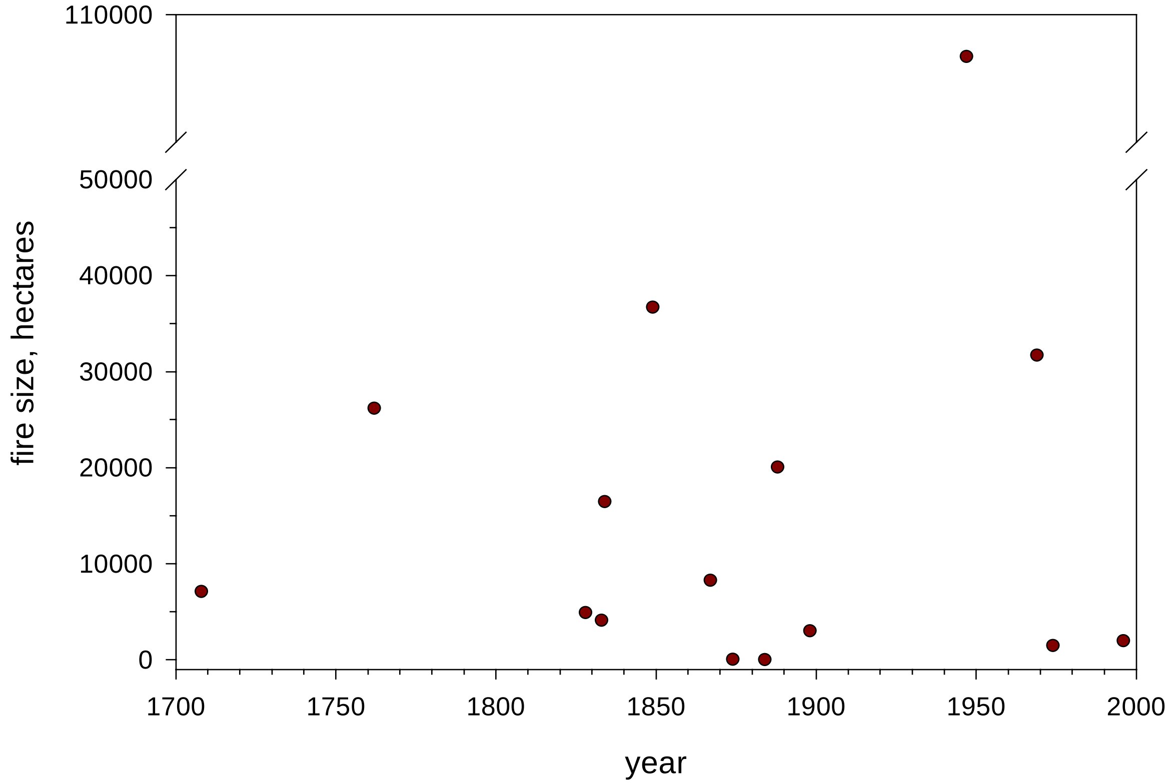

FIGURE 12. Distribution of fire sizes through time. Note the increase in the number of fires after 1828 and the apparent gaps in fire occurrence in the time period 1700-1830, and from 1900-1947.

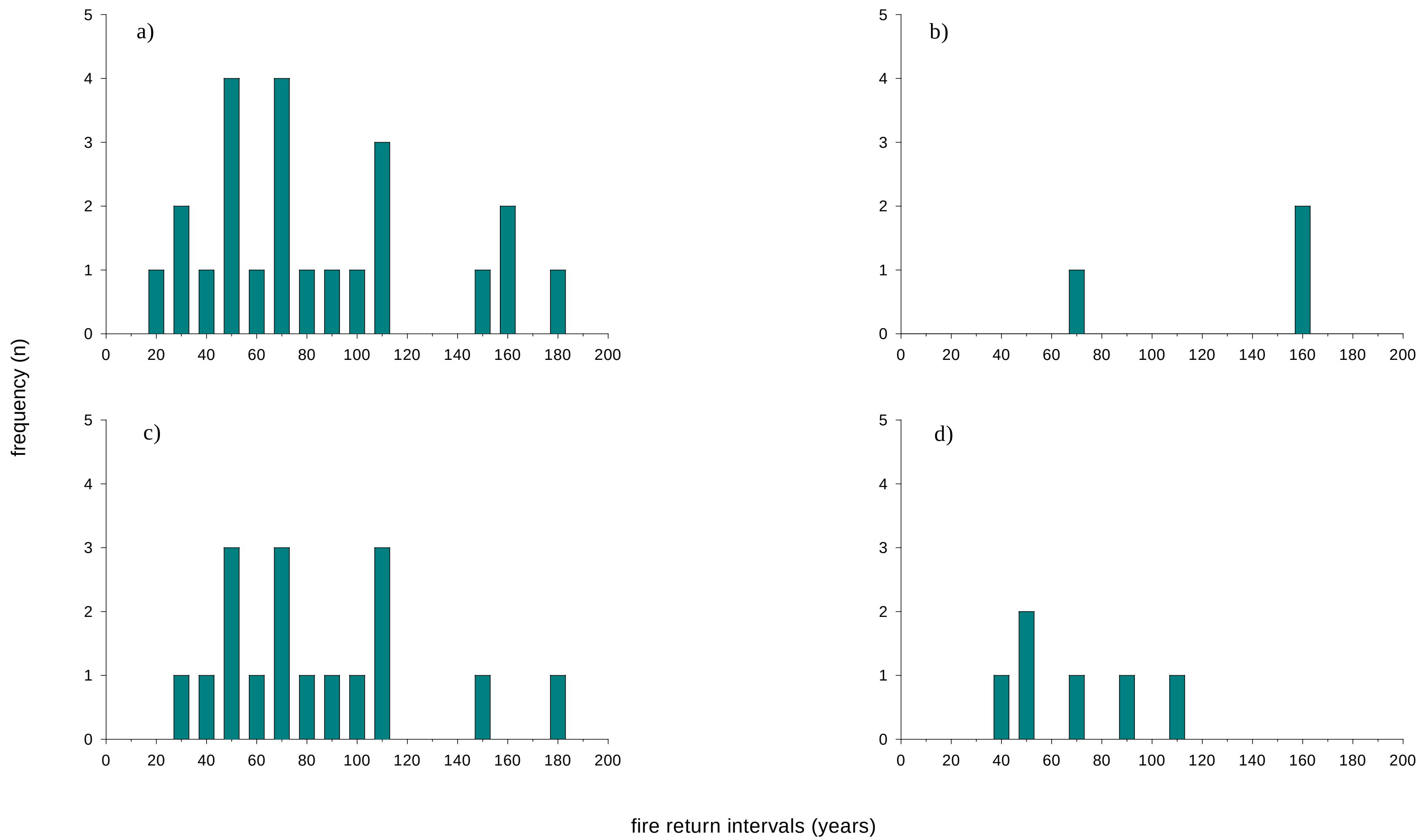

FIGURE 13. Fire return intervals for the entire study area (a), and partitioned into the physiographic regions Mountains (b), Rainshadow (c), and Lakes (d).

Table III. Fire return matrix for Kenai NWR lowland black spruce forests. Years at the top of columns represent fires that overburned fires shown at the left of each row. Numbers within the body of the matrix are the intervals, in years, between the two events. For instance, the 1762 fire overburned the 1708 fire and the interval between the two events was 54 years.

Fire Year	1762	1828	1833	1834	1849	1867	1874	1884	1888	1898	1947	1974	1996
1708	54_R					159_R							
1762			$71_{M/R}$	72_R	87_R						185_R		
1828								56_R			$119_{R/L}$		
1833											114_R		163_M
1834					15*			50_R			113_R		162_M
1849						18*	25_L		39_L		$98_{R/L}$		
1867										31_R		107_R	
1874											73_L		
1884											63_R		
1888											59_L		
1898											49_R	76_R	
1947													
1974													
1996													

* possible edge of fire, uncertain of complete overburn

$_R$ = rainshadow, $_L$ = Lakes, $_M$ = Mountains

TABLE II. Descriptive statistics of fire return intervals

Category	N	Range (years)	Mean	Standard Deviation
All	26	25-185	89	43
Mountains	3	71-163	132	53
Rainshadow	17	31-185	88	41
Lakes	6	25-119	69	36

I constructed a time-since-fire map of living stands within the study area as it appeared in 1946 (Figure 14). One of the assumptions of fire cycle calculations is that fires burning within the area investigated can be no larger than 1/3 of the entire area (Johnson & Gutsell, 1994). The 1947 burn which burned over 85% of the study area obviously violates this assumption, therefore the time-since-fire map was constructed for the year 1946. I plotted the cumulative area burned (represented by living cohorts in 1946) by fires occurring in 1828, 1833, 1834, 1849, 1867, 1874, 1888, and 1898. This plot is presented in Figure 15 and approximates a Weibull distribution, indicating an increased hazard of burning as forests get older (Johnson, 1979; Johnson and Gutsell, 1994). The shape (c) and scale (b) parameters of this distribution are 1.08 and 0.56, respectively. The scale parameter of this distribution represents the mean age of forest stands on the landscape (Johnson, 1979), therefore it is also the mean frequency of fires for the study area. In this case the mean fire frequency is approximately 56 years. Two different probabilities of burning are evident in Figure 15 and correspond to the time periods of 1828 to 1834 and 1849 to 1898 (Johnson & Van Wagner, 1985). The cumulative hazard of burning for this model is presented in Figure 16.

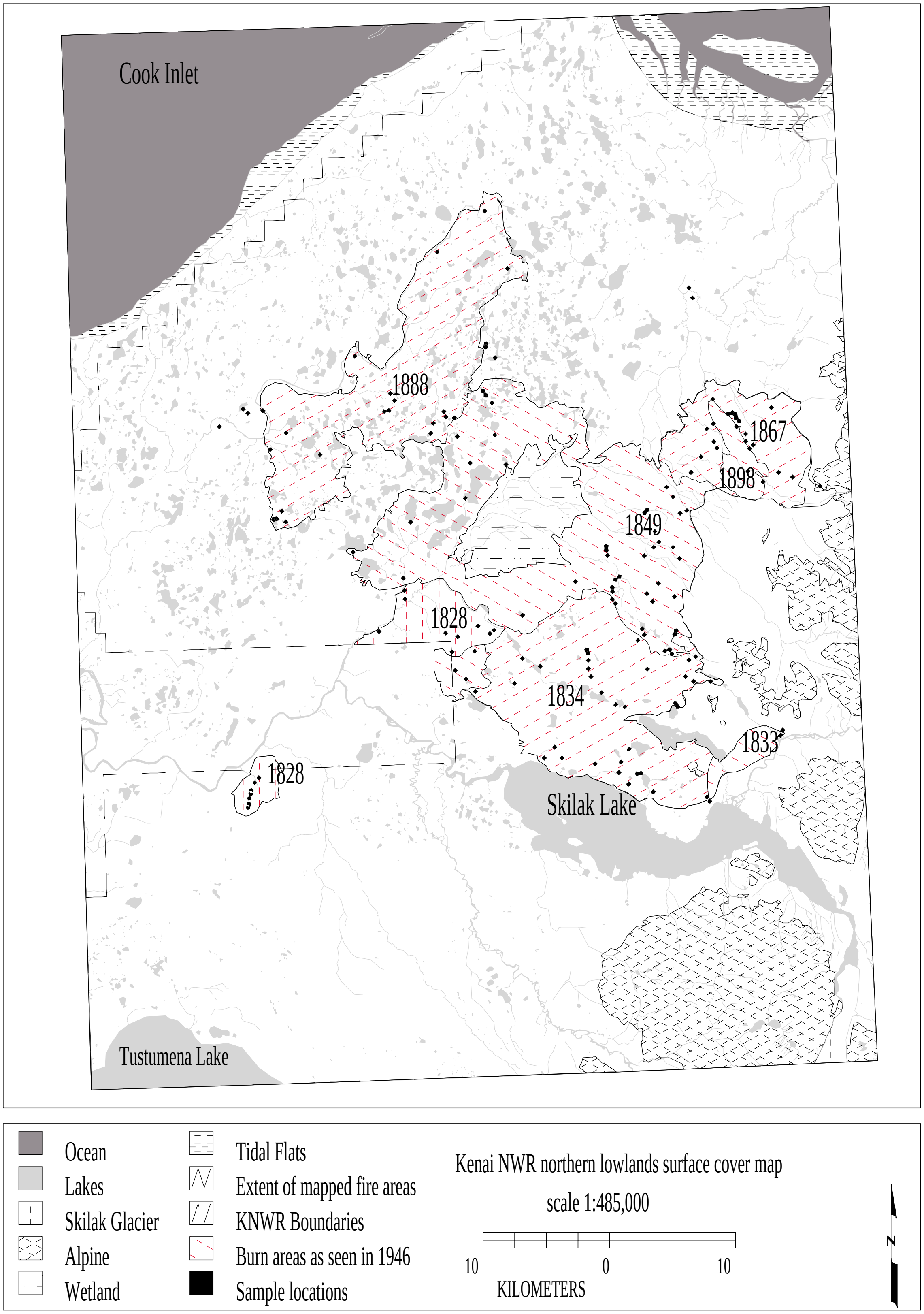

FIGURE 14. Time-since-fire map of forest stands as seen in 1946.

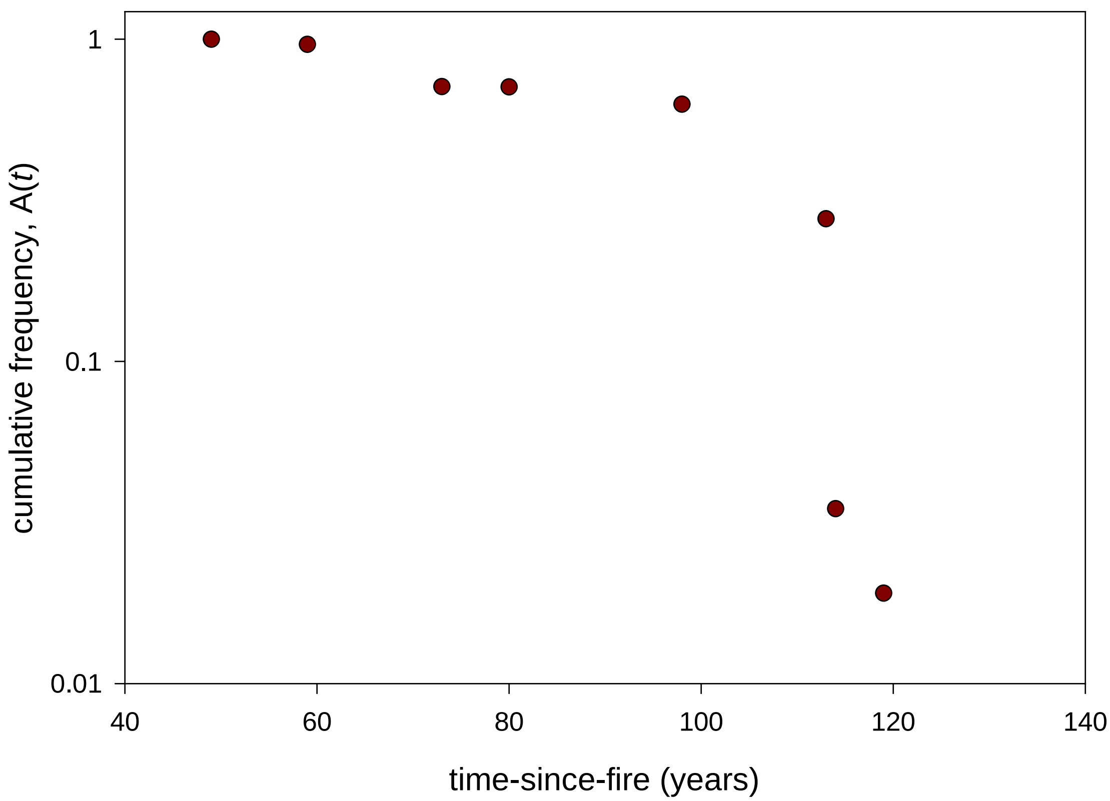

FIGURE 15. Time-since-fire distribution for Kenai NWR lowland black spruce forests. Note the shape of this curve which approximates a Weibull distribution.

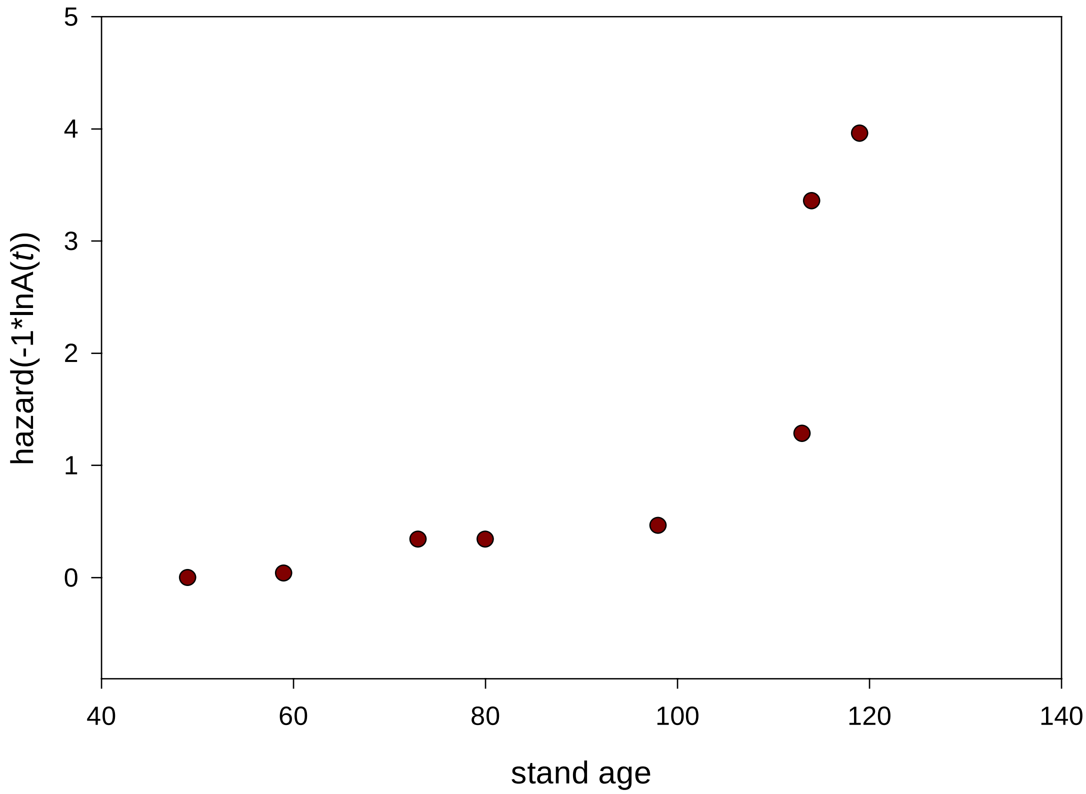

FIGURE 16. Cumulative hazard of burning for the Weibull model. Note the hazard of burning increases in stands older than 110 years.

Very few trees which germinated after the 1762 fire event survived to 1946. Those which did survive existed as scattered fire-scarred residuals within younger forests. However, a single patch of several dozen post-1762 fire black spruce trees were found alive in 1996. If I use a conservative estimate of 50 hectares of post-1762 fire trees alive in 1946, I can produce a new cumulative area burned curve (Figure 17). Again, this plot appears to have a Weibull distribution, and its shape and scale parameters are 0.71 and 0.42, respectively. The cumulative hazard of burning derived from this distribution is presented in Figure 18

FIRE DESCRIPTIONS

The earliest fire that I was able to date occurred in 1708 and burned a minimum of 7,119 hectares (Figure 19, Table I) in the PRS area. This fire is defined by age-class evidence from 13 sample points and one scarred burn pole. The date of 1708 hinges upon the validity of the scarred burn pole; however, there is ample age-class evidence (Figure 20) to support this fire date. The seasonality of this fire is determined only by this one scar, and therefore is equivocal.

A total of 33 sampling points define the area burned in 1762. This fire burned a minimum of 26,174 hectares early in the growing season (Figure 21, Table I) as determined from two fire scars from separate sites. The majority of the fire area is defined by age-class evidence (Figure 22). However, several burn poles have predicted germination dates prior to 1762 which is likely a result of height growth variance of individual trees as compared to the predictive capabilities of the height-age correction equation.

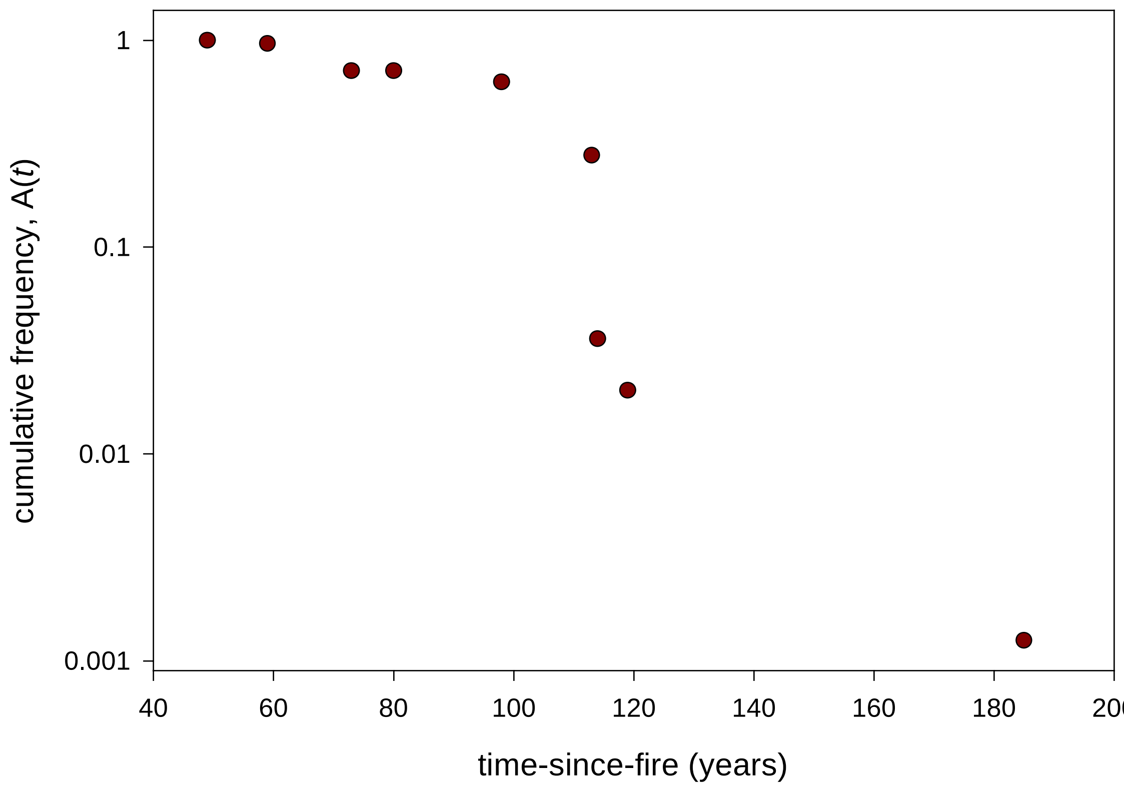

FIGURE 17. Time-since-fire distribution for Kenai NWR lowland black spruce forests. Note, the cumulative area burned curve is sigmoidal, indicating the use of the Weibull model is appropriate. Time-since-last fire is based on 1947.

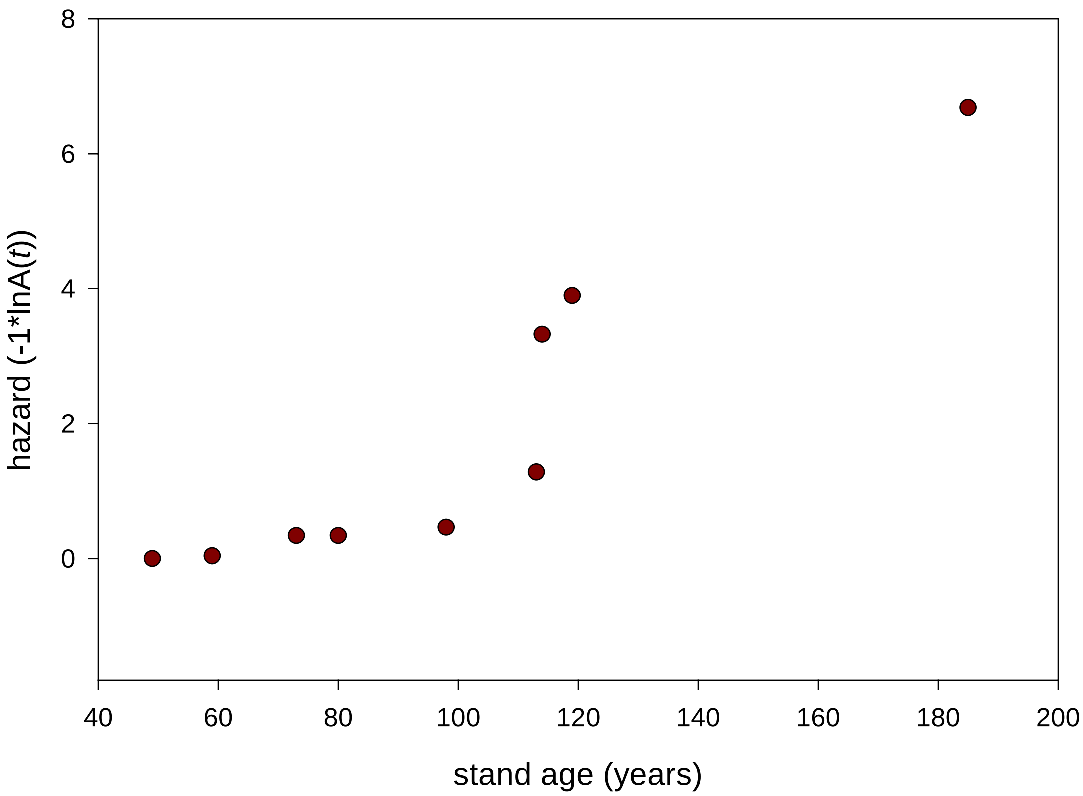

FIGURE 18. Cumulative hazard of burning for the Weibull model. Note the hazard of burning increases in stands older than 110 years.

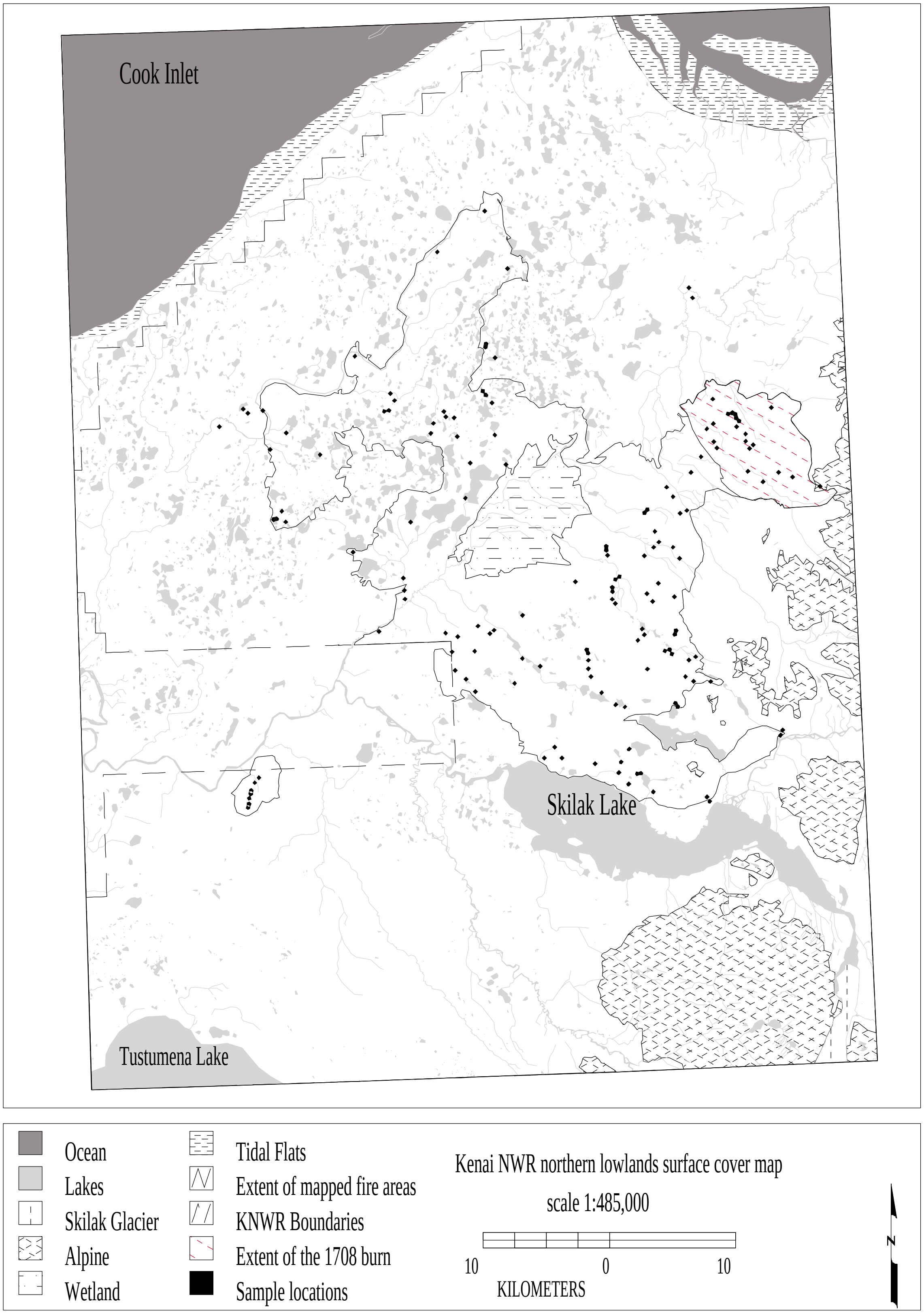

FIGURE 19. Location and extent of the 1708 burn.

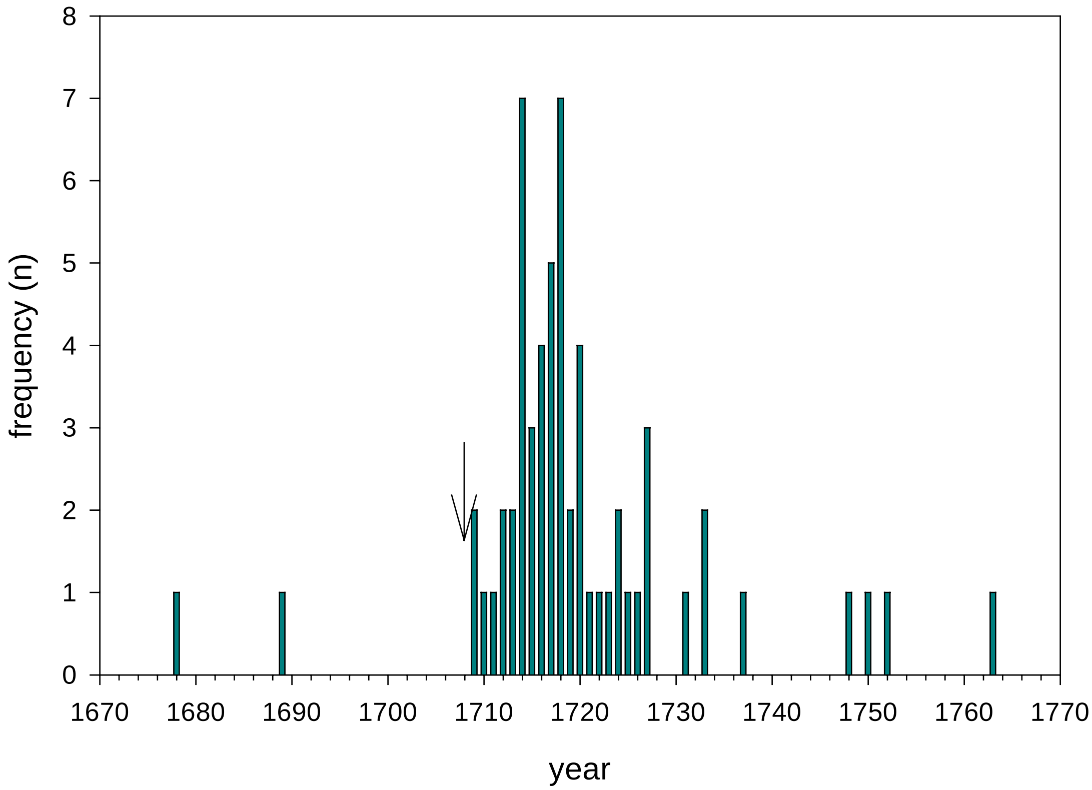

FIGURE 20. Estimated germination dates of 58 burn poles from the PRS area that are supporting evidence of a fire in 1708 (arrow).

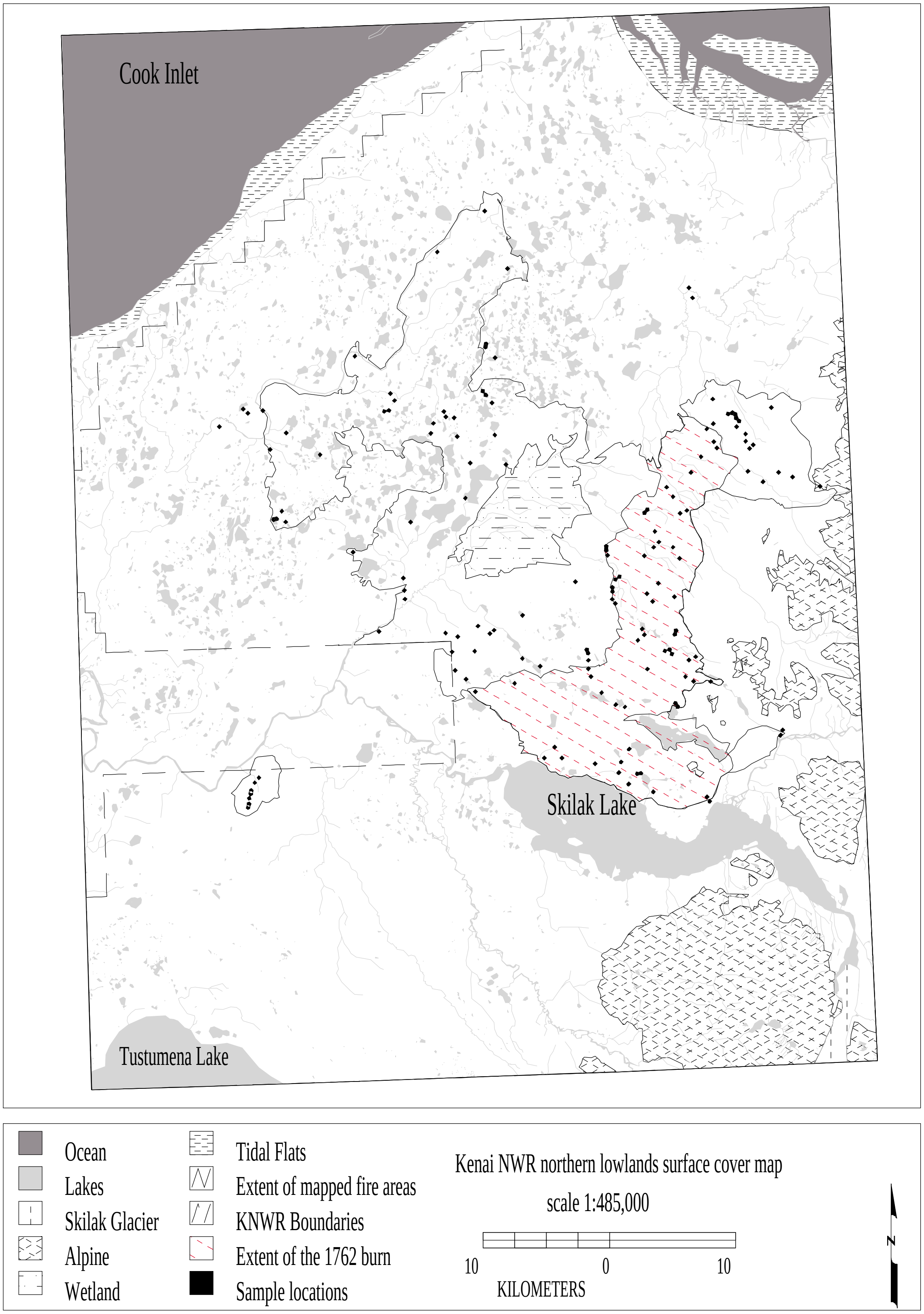

FIGURE 21. Location and extent of the 1762 burn.

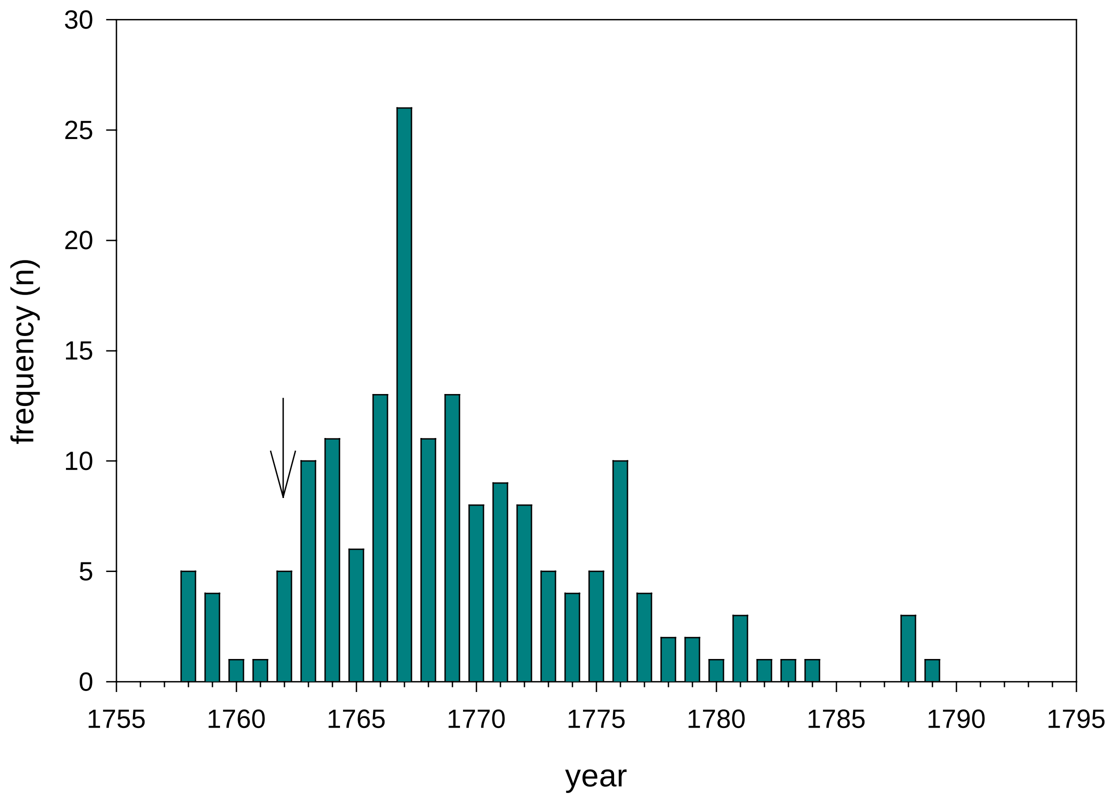

FIGURE 22. Estimated germination dates of 174 post-1762 fire burn poles. Note that several burn poles have predicted germination dates before 1762 (arrow).

An early season fire in 1828 burned a minimum of 4,887 hectares (Figure 23, Table I). Two separate areas are defined by fire-scar and age-class evidence (Figure 24) from a total of 8 sample points. Two areas were defined because no sample locations were visited on the private and corporate land that separates the two fire areas.

Fires in 1833 and 1834 burned 4,100 and 16,455 hectares, respectively (Figure 25, Table I). Both of these fires burned early in the growing season, however, the 1833 fire may have burned into the end of the growing season. The 1833 fire is defined by fire-scar evidence from three sample points and the 1834 fire is defined by 17 sample locations where both fire scars and age-class evidence (Figure 26) were found.

The largest fire mapped and dated in this study (other than 1947) burned over 30,100 hectares during the middle to late growing season of 1849 (Figure 27, Table I). Defined by 32 sample locations, this fire was dated by means of fire scars, age-class data, and outer-ring analysis. A large wetland dominates the center of this fire area, and I am uncertain if this area burned in 1849. If so, the total area of the 1849 burn exceeds 36,600 hectares (Table I). The pooled age-class distribution from nine sites that record the 1849 burn shows a slightly uneven distribution of forested areas burned in 1849 (Figure 28). This is a result of trees that survived the 1849 fire persisting within these stands until being killed by fire in 1947. The northeastern boundary of this fire, within the PRS, was dated by outer-ring analysis. From an area that I thought to be a fire boundary, I collected burn poles that were completely charred except for small areas on their stems which were neither charred or weathered. My interpretation was that the uncharred and un-weathered surfaces on these burn poles were death dates of these

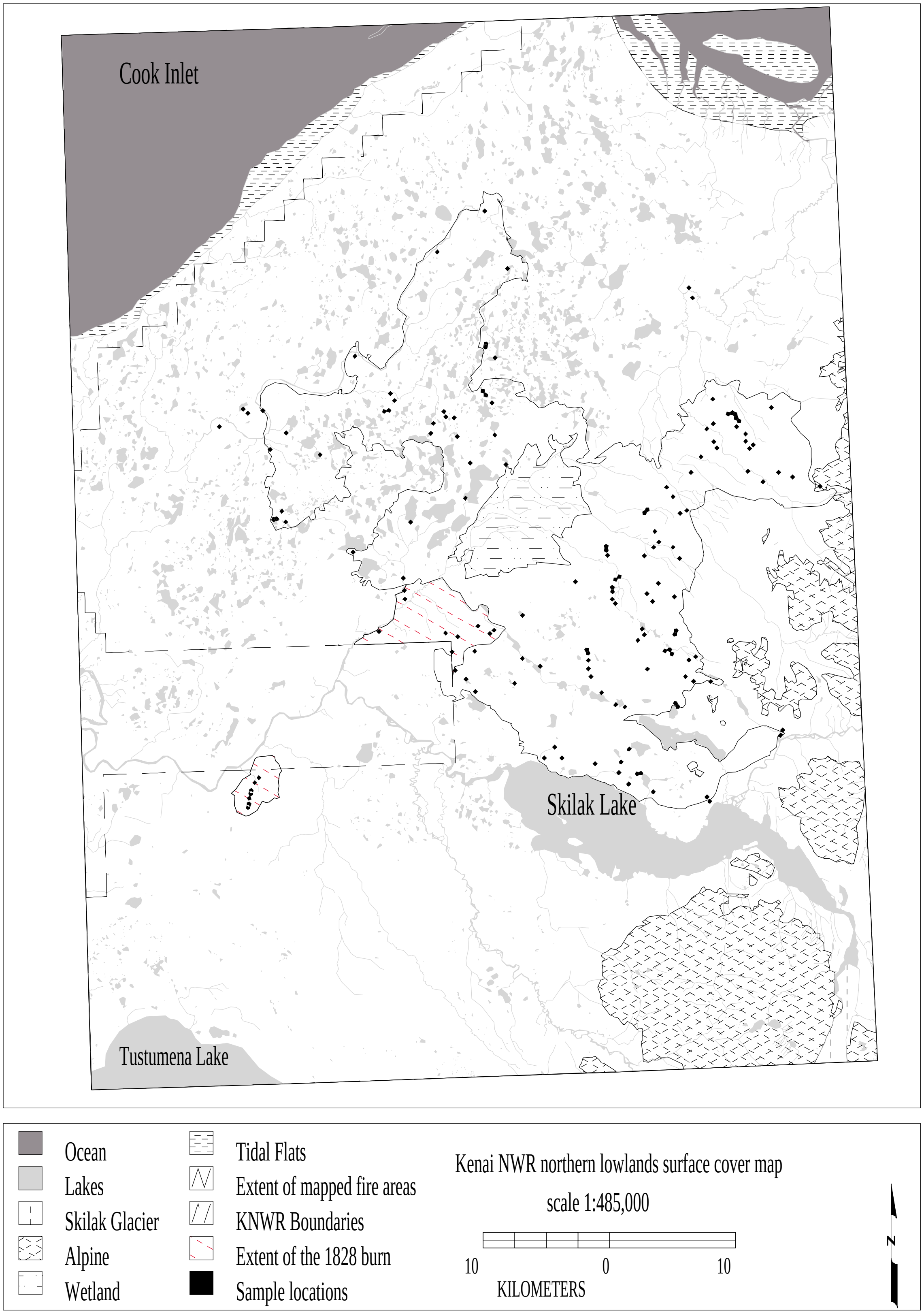

FIGURE 23. Location and extent of the 1828 burn.

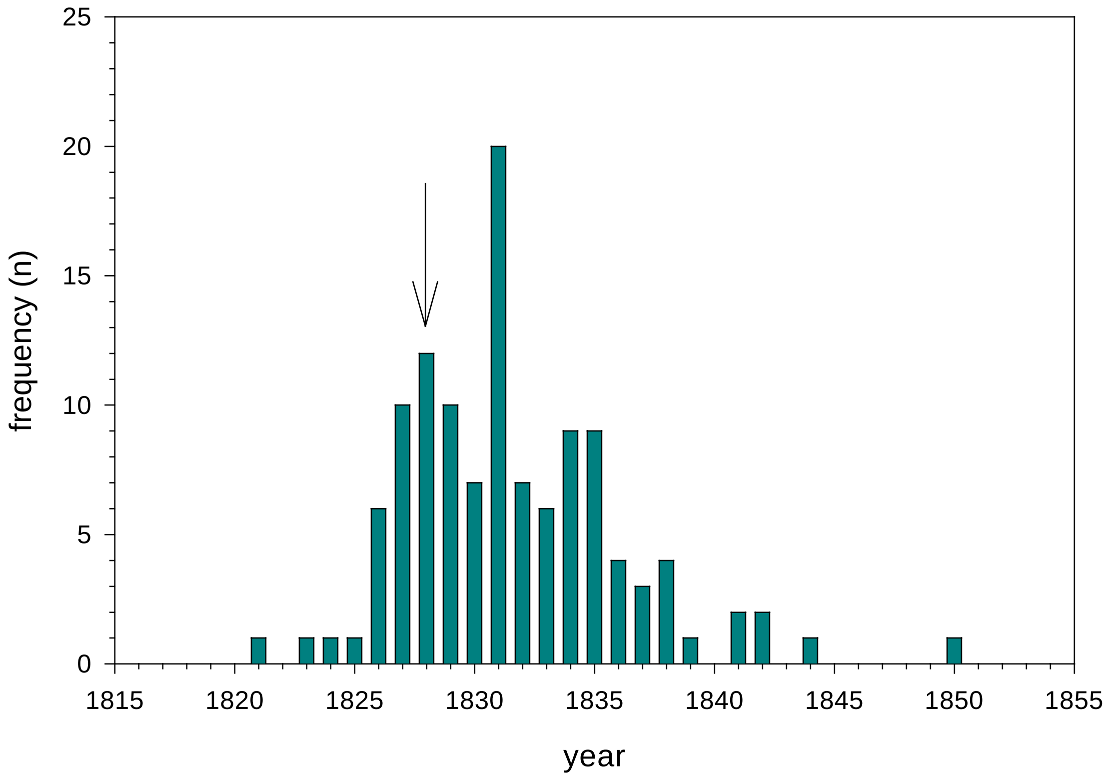

FIGURE 24. Estimated germination dates of 118 post-1828 fire burn poles. The date of this fire (arrow) is confirmed by two fire scars.

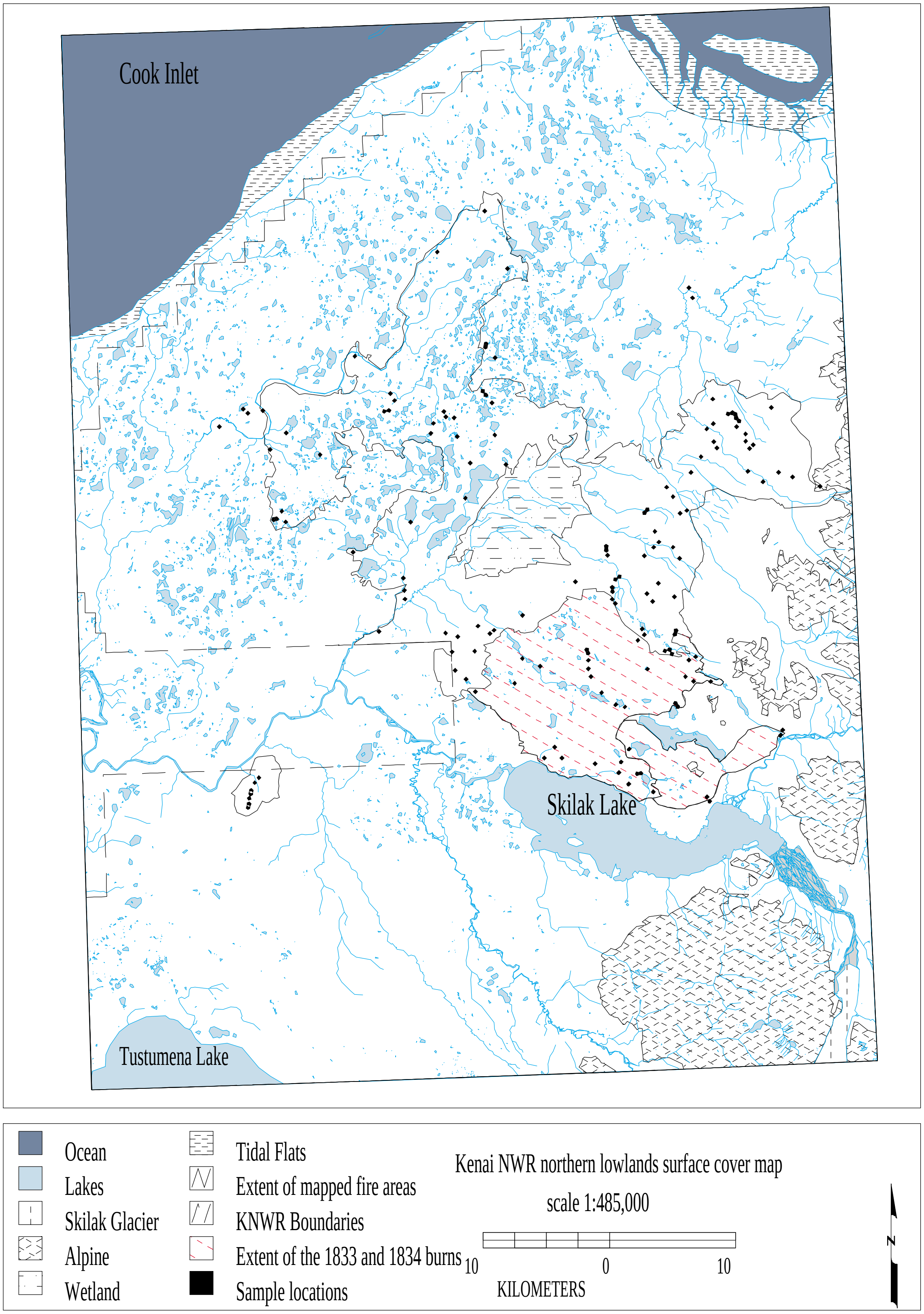

FIGURE 25. Location and extent of the 1833 and 1834 burns.

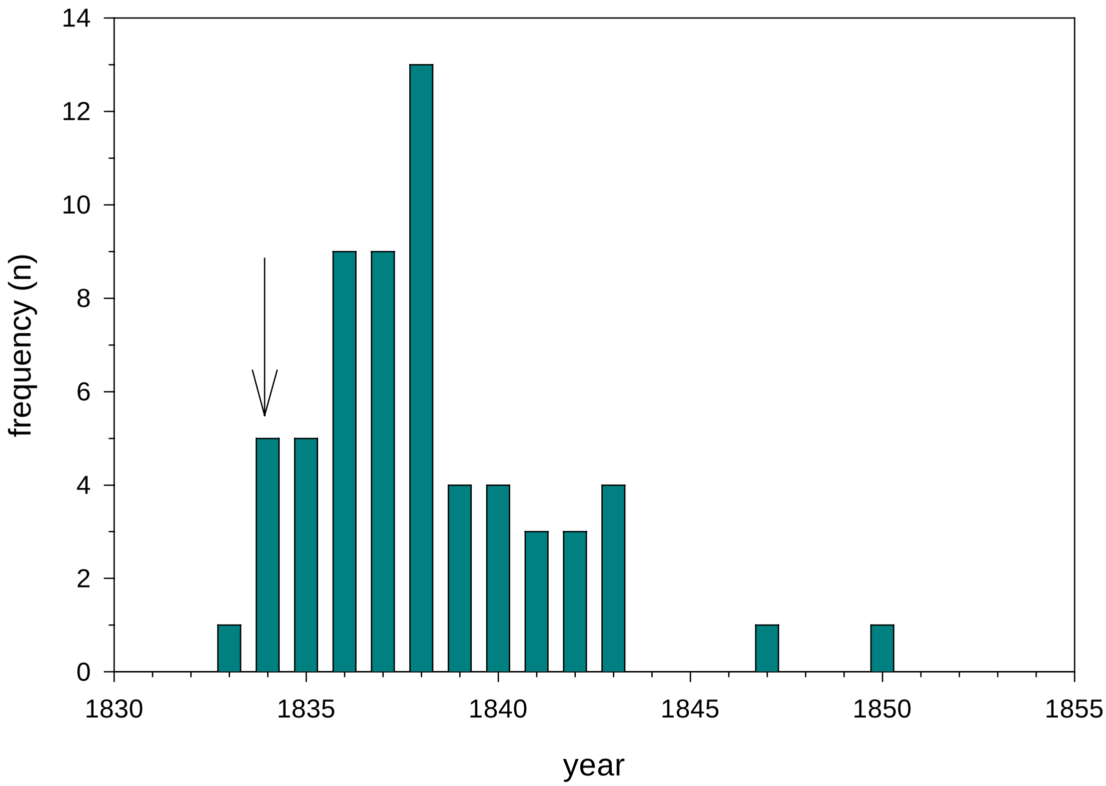

FIGURE 26. Estimated germination dates of 62 post-1834 fire burn poles. Arrow indicates the fire date.

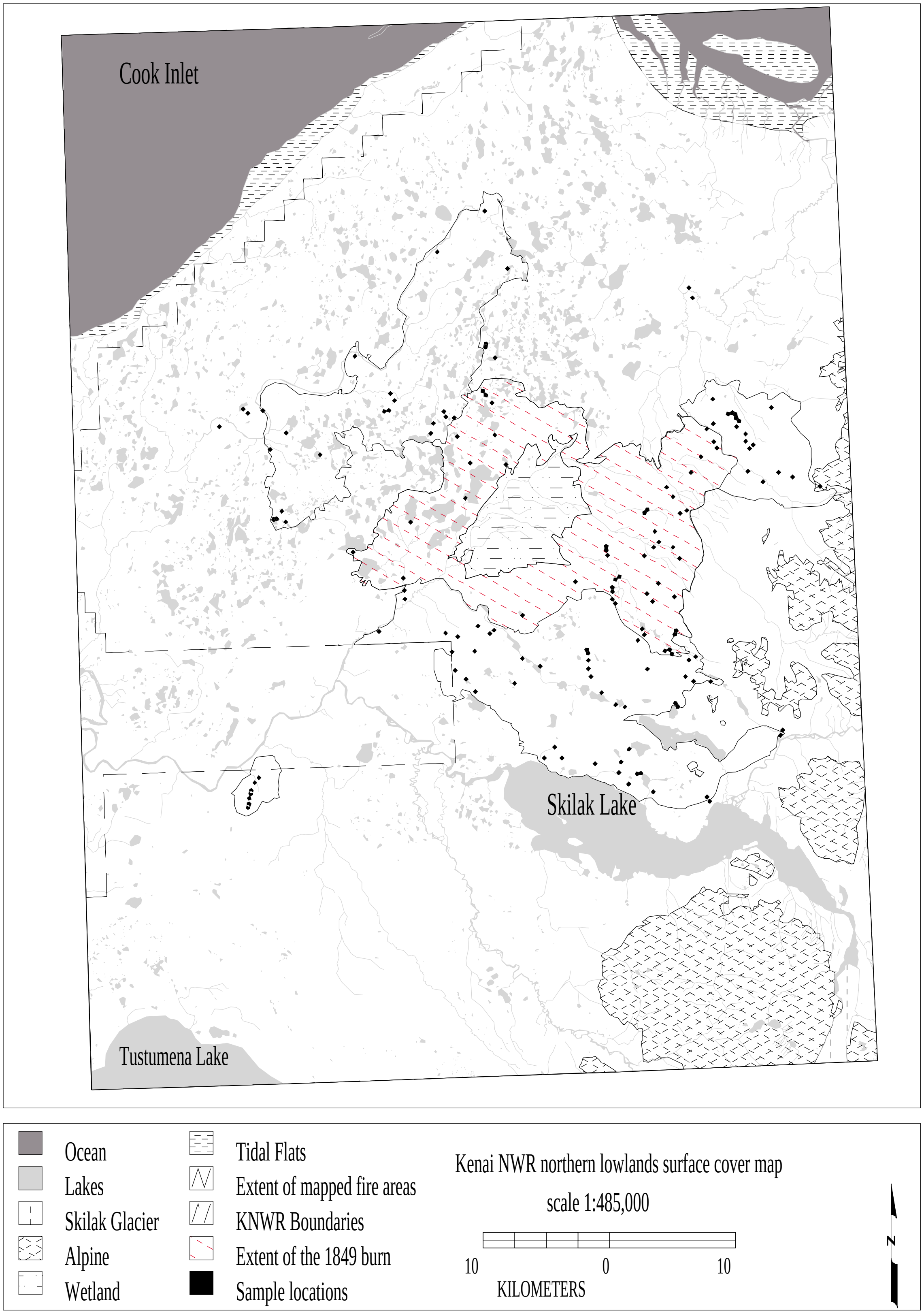

FIGURE 27. Location and extent of the 1849 burn.

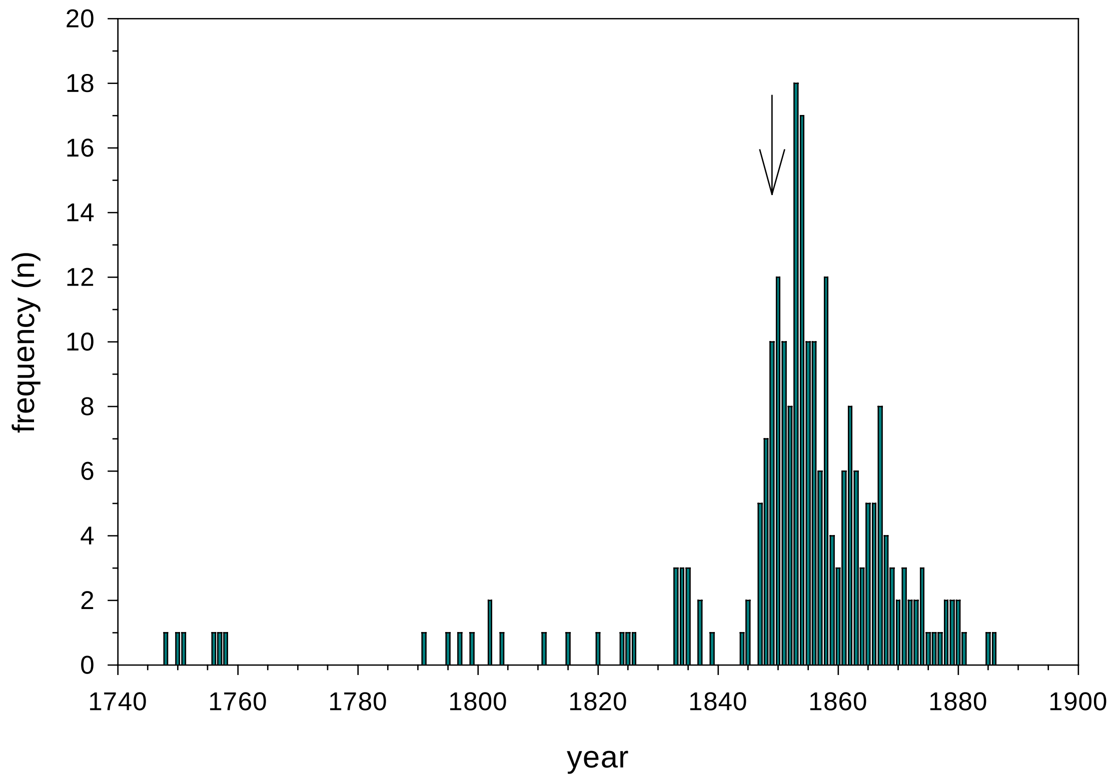

FIGURE 28. Estimated germination dates of burn poles from nine sites that recorded the 1849 fire. Note, 19% (46) of the 238 un-scarred burn poles in the sample have germination dates before 1849 (arrow).

individuals. Figure 29 shows the outer-ring type and date distribution of these burn pole samples. From these dates, and in comparison to the 1947 burn outer-ring date distribution (Figure 9), it is obvious that a fire killed these trees in 1849, and that one survived until being killed by fire in 1867.

Dated entirely by outer-ring analysis of burn poles and age-class (Figure 30) from 12 sample locations, and mapped partially from air photos, the 1867 fire burned a minimum of 8,251 hectares (Figure 31, Table I). Figure 32 shows the dates and types of outer-rings of uncharred burn poles from the PRS area. If one compares this distribution to that of the 1947 burn, the two look remarkably similar, therefore supporting the interpretation of the 1867 fire date. However, the seasonality of this fire cannot be determined from outer-ring analysis.

Three fire scars from one sampling location define the point of the late season 1874 burn. Buffering this single point by one kilometer produces a minimum area burned of 35 hectares (Figure 33, Table I). No other fire scars or age-class data support expansion of this fire.

Covering more than 20,000 hectares, the middle-to-late growing season 1888 fire is the third largest dated and mapped fire in this study (Figure 34, Table I). Fire scars, age-class data (Figure 35), and outer-ring dates define this fire from a total of 18 sampling points. Figure 36 shows the distribution of outer-ring types and dates for the western portion of the FSB study area. Again, this distribution is nearly identical to the 1947 burn outer-ring date distribution, thereby confirming the passage of the 1888 fire.

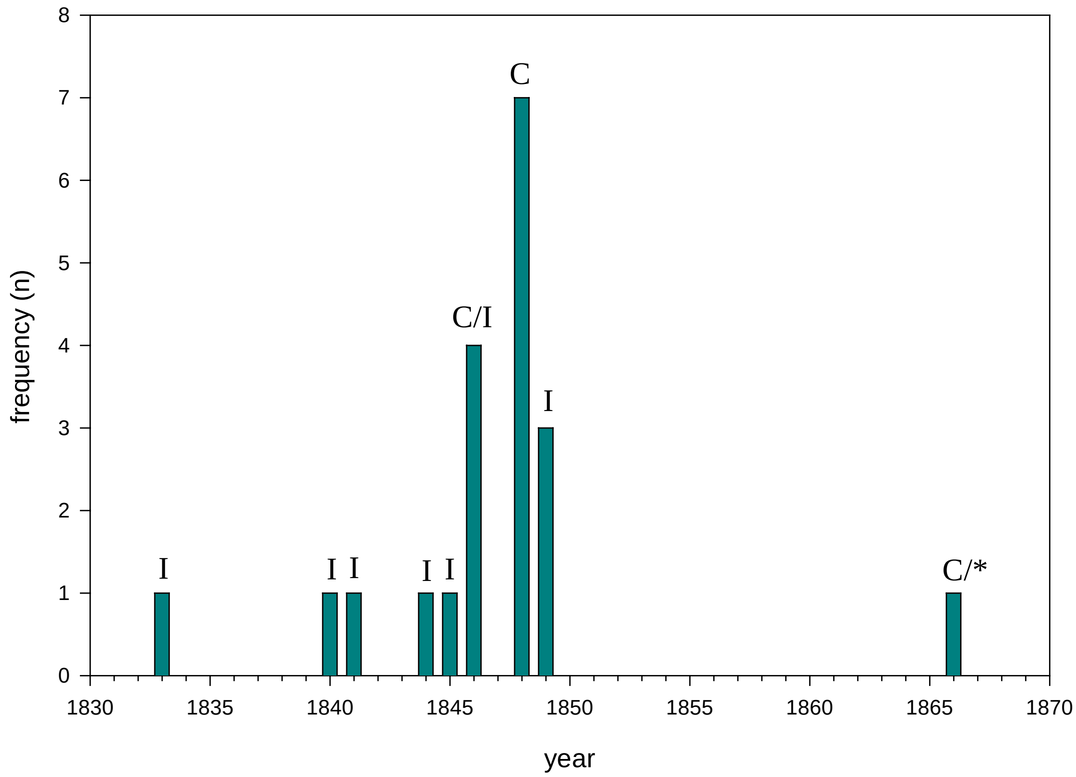

FIGURE 29. Dates and types of outer rings from the PRS area inferring a fire in 1849 and 1867. I = incomplete outer-ring, C = completely formed outer-ring, * = resin ducts in the 1849 ring. Note the shape of the distribution as compared to FIGURE 9.

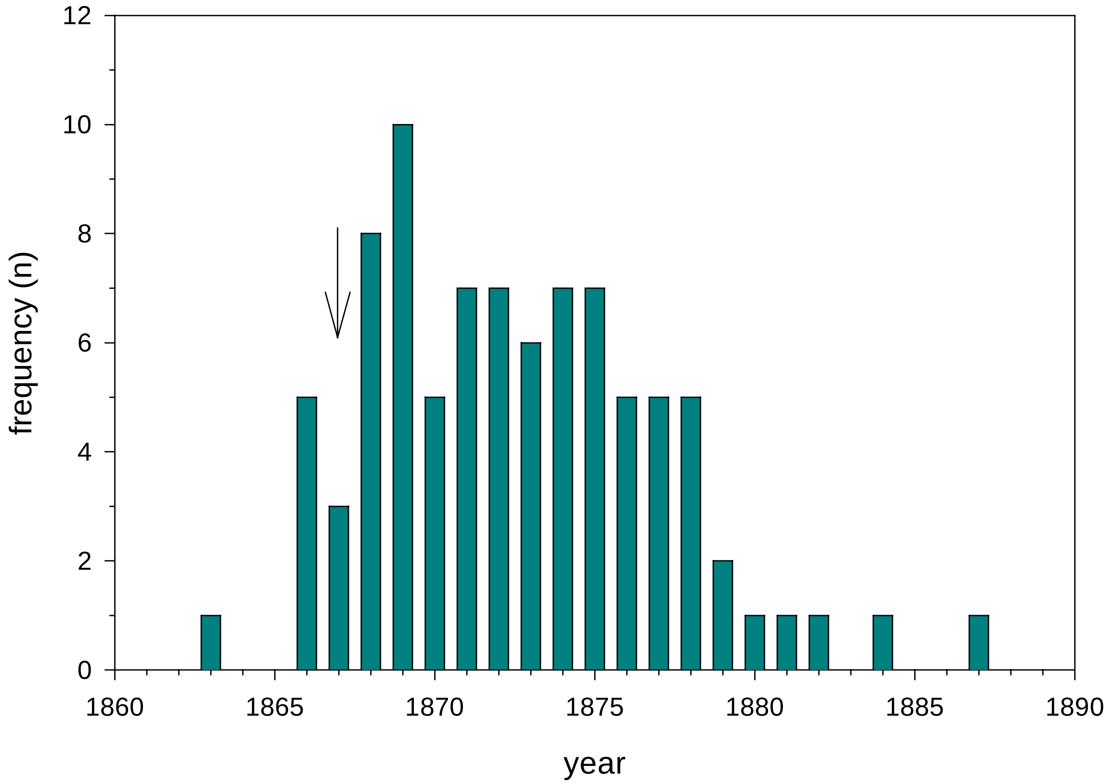

FIGURE 30. Estimated germination dates of 88 living trees from three sites recording the 1867 fire (arrow) within the PRS area.

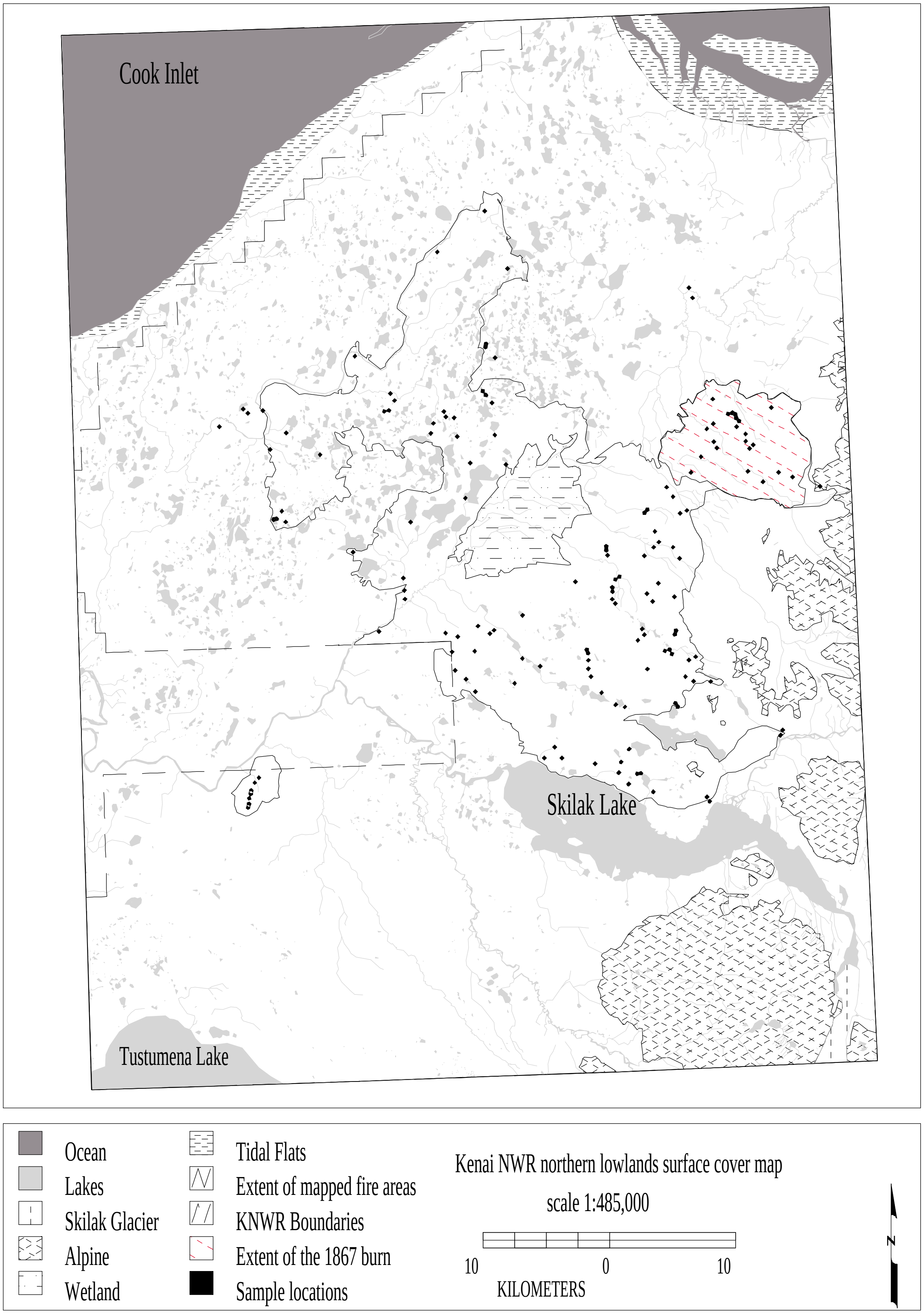

FIGURE 31. Location and extent of the 1867 burn

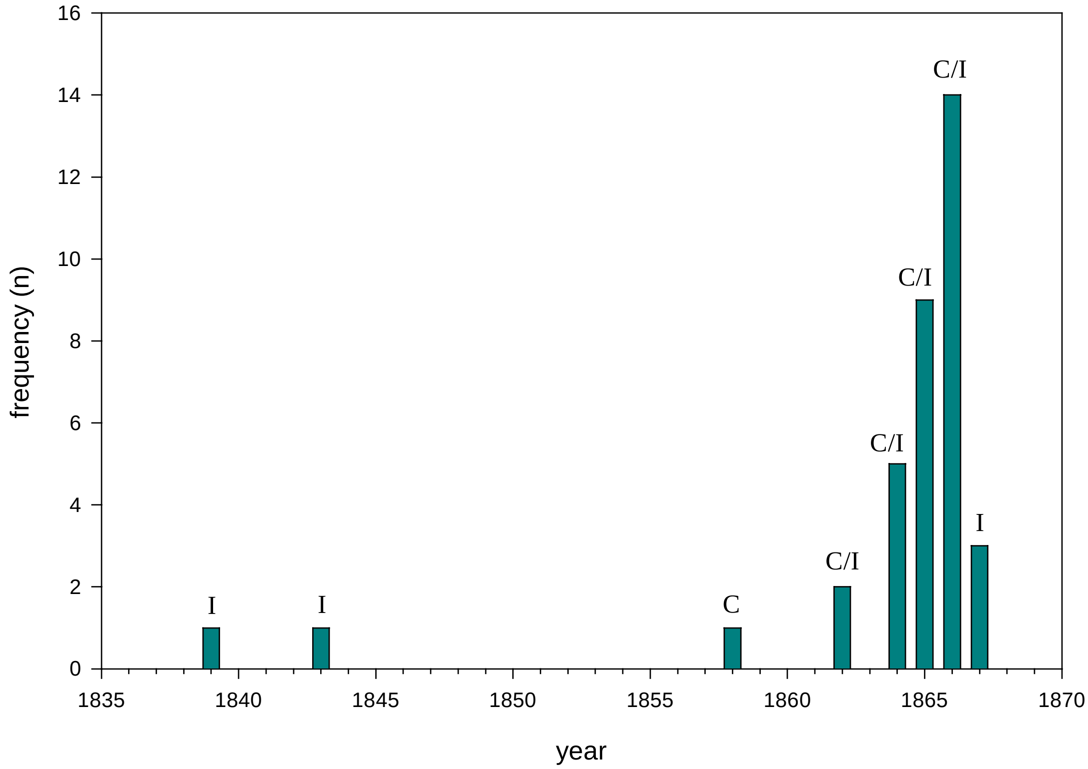

FIGURE 32. Dates and types of outer-rings from the PRS area inferring a fire in 1867. I = incomplete outer-ring, C = completely formed outer-ring. Note the shape of the distribution as compared to FIGURE 9.

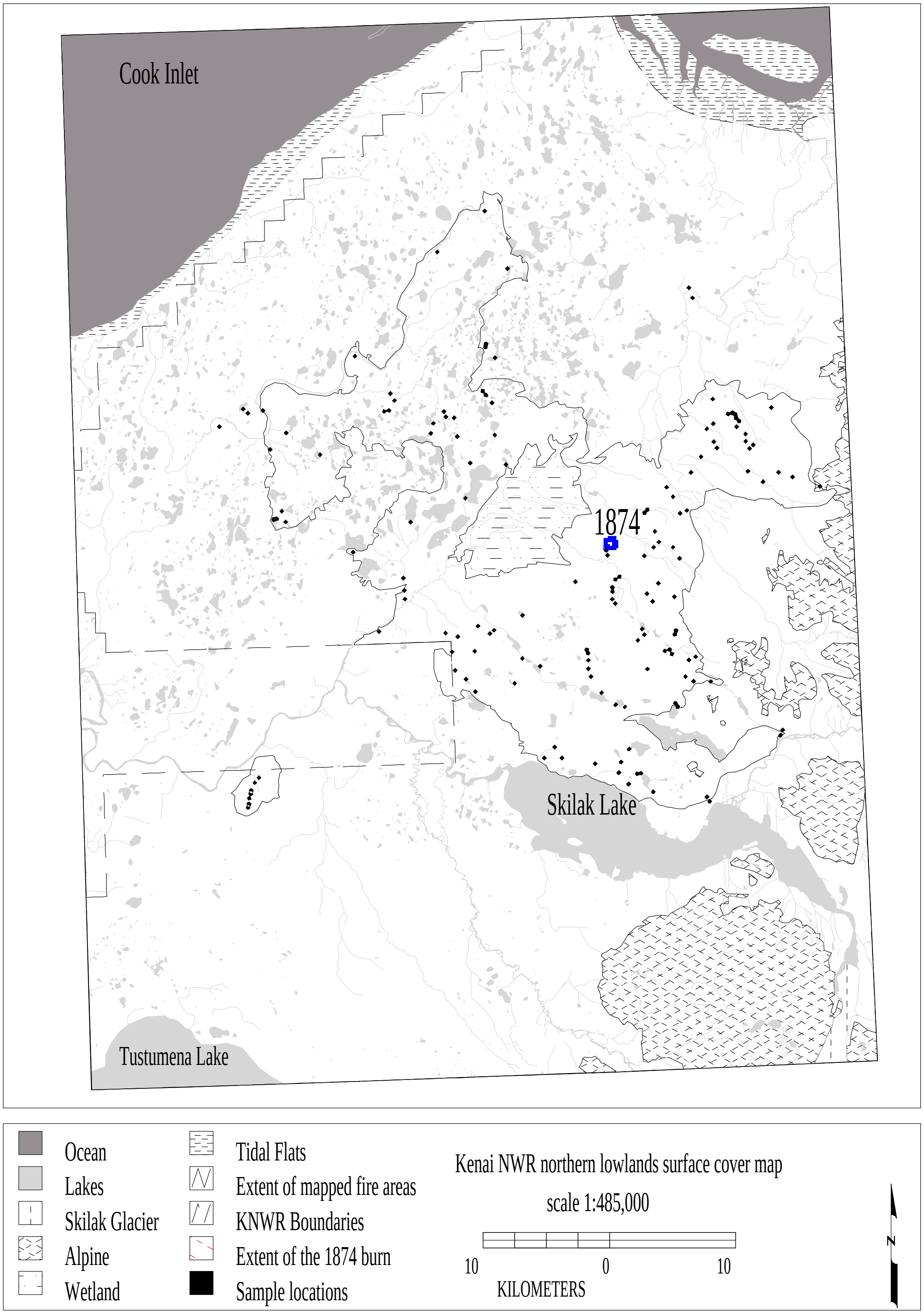

FIGURE 33. Location and extent of the 1874 burn.

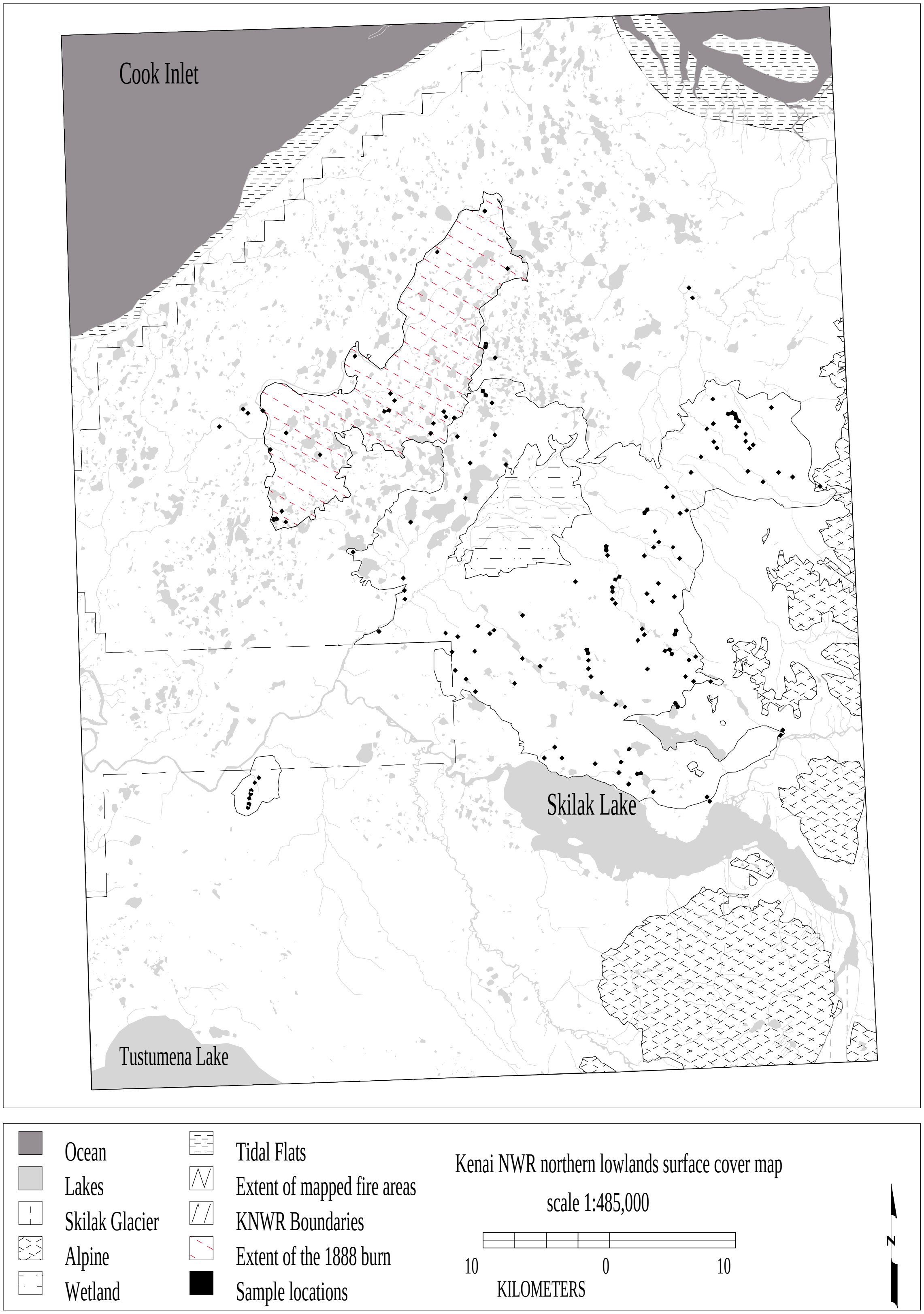

FIGURE 34. Location and extent of the 1888 burn.

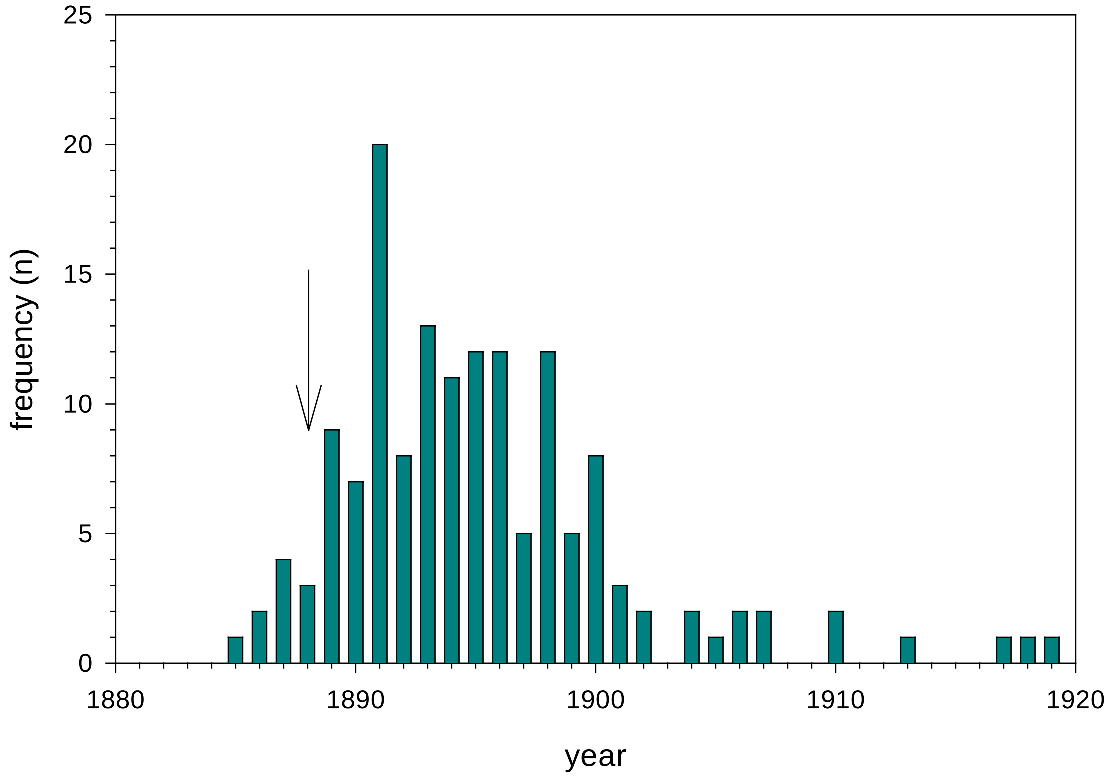

FIGURE 35. Estimated germination dates of 150 trees from five sites recording the 1888 fire (arrow). One tree had a gemination date of 1813 (not shown).

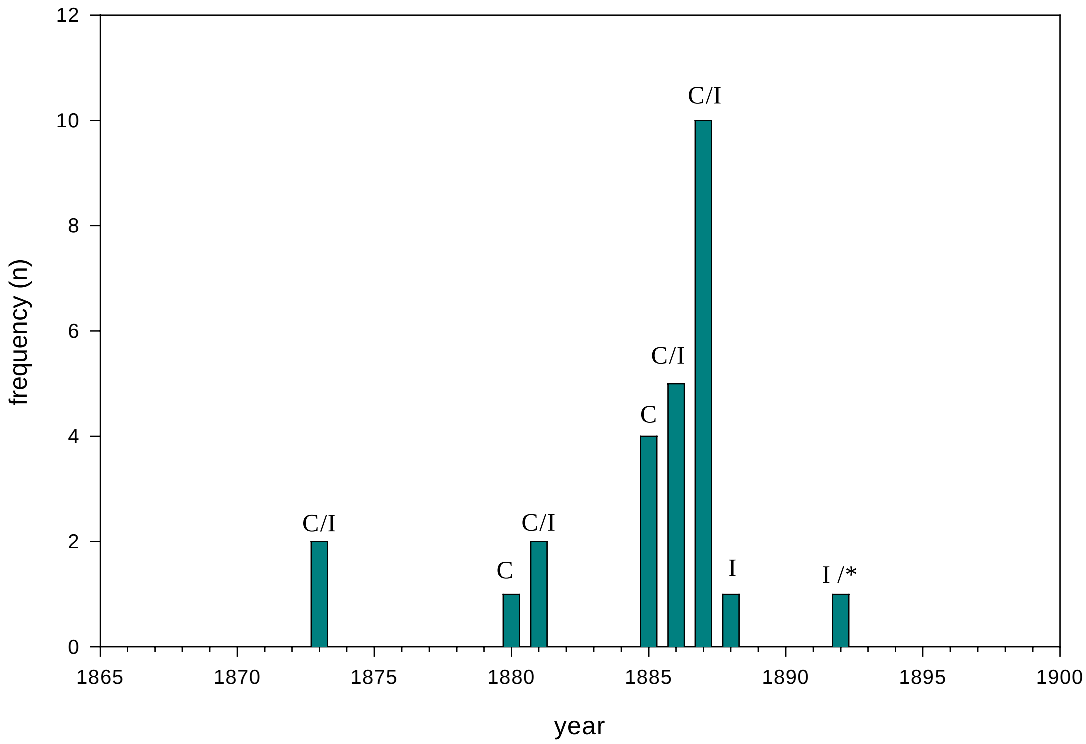

FIGURE 36. Dates and types of outer rings from burn poles collected along the western margin of the 1947 burn study area inferring a fire in 1888. I = incomplete outer ring, C = completely formed outer-ring, * = resin ducts in the 1888 ring. Note the shape of the distribution as compared to FIGURE 9.

Two geographically distinct fires burned in 1898; one covering more than 1680 hectares in the PRS area and another covering more than 1,325 hectares in the western lowlands (Figure 37, Table I). The late-season fire in the PRS area was dated using fire scars from six sampling locations and mapped from air photos taken in 1950, 1974, and 1988. The area of this fire is a maximum area burned, unlike the hitherto discussed burn area estimates which are minimum estimates. The mid-to-late season western lowland 1898 fire is defined by fire scars, age-class (Figure 38), and photo interpreted unburned forest patches.

Several other fires were dated, but were not mapped due to insufficient number of samples and poor spatial coverage. Convincing fire scar evidence of an early season fire during the 1801 growing season was found at one site, on one burn pole. This site is located within the area burned in 1849, however, no associated age-class or other fire scars could be located at this, or any adjacent site (Figure 39). Therefore this fire is unsupported and represented as only a point.

Evidence for a fire which burned in 1884 is found at several sites in the form of age-class, outer-ring dates, and fire scars (Figure 40). However, adjacent to a site where a single 1884 fire scar was found, scars dating from 1883, 1885, and 1886 were also found. Age-class evidence and outer-ring dates support a fire date of 1884, however in the light of conflicting fire scar evidence, the date of 1884 is equivocal. This fire could be a most northerly extension of the great 1884 (1883?) benchlands fire mapped and dated by Gracz *et al.* (unpubl.).

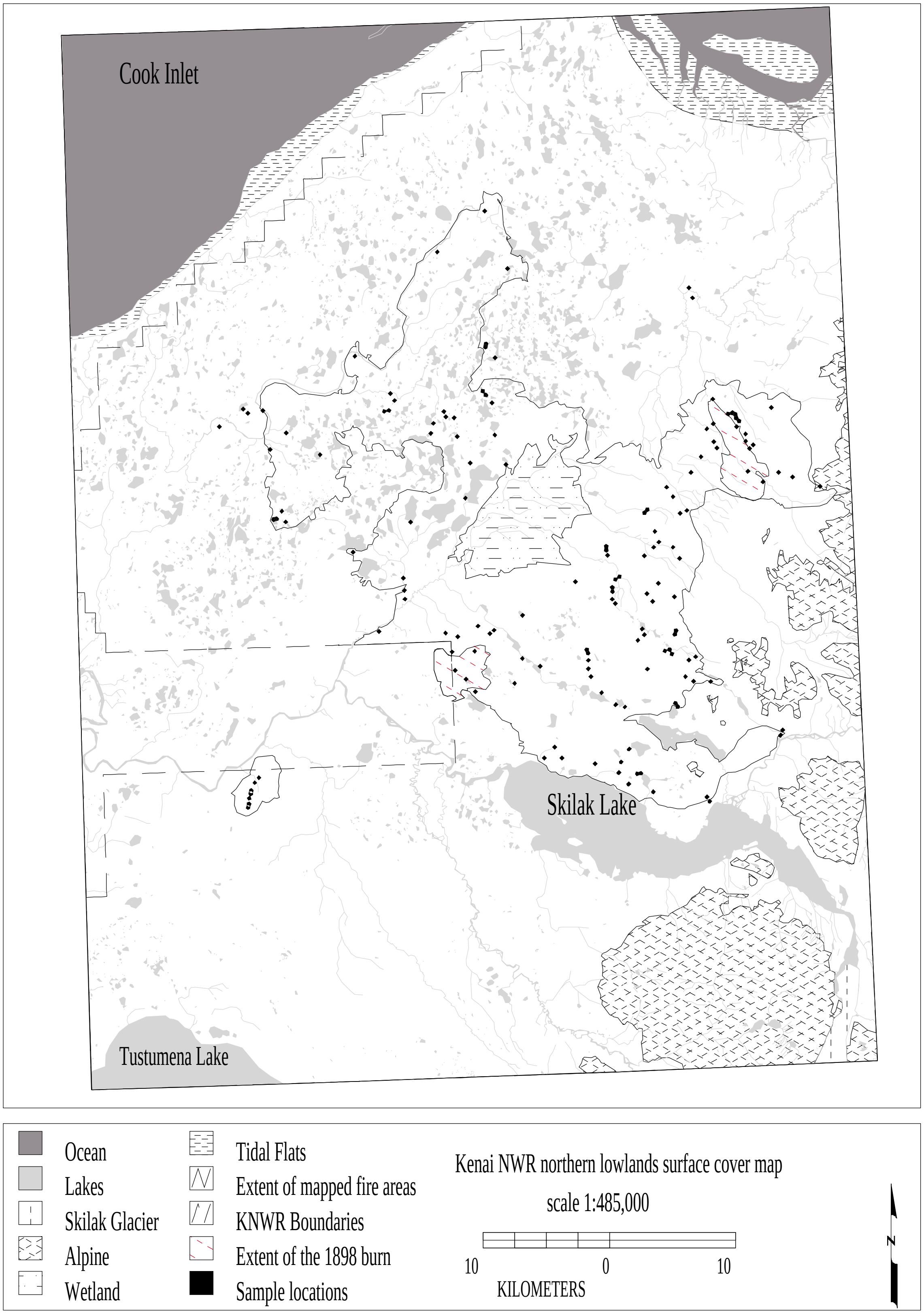

FIGURE 37. Location and extent of the 1898 burns.

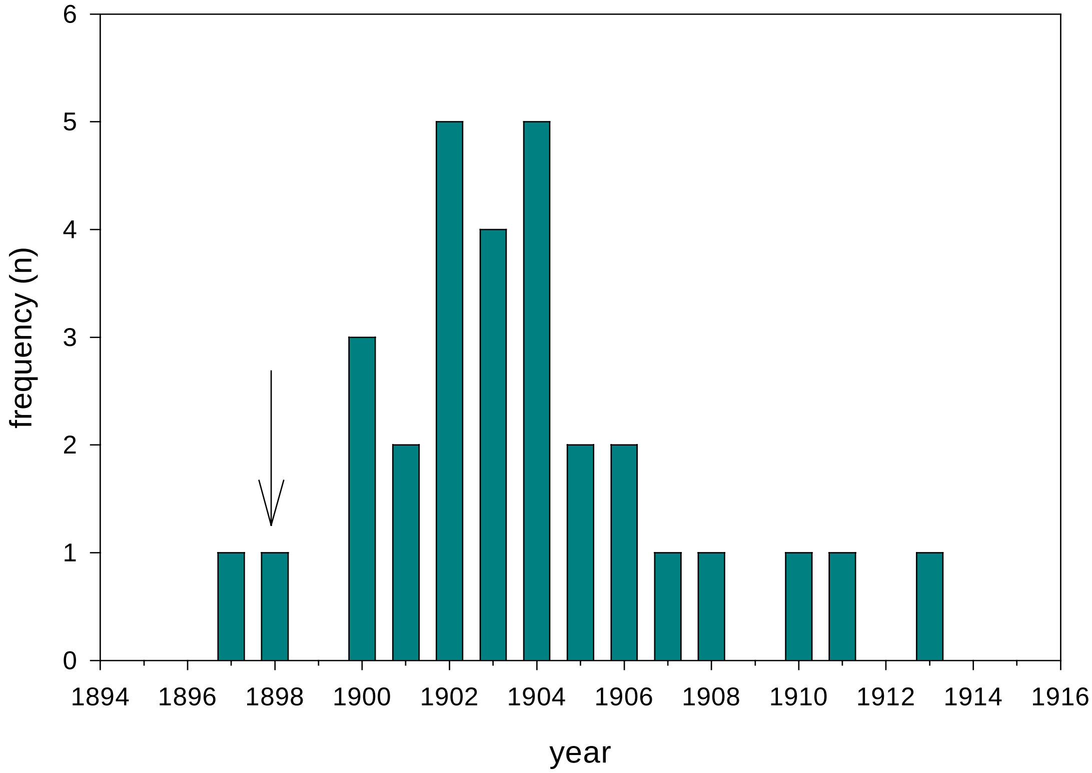

FIGURE 38. Estimated germination dates of 30 trees from one site recording the 1898 fire (arrow) in the western lowlands.

FIGURE 39. Location of the possible 1801 burn point.

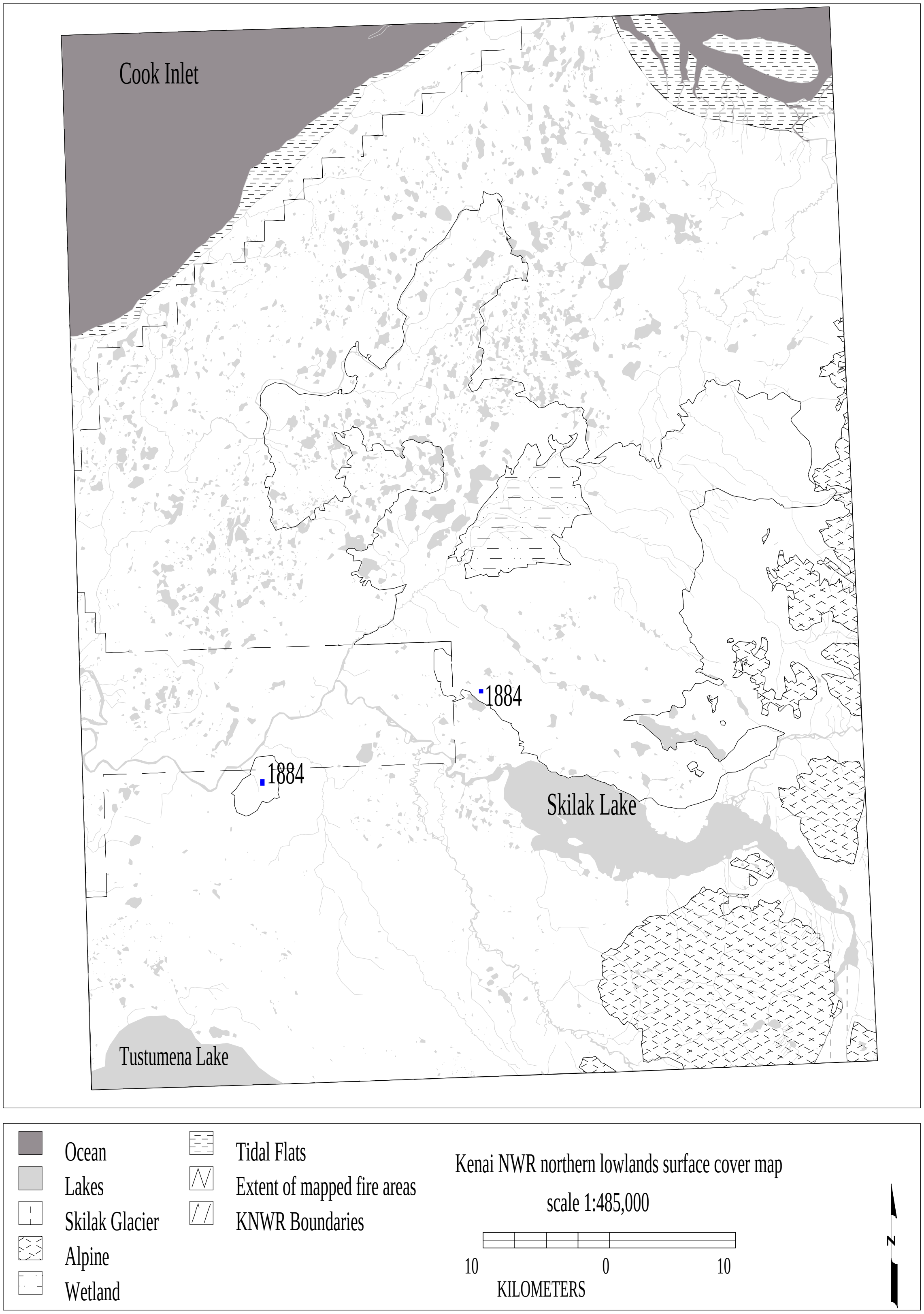

FIGURE 40. Locations of points recording fire in 1884.

DISCUSSION

SPECIFIC FIRE EVENTS

The earliest fire that I dated burned a minimum of 7,100 hectares in 1708, and likely burned considerably more area (Figure 19). Burn poles sampled at a site in the foothills of the Kenai Mountains (east of the FSB study area) have a similar age structure to those sampled in the PRS area (Figure 41). This indicates the size of the 1708 fire is substantially underestimated. Because of mountainous topography, it is unlikely that this fire burned in a straight line through the mountains (a distance of over 19 kilometers). It is more likely that this fire burned a considerable portion of the lowlands at least near the mountains. A minimum estimate of area burned during the 1708 fire including this extension is 30,000 hectares. However, because evidence of older fires is lost with each succeeding fire (Van Wagner, 1978; Johnson & Gutsell, 1994), it is unlikely that evidence for the 1708 fire exists between the two locations.

The extent of the 1762 fire is reasonably accurate based on the presence and absence of supporting estimated germination date data (Figure 21). Burn poles from four sites near the northwestern corner of the fire area, two sites to the northwest of the fire area, and from two sites to the southwest, have inner ring dates in the late 1740s to mid-1750s (Figure 42). This suggests the 1762 fire did not burn over these sites. However, this does suggest that another yet undated fire may have burned over these outlying areas, perhaps in the early 1750s. Unfortunately I cannot accurately assign a calendar year to this fire. The eastern border of the 1762 burn is poorly defined by sample locations and could have burned further into the foothills. Further extension of this eastern fire boundary could be made by collection of age-class data from living white spruce in the eastern foothills, or from black spruce residual patches, or fire-scarred black spruce burn poles in the lowlands.

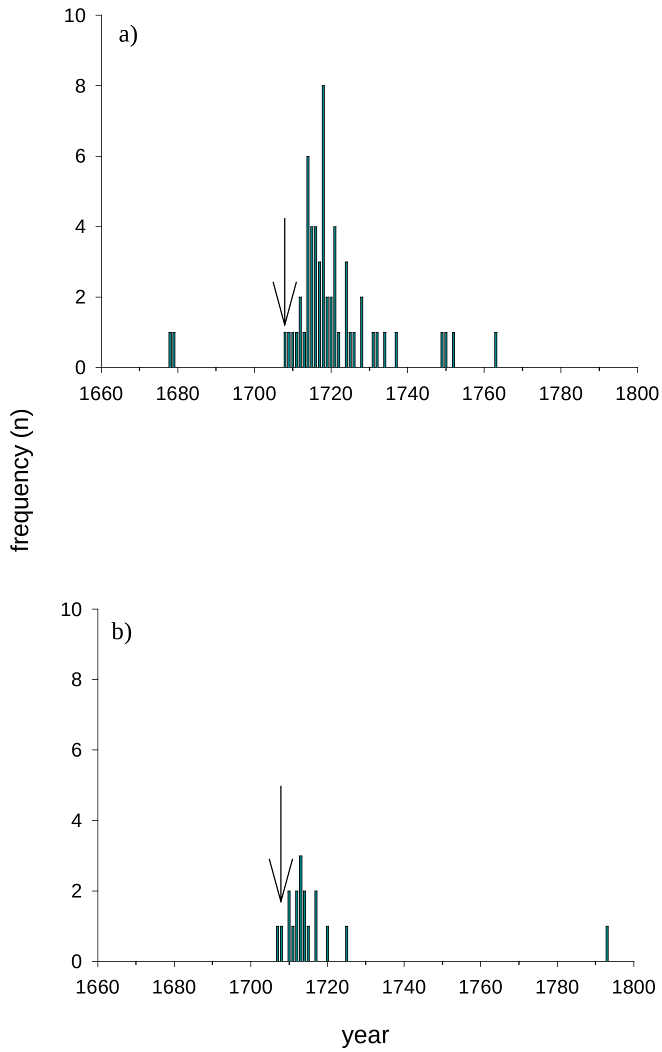

FIGURE 41. Estimated germination dates of trees from the PRS area (a) and the Jim's Landing site (b). The PRS distribution supports fire scar evidence of a fire in 1708 (arrows), while the Jim's Landing distribution also lends support to a fire at this time. The Jim's Landing site is nearly 19 kilometers south of the PRS area.

FIGURE 42. Estimated germination dates of 20 burn poles from eight sites not burned in 1762. This distribution suggests a fire burned in the early-to-mid-1750s at these sites.

A curious disturbance occurred in 1812 or 1813 in the lowland black spruce forests of the Kenai Peninsula. I recovered several burn poles in the eastern portion of the FSB study area that had scars dating to 1813, with no consistent seasonality. Within the area defined by these scars, there was no evidence of an age-class which could have suggested a stand-replacing fire. It is inconceivable that a fire burned this area and did not initiate an age-class since every fire dated in this study has had an associated age-class. A much larger area for this event can be outlined by including severe and sustained growth reductions beginning in 1813, and traumatic resin ducts found in the 1813 ring of many burn poles. Given the spatial extent of this evidence, I believe this was an event of some kind, but not a fire event. This time period, 1810-1820 includes the coldest mean summer temperatures of the last 300 years (see chapter 4). One could argue that the observed growth reductions and traumatic resin ducts are simply a result of unfavorable climatic conditions for tree growth beginning in 1813. However, if this were true, the conditions for growth would have had to change abruptly and remain unfavorable for up to one decade, in some instances, to produce the growth changes observed in the burn poles (Figure 43). The presence of traumatic resin ducts indicates some physical injury or stress to these trees. Another possible explanation is deposition of a thick blanketing tephra deposit from Augustine volcano. Augustine erupted in 1812, however the season and magnitude of this eruption is unknown (Simkin & Siebert, 1994). Unfortunately, this is an unlikely possibility given proxy evidence of an ash fall from Katmai volcano in 1912. If an ash fall were to cause a sudden and sustained reduction in growth, any tree surviving past 1912 should show a similar sudden growth reduction.

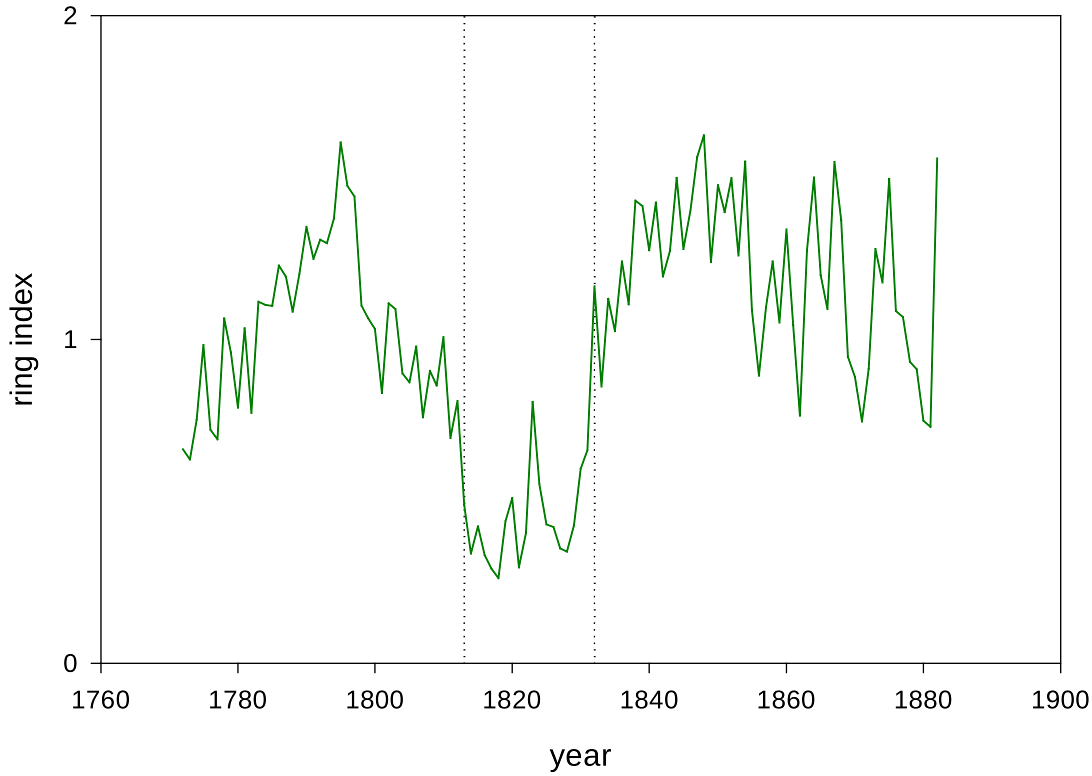

FIGURE 43. Partial STANDARD chronology from four lowland black spruce trees exhibiting an abrupt and sustained growth reduction beginning in 1813 and lasting until 1831. Many other black spruce trees exhibit this pattern, however, the growth reduction in those trees is not as abrupt.

Trees surviving through this event do not. One last explanation involves defoliating insects. Spruce budworm is a defoliating insect that causes marked growth reductions in host spruce and fir trees (Swetnam *et al.*, 1985; Ryerson, 1998, personal communication). It is conceivable that a small population of spruce budworm was active during this time period, however, no evidence exists for prior or subsequent budworm outbreaks. Other Kenai Peninsula tree-ring chronologies should be systematically examined for this growth reduction to determine whether or not black spruce in a limited area were only effected or if other tree species show a similar pattern during this time. Currently, this is a mystery which remains unsolved.

Some portion of the 1833 fire area could have burned in 1834 (Figure 25). The date of 1833 is corroborated by seven well-dated, early growing season fire scars from the eastern boundary of this fire. Three other fire scars from a site defining the western edge of the 1833 fire, appear to date to the late growing season of 1833. This implies the 1833 fire burned for the entire growing season, covering a distance of only12 kilometers. This is an unlikely scenario, given the synchrony of seasonality observed in fire scars from other fires covering greater areas. All of the fire scars that I dated to 1834 are early season fire scars, perhaps before, or just as growth was initiated in June. Fire scars from some more northerly located sample points do show some wood cell development before the scarring event, thus insuring the date of 1834. It is possible an early-to-late May 1834 fire adjoins an early season 1833 fire, and that I did not obtain samples adequate enough to determine this boundary. The proposed late-season 1833 fire scars could be dormant season 1834 fire scars. This scenario presents major dating problems. During an average summer, wood cell production will not begin before June, therefore only the latewood of the previous year will be seen in June. Likewise, in late-August to early September, latewood is fully, or nearly fully formed. Therefore, a fire at either of these times during the growing season is very troublesome to date, especially when the fires adjoin one another. I believe the extent of the 1834 fire is fully determined, however, the 1833 fire could have burned from the Kenai Mountains, or it could be a small fire event restricted to the eastern lowlands. Figure 44 presents a best evidence map of the 1833 and 1834 fires, compare this to Figure 25.

The mid-to late season 1849 fire is the largest mapped fire and is well-mapped in its southern, eastern and western boundaries (Figure 27). The southern margin of this fire adjoins the area burned in 1834. It is likely that the boundary between these two fires could be shifted north or south based on further field collections. It is unlikely the 1849 fire overburned any area burned in 1834. Since areas burned in 1834 would have been sparsely forested with 15 year old spruce trees, fuel accumulation would not have carried a fire at this time. Also, evidence from other fire return intervals within the study area suggest re-burning of a site does not take place in stands less than 25 years of age. Minimal burning at the edges of these two fires did occur, as evidenced by three burn poles that had both 1834 and 1849 fire scars. The eastern and northeastern boundaries of this fire are well-defined, however, the lack of sample locations in the northern areas of the 1849 fire area make the mapped area of this fire a minimum estimate. Additional collection of burn poles and increment cores from living trees from the western edge and northcentral portion of this fire area could efficiently increase the mapped size of this fire.

The sale of Alaska from Russia to the United States occurred in 1867 which was also the year in which a minimum of 8250 hectares of lowland black spruce forests burned (Figure 31). I was able to map most of this fire from air photos,. However, outer-ring analysis of burn poles collected in 1998 extended the eastern edge of this fire past the previous mapped boundary. Since the topography to the north of the mapped boundary is relatively homogenous, the 1867 fire could have spread further to the north. Some evidence to support this contention exists in the

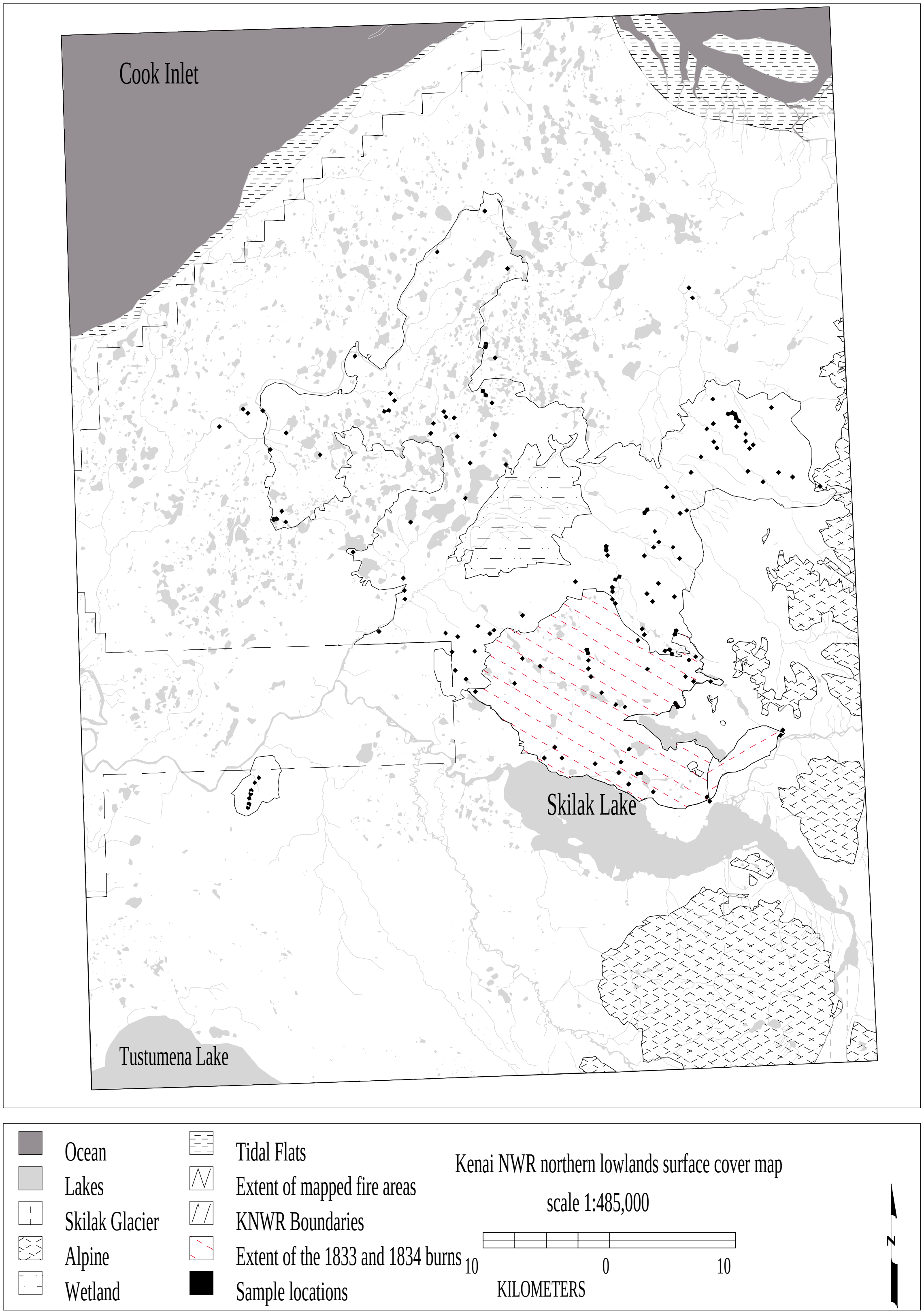

FIGURE 44. Revised extents of the 1833 and 1834 burns.

form of age-class data from a white spruce stand near Trapper Joe Lake, three miles to the north (Gracz *et al.*, unpubl.). Figure 45 shows the estimated germination dates of living black spruce trees within the PRS area and estimated germination dates of living white spruce and white birch trees from Trapper Joe Lake. Both sites show a classic post-fire signature, with stand initiation beginning after the 1867 fire. Without additional sampling locations to the north, I cannot accurately map the extent of this fire. However, a conservative estimate of an additional 1,500 hectares can be added to the size of this fire bringing the total estimate of this fire size to approximately 9,750 hectares.

Most of the area north of the 1849 fire, including a small portion of the 1849 fire, was burned in 1888. This large July to August fire event likely burned considerably more area than is currently mapped (Figure 34 , Table1). The northwestern boundary of this fire is defined by the Swanson River, which did not provide a substantial fire break to the spread of this fire in areas to the south. Therefore, it is likely that this fire burned more area to the north and west of its currently mapped boundaries. Residual forest stands at the northernmost tip of this fire area not burned in 1947, are of post-1888 origin. Sampling living trees in this area could reveal substantially more area burned.

FIRE RETURN INTERVALS

No significant difference exists between fire return intervals in the Rainshadow and the Lakes regions ($\alpha = 0.05$). This suggests topographic differences do not play a significant role in controlling fire spread or ultimate size in the northern lowlands. However, there is limited evidence to suggest fire return intervals are much longer further from the foothills (nearer Cook

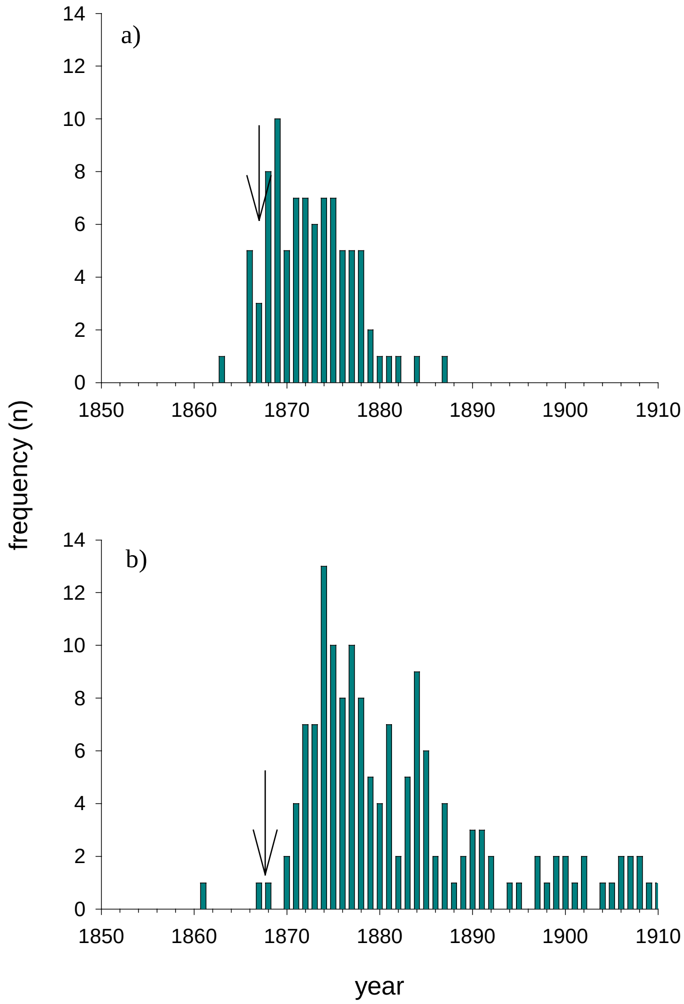

FIGURE 45. Estimated germination dates of (a) black spruce in the PRS area and (b) of white spruce near Trapper Joe Lake. Notice the similarity in the shape of the histograms both indicating a fire in 1867 (arrow). The absence of a long, right-skewed tail in the PRS area histogram is a result of a different sampling technique used as compared to the Trapper Joe Lake sample.

Inlet), in the western portion of the study area where fewer samples were obtained. However, since only two fires were dated there (1888 and 1947) this hypothesis cannot be evaluated. My assumption is that the Rainshadow area, with fewer fire breaks, would have large fires, but that they would burn less frequently since more area is burned at once (cf. Dansereau & Bergeron, 1993). Smaller but more frequent fires should occur in the Lakes area due to the numerous potential fire breaks (wetlands, lakes, rivers), which would limit fire spread.

These two hypotheses assume a similar frequency of fire ignitions for both areas. However, if ignitions are limited mainly to the Rainshadow area due to convective thunderstorm activity near the mountains, and topographic barriers do not limit fire spread as my data seem to suggest, then an assumption of a similar frequency of fire ignition does not apply. The seemingly simple question of fire origins plays a critical role here. Unfortunately, I did not collect a key piece of information while in the field that potentially could have been used to address this question. The direction that a fire scar faces can determine direction of fire movement because fire scars typically are formed on the leeward side of trees (Gutsell & Johnson, 1996). One could analyze the seasonality of fire scars across the landscape from large fires. This could yield some gross information as to the direction of travel of the fire, although only for slow moving fires. It is likely that fires that burned in lowland black spruce forests were not slow moving, but rather were relatively rapid in their progress. This is borne out by seasonality of fire scars from large scale fires such as the 1834 and 1849 burns. No discernable pattern of seasonality is observed in scars from these fires.

The wide range of fire return intervals in this study suggests some forest stands burn with regularity while others escape disturbance by fire for long time periods (Table II). This is a typical condition noted in many fire history studies in the boreal forest (cf. Heinselman, 1973;

Rowe *et al.*, 1974; Zackrisson, 1977; Engelmark *et al.*, 1994). Rowe *et al.* (1974) found a range of 125 years (35-160) in fire return intervals of black spruce stands in the Mackenzie Valley, N.W.T., Canada. Johnson and Strang (1982) found fire return intervals to range widely, from 14 to over 340 years, in western Yukon black spruce stands. The wide range of fire return intervals reported by Rowe *et al*. (1974), Johnson and Strang (1982), and in this study suggest some forest stands may be physically protected from fire spread or some areas have limited ignition sources. Shorter fire frequencies in western Yukon may be a result of climatic influences where conditions are substantially drier and lightning more prevalent as compared to the Kenai Peninsula.

Whether determined by chance or by physical isolation, over the past 300 years the wide range of fire return intervals suggests a landscape mosaic of different age forest stands throughout Kenai NWR lowland black spruce forests. A large single post-fire cohort such as the one that initiated after the 1947 burn has major consequences for future fire hazard and wildlife habitat. Is a large fire event such as this unusual? A question as grand as this one is fraught with difficulties. Limited evidence exists to suggest the 1708 fire was a very large event, perhaps covering 30,000 hectares or more. A benchlands fire in the early 1880s in the white spruce forest type, south of the current study area, may have burned as much as 43,000 hectares (Gracz *et al.*, unpubl.). The 1888 fire likely burned much more than 20,000 hectares of northern lowland black spruce forests. However, just how much more is unknown. The fires dated and mapped in this record are no larger than 33,600 hectares, less than one third the size of the 1947 burn. Based on the evidence recovered in the 300-years of this study, the 110,000 hectare 1947 fire is unusual and unprecedented. Johnson (1992) indicates that very large and intense fires that burn infrequently are common in the boreal forest. However, due to the problem of decreasing sample depth with increasing time, and the short fire record of this study, it is difficult to evaluate the uniqueness of the 1947 burn within the context of this study.

FIRE FREQUENCY CHANGES

A hiatus in fire occurrence appears to have occurred between 1762 and 1828 (Figure 12). The hiatus could be the result of too few samples recovered from that time period, or temporal differences having to do with large scale climate or human factors (Johnson, 1992; Johnson & Gutsell, 1994). A climatic explanation will be advanced in Chapter 4. Poor sample recovery is unlikely to explain an absence of fire evidence during this time period. Since two fires were dated prior to this time (1708 and 1762) and at least two more are inferred from sparse age-class evidence in the middle 1700s, general sample preservation from ca. 1790 to 1830 should be adequate for recovery of a fire record. However, evidence from a single scarred burn pole suggests a fire in 1801, and additional age-class evidence from areas that burned in 1849 show some germination during this time period (Figure 28). However the date of 1801 hinges on a single sample with no convincing age-class, therefore the nature of this evidence is equivocal.

A complex situation arises when one considers the time period from 1830 through the 1900s. Russian and American influences increased dramatically during this time period of improved (warming) climatic conditions. The question remains whether increasing temperature with improved drying of fuels (and possibly of an increase in natural ignition sources), or increased human ignition sources brought about a greater area burned and higher fire frequency beginning in the middle 1800s. It is likely both factors contributed to the increased fire frequency, however to what degree each is responsible is impossible to determine.

THE FIRE CYCLE

Calculation of the fire cycle depends on having a complete census of forest stands on the landscape at time *t*. In this case, call time *t* 1946, one year before the large 1947 burn. In 1946 there were components of many post-fire cohorts on the landscape from fires burning prior to this time. Based on my collections I can identify cohorts of trees living in 1946 but which originated from fires in 1762, 1828, 1833, 1834, 1849, 1867, 1874, 1888, and 1898. Unfortunately, the methods employed in this study did not take into account mapping of small older forest patches. These older, often small forest patches become more fragmented over time to a point where scattered individual survivors are not able to be mapped as a distinct age-class (Finney, 1995). In 1946 there were very few living trees that had survived since the 1762 fire, most of which were scattered fire-scarred individuals, and I found no trees that could have been alive in 1946 that survived from the 1708 fire. This leaves the fire cycle calculation for the above set of years beginning in 1762 or 1828. I argue the methods used to determine the fire history in this study amount to a census of fires and their areas as can be determined from remnant and residual material. Therefore, calculation of the fire cycle based on the above set of years provides a good estimate of the true fire cycle in lowland black spruce forests.

Two different probabilities of burning are evident in Figure 15; 1828-1834 and 1849-1898. However, with the short time span and only three fire dates between 1828 and 1834, I am hesitant to assign this period a different frequency of burning than the later time period. Sampling bias resulting in smaller that actual cohort sizes in 1946 could explain the apparent change in probability of burning. The time period of 1849-1898 is likely a very different time period in terms of probability of burning due to ameliorated climate conditions and increased human ignitions on the Kenai Peninsula.

Figure 17 presents an alternative view of the fire cycle which includes a very small estimate of area occupied by post-1762 fire trees alive in 1946. The 'missing tail' (Finney, 1995) of Figure 15 is 'found' in Figure 17, however, the resultant estimate of the scale parameter (which is recurrence time of fire within the study area) is 42 years as compared to 56 years for Figure 15. This indicates that the fire cycle is shorter over a longer time period. As mentioned above, fires likely burned between the 1730s-1750s, however, either fire cycle calculation does not include these fires. Therefore, each of these fire cycle calculations (Figure 15 and 17) are slightly biased.

This bias is a result of the sampling technique used in this study. I used a non-random, opportunistic sampling strategy that relied on locating evidence of older fires where ever I could find it. However, in comparison to a random sampling strategy, I was able to recover more information about past fires. For instance, the 1874 fire is determined from three fire scars at only one point, and the area of 35 hectares is derived from a minimum mapping unit. Using a random sampling strategy, if I found those fire scars close to but outside of a random sampling unit, I would not have been able to collect them. However, detection of old fires and small fires using burn poles for stand age and outer-ring analysis can be problematic. For instance, I found very few burn poles in the area where the 1888 fire burned. I believe that the 1849 fire was the last fire in many areas that were burned in 1888. In the western portion of the study area where the 1898 fire burned, I found no burn poles except the few that survived and were scarred by the 1898 fire. Therefore when young forests are burned burn pole evidence is lost quickly and evidence for more recent fires is not recovered. Evidence of older fires is lost with each successive fire on the landscape. Living trees are killed, forest stands are fragmented, and burn poles are consumed in subsequent fires. All of these problems contribute to the bias of fire frequency calculations in this and other studies of boreal forest fire history.

CONCLUSIONS

From the above fire descriptions a generalized natural history of fire in black spruce forests on Kenai NWR can be aggregated. Obviously, without a complete census of fire events over time, only generalizations about fire size, frequency, and intensity can be made. All of the fires in the 300-year record produced a substantial post-fire cohort, typical of boreal forest post-fire stands (cf. Heinselman, 1973; Cogbill, 1985; Desponts & Payette, 1992; Riverin & Gagnon, 1996). With the exception of the 1849 fire, all fires mapped in this study appeared to be complete stand-replacing fire events (cf. Figures 20, 26, 30). Age-class evidence from stands burned in 1849 reveal a small uneven-aged component (Figure 28). This may be an indication that the 1849 fire was not particularly intense in these locations, perhaps creeping along the forest floor torching individual trees, while leaving residual living individuals. This would contrast with a fire such as the 1867 event that has no evidence of residual post-fire survivors (Figure 30), thus indicating a complete stand replacing fire event.

The record of fire occurrence presented in this study serves as a baseline fire history for the Kenai NWR northern lowland black spruce forests. Fire frequencies and the fire cycle are similar to other areas in the western boreal forest with the same forest vegetation type. However, caution must be used in interpretation of the fire frequencies and fire cycles presented here since they do not incorporate all fires that have burned over the past 300 years. Fire frequencies may have been significantly influenced by human ignitions after 1830. Biases in the method of sample collection and sample preservation contribute to the lack of a complete fire record.

Topographic differences within the study area do not seem to have an effect on fire frequency or size. Climatological controls, however, may have played a role in determining fire ignition and spread, especially during the time period of ca. 1762 to 1828 when a curious lack of fire ignitions occurred. Future studies should focus on completing the fire history of lowland black spruce stands in areas outside of the 1947 burn area, with an aim towards recovery of the most complete and longest fire record available.

Chapter Four: Fire and Climate Relations on the Kenai Peninsula

"Fire is a serious menace to the forests of the mountain and plateau regions. The fire season begins about May 15 and lasts until August. The first month of this period is the most dangerous, when, as a rule, the skies are clear, with prevailing westerly winds which dry the dead grasses and plants until they are like tinder, and catch fire at the least opportunity, the fires spreading rapidly, killing everything in its way." *W.A. Langille*, on the general fire season of the Kenai Peninsula, 1904.

OVERVIEW OF SYNOPTIC FIRE WEATHER

During the growing season, strong linkages exist between climate variables and fire conditions in the boreal forest (Johnson, 1992; Johnson & Wowchuk, 1993). In particular, critical fire weather is linked to the formation and breakdown of a persistent 500mb long-wave ridge (Schroeder *et al.*, 1964; Newark, 1975; Nash & Johnson, 1996). This ridge is a high pressure system (anticyclone) that produces warm and dry conditions and light winds with low humidity (Flannigan & Harrington, 1988). Under these weather conditions, forest fuels will dry rapidly setting the stage for a critical fire situation. Because the high pressure system is relatively stable, fire ignitions during these conditions are usually human-caused (Johnson, 1992). However, as this ridge breaks down, a low pressure trough forms causing air mass instability and lightning (Timoney & Wein, 1991; Johnson, 1992). With dry fuels, a lightning ignition source, and variable strong winds, fire spread is rapid.

Over long time periods, changes in the fire cycle and fire frequencies in the 20th century within the boreal forest have been shown to coincide with increased fire suppression activities (Heinselman, 1973; Zackrisson, 1977; Van Wagner, 1978). During the 19th century, with absence of compelling evidence for a lengthening of fire cycles due to fire suppression, some authors assume that changes in fire cycles are due to a change in climate (Clark, 1990; Johnson *et al.*, 1990; Masters, 1990; Bergeron, 1991; Swetnam, 1993). This change in climate is usually attributed to the Little Ice Age (LIA) which globally produced highly variable climate conditions (severe winters and exceptionally wet or hot, dry summers) during the period from approximately 1500 to 1850 (Grove, 1988). Studies that cite LIA effects, however, have not investigated this proposed linkage between reduced fire activity and climate using dendroclimatic analysis.

Using fire frequencies and occurrences, and reconstructed temperature from Briffa *et al*. (1992) I evaluated the association of climate and fire occurrence on the Kenai Peninsula for the past 300 years. Two questions are of interest: 1) is there a significant association between inter-annual changes in growing season temperature and fire occurrence? and 2) is there a discernible pattern to fire occurrence and large scale temperature trends over time?

METHODS

I used Superposed Epoch Analysis (SEA) to evaluate the association of fire events and temperature through time (Kelly & Sear, 1984; Lough & Fritts, 1987; Swetnam, 1993; Swetnam & Betancourt, 1998). SEA is a powerful tool that determines a mean pattern of association between specific events and a continuous time series of a driving variable. Mean climate conditions are computed for a set of years prior to, during, and after the set of fire events being evaluated (Grissino-Mayer, 1995). In this way, lagging and leading relationships may be evaluated. I used the temperature reconstruction of Briffa *et al.* (1992) as the continuous time series and fire event years dated in this study along with 20th century fire years from the Kenai Peninsula. The probability of a random association was evaluated by using Monte Carlo simulations. This involved randomly selecting 1,000 event years and comparing those to the temperature and ring index time series as described above for the actual event years (Lough &

Fritts, 1987). Climate conditions prior to, or during the fire year would be important by affecting fuel moisture content. Climate conditions after a fire year could have no effect, so any observed patterns would be spurious.

I also evaluated the temporal pattern of fire occurrence and recruitment pulses following each fire compared to large scale patterns of reconstructed temperature. I defined a post-fire window of 30 years which encompasses the range of time that includes the time of post-fire recruitment (i.e. Figures 22, 26, 35) and the beginning of canopy closure in boreal spruce forests (Johnson, 1992). This window begins one year after the fire event and, where two or more windows overlap, I merged them into one continuous window. Thus, each continuous window represents active post-fire recruitment somewhere in the study area.

RESULTS

I used the 12 fire event years of 1762, 1828, 1833, 1834, 1849, 1867, 1874, 1888, 1898, 1947, 1969, 1974, and 1996 as event years and the reconstructed temperatures from Briffa *et al*. (1992) as the climate variable. No significant ($\propto = 0.05$) relationships existed between reconstructed temperature and fire events in fire years, or years previous to fire events (Figure 46).

Figure 47 shows the temporal patterning of recruitment pulses as they relate to temperature variations over the last 300 years. Between 1828 and 1928 a long series of overlapping recruitment pulses are seen which correspond to eight individual fire events which occurred during this time period. A short hiatus in post-fire recruitment is seen between approximately 1740 and 1760 and between 1930 and 1947. From approximately 1790 through

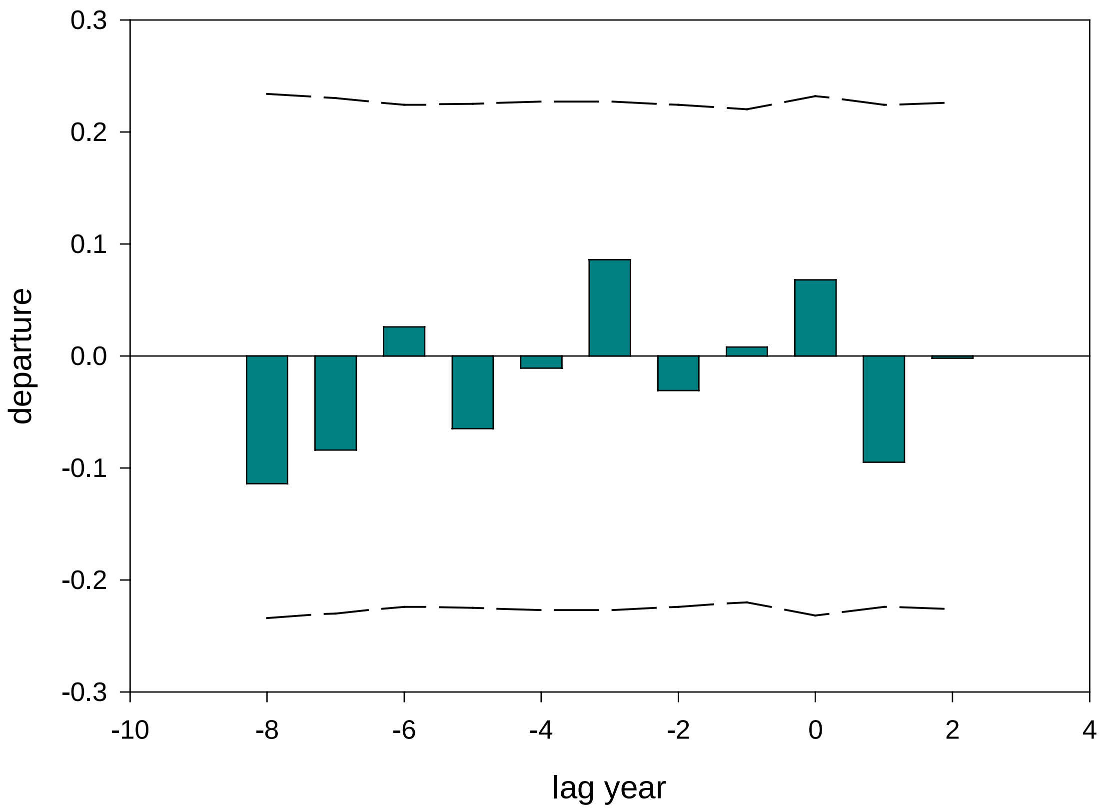

FIGURE 46. Superposed epoch analysis results showing no significant relationship between fire events (lag year zero) and the Briffa et al. (1992) temperature reconstruction. Broken lines indicate 95% confidence limits.

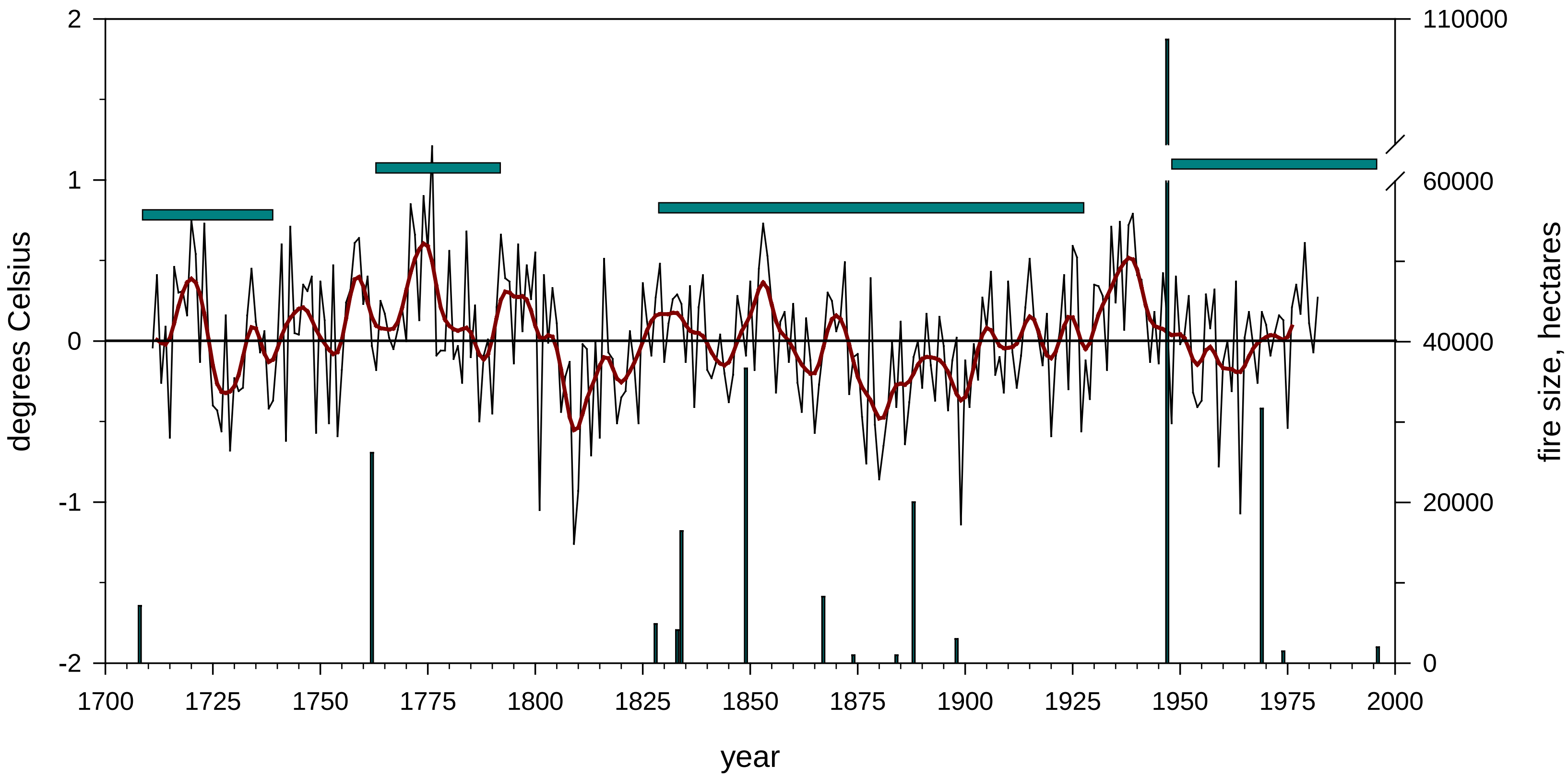

FIGURE 47. Briffa *et al.* (1992) reconstructed temperature (horizontal line, left axis) departures from the 1881-1982 mean, temporal distribution of fire events (vertical bars, right axis), and post-fire recruitment events (horizontal bars) in Kenai NWR lowland black spruce forests. Horizontal black bars represent one or a series of overlapping 30-year post-fire recuritment episodes. Note the hiatus in fire activity and post-fire recruitment from 1792 through 1828.

1820 a longer gap is seen which corresponds to the coolest temperatures of the entire record. Reconstructed temperatures after ca. 1940 are biased. Briffa *et al.* (1998a,b) indicate that a change in the relationship between tree-ring density and summer temperature occurred around 1940 resulting in poor retrodicted temperatures.

DISCUSSION

Fires in boreal forests tend to be high intensity stand-replacing fires (Rowe & Scotter, 1973; Dyrness *et al.*, 1986; Johnson, 1992; Goldammer & Furyaev, 1996). As with most wildland fire regimes, the availability of an ignition source, fuel type, topography, and weather conditions play an important role in determining fire ignition, rate of fire spread, and total fire size. Critical fire weather typically has characteristics of low humidity (low fuel moisture) and high temperatures, with or without strong, drying winds (Schroeder *et al.*, 1964). Persistent high pressure ridges over large areas of Alaska (including southcentral) combined with airflow patterns from the north or northeast, combine to produce warmer daytime temperatures and dry conditions. This pattern can last for several weeks, thus producing critical fire weather conditions (Finklin, 1982). This combination of temperature and drying conditions leading to low fuel moisture is key for the occurrence of fires in southcentral Alaska. The results of superposed epoch analysis show no significant relationships between fire events and ring-width indices, nor between fire events and reconstructed temperature. The lack of a temperature association with fire occurrence is common to many fire regimes, especially in the western and southwestern United States (Swetnam, personal communication, 1998). Rather, a precipitation linkage is most common to many fire regimes. As noted above, fuel moisture conditions are the limiting factor in determining fire ignition and rate of fire spread. Temperature can have an influence on fuel moisture, however, precipitation and relative humidity are more important factors contributing to initial fire spread.

FIRE OCCURRENCE AND CLIMATE FORCING

There is evidence that large scale changes in temperature have affected fire ignition and recruitment patterns on the Kenai Peninsula. Several gaps in recruitment exist during the 300 year record. Disappearing evidence of early fires could explain the gap in post-fire recruitment between ca. 1740 to 1760. Some evidence suggests fires did burn in lowland black spruce forests prior to 1730 near the Kenai mountains, and in the middle 1750s in the western portion of the study area. The early to middle 1700s is a time of increasing temperatures (Figure 47) and marks the beginning of retreat of several glaciers on the Kenai Peninsula and Alaska (Wiles and Calkin, 1994; Wiles *et al.*, in press). Fire history studies from the western United States (Pitcher, 1987; Baisan & Swetnam, 1990; Brown & Swetnam, 1994) and northern Europe (Zackrisson, 1977) indicate numerous fires did burn during time period. Therefore it is not unlikely that fires burned in the early to mid-1700s on the Kenai Peninsula, even though a paucity of evidence exists to support this contention.

Sampling bias could explain the later gap in recruitment, from ca. 1930 to 1947. Due to the sampling strategy used in this study (the use of burn pole age-class, outer-ring analysis, and fire scars), fires that burned after 1900 may be underrepresented in the sample. For instance, if a fire burned in 1910, recruitment would have occurred actively from 1911 through the early 1940s. At the time of the 1947 burn, trees within this fire area would have ranged in age from less than 10 to as much as 35 years old. As most black spruce trees are shallowly rooted, these small trees would have fallen over quickly after 1947. Once on the ground, trees would have rotted rapidly and burn pole evidence of this 1910 fire would have been lost. The turn-of-the 20th century was a time of increased human exploration of the Kenai Peninsula and it is almost a certainty that fires did burn after 1900.

During the late-1700s through the early-1800s (ca. 1790-1830) a substantial gap in fire activity and post-fire recruitment is seen which also corresponds to the coldest temperatures of the entire record (Figure 47). This gap could be due to a sampling bias as described above. However, I believe it is due to a lack of fire ignition during this time period. Since two fires were dated prior to 1800, preservation of wood should be adequate for sample recovery if fires burned between 1762 and 1828. The very cool temperatures during this time period were likely accompanied by wetter or more humid conditions. This change in climate may have reduced the incidence of natural fire ignitions (and subsequent fire spread) from lightning strikes. However, if small fires did occur during this time period (as suggested by evidence presented in Chapter 3), the sampling strategy used in this study missed them. This time period also corresponds to reduced fire activity or small fires in western Canada (Rowe *et al.*, 1974), central Sweden (Zackrisson, 1977), the western and southwestern United States (Pitcher, 1987; Baisan & Swetnam, 1990; Swetnam & Betancourt, 1992; Brown & Swetnam, 1994), and in northwestern Quebec (Bergeron & Brisson, 1990; Dansereau & Bergeron, 1993). Therefore, rather than an isolated local phenomena, it is likely that the late 1700s through the early 1800s was a period of reduced fire occurrence and area burned for a large portion of western North America and the Northern Hemisphere.

We have no absolute proxy of this type of change in fire regime associated with a change in the climate system. A shift in fire frequency likely occurred ca. 1790 and after the early 19th century cold period (ca. 1830) (Figure 17), however, this shift in the fire frequency may also have had to do with an increased European presence on the Kenai Peninsula. From the late 1700s, Russians lived and subsisted on the Kenai Peninsula. Beginning in the early to mid 1800s many more Russians came to the Kenai Peninsula in search of furs and gold. With increased human activity on the Kenai Peninsula at this time, one would expect that the incidence of human-caused fires would have increased. An increase in the incidence of fires after 1830 is recorded in this study, however, the causes of these fires cannot be determined.

Currently, there may be a similar change occurring on the Kenai Peninsula with increased warming and drying (unprecedented in recent times), and increased human presence in the forests of the Kenai Peninsula. Changing fire frequencies now could be due to active fire suppression, changes in ignition sources due to humans or climatic influences, or changes in the fire hazard on a seasonal basis due to climatic changes. With a continued increase of human activity on the Kenai Peninsula, modified weather patterns and increased lightning activity need not occur to increase fire frequencies. Human ignitions alone would be enough to change the fire frequency and overall structure of Kenai lowland forests (cf. the 1947, 1969, and 1996 burns). However, with an increase in summer temperatures, the likelihood of an increase in summer storms and lightning is high. Therefore, with increased seasonal drying of forest fuels and a likely increase in ignition sources, changes in forest structure due to fires is inevitable.

CONCLUSIONS

Large scale climatic patterns have, and will continue to influence fire ignition and spread on the Kenai Peninsula. Since circa 1976, the Kenai Peninsula is experiencing an increase in summer temperatures without an concomitant increase in precipitation. This may lead to drier summer weather, contributing to an increased drying of forest fuels, resulting in more frequent hazardous fire seasons than existed in the past. With a complicated interaction of changing climate and changing ignition sources due to climatic or human interaction, predicting the future fire regime not possible with our current knowledge of fire and climate relations. Certainly with an increase in human presence on the Kenai Peninsula, the chance for accidental ignitions is greatly increased. With the increasing temperatures an increase in convective thunder storms and lighting may also occur.

A better knowledge of past disturbance (fire) regimes and climatic conditions will allow the correct interpretation of current and future disturbance regime changes under different climatic conditions. However, at this point we have but a small portion of the larger picture of disturbance regime and climate history on the Kenai Peninsula. With additional field investigations, a clearer understanding of the disturbance regimes and climate history of the Kenai NWR can be attained. From these additional studies management of the forest and wildlife resources will be greatly benefited.

Future Research

Future research should be focused on completion of the fire history of lowland black spruce forests. In this study, I was able to sample approximately 80% of the lowland black spruce forest stands within the 1947 burn. However, many areas outside of the 1947 burn remain unsampled, and therefore have an unknown fire history. Using the techniques presented and described here, gaining a complete picture of the fire history of lowland black spruce forests is an attainable goal. Serious attention should also be given to completing the disturbance history of the white spruce forest type on the Kenai NWR. Integration of these completed disturbance histories with a high resolution vegetation GIS (Geographic Information System) layer is essential for the development of a GIS forest succession model. This model could be used to define wildlife habitat usage and home ranges of moose, lynx, bears, and caribou using GPS locations of radio-collared animals. Using the vegetation layer in combination with climate layers, one could develop a forest fire hazard and spread model that could be used in fire management activities on the Kenai NWR. One could also use such a model to generate future scenarios of forest change under different disturbance regimes and climatic conditions.

Construction of multiple tree-ring chronologies from a variety of treeline sites around the Kenai Peninsula should be pursued. This would allow one to determine the spatial trend of temperatures over time, and to evaluate the fidelity of temperature change on the Kenai Peninsula as compared to proxy temperature records from the Arctic and Northern Hemisphere. If possible, white spruce and mountain hemlock should be sampled at the same site in order to evaluate changes in climate as recorded by different species. Extension of a temperature sensitive tree line chronology prior to 1700 would allow the evaluation of longer term climatological and ecological trends on the Kenai Peninsula. The construction of maximum latewood density (MXD) treeline chronologies should be pursued. MXD chronologies developed from tree-rings have been used to reconstruct summer temperatures in high latitude regions (Schweingruber *et al.*, 1993; Briffa *et al.*, 1994; Jacoby & D'Arrigo, 1995). Tree-ring densities used in combination with total ring-width can provide a better temperature reconstruction than using either variable alone (Briffa *et al.*, 1990; D'Arrigo *et al.*, 1992).

Rising treeline on the Kenai Peninsula is another indication of an increase in summer growing season temperatures. From the few treeline sites visited in this study, and in other field investigations, very little, or no dead woody remains have been found above current treeline. This indicates that in recent times, rising treeline is a unidirectional process, and there has been no significant lowering of treeline in the recent past. However, old slow-growing, stunted trees may currently be growing with more vigorous, recent (< 300 years old) treeline recruits. These older trees may be a portion of an older treeline which is now being surpassed by more recent recruitment. Therefore a comprehensive treeline demographic study should be undertaken. This study would involve sampling multiple treeline sites within the Kenai Mountains. At each site, increment cores from living trees, and cross-sections from dead trees, would be obtained along an elevational gradient to reconstruct the dispersal of trees over time and space. Different slope aspects would also be sampled, with the exception that trees on south-facing slopes tend respond more rapidly to increases in summer temperatures as compared to trees growing on north-facing slopes. This study would provide the answer to the question of whether or not the current warming trend is an unusual occurrence, or, if as recorded in treeline movements, a warming trend has occurred in the past. One could also address the question of whether or not the warming has accelerated in the 20th century or if it is a continuation of a warming trend begun in earlier centuries.

Additional research should be focused on determining the set of conditions that exist prior to and during fire years starting first with 20th century fire years and then using fires dated in this study. Proxy records of drought stress from stable carbon isotopes ($\delta^{13}C$) can be used as a measure of drought stress in conifers (Hemming *et al.*, 1998). This type of chronology would provide information about dry conditions during the growing season and would be a substitute for a precipitation sensitive chronology. Correlation of stable carbon isotope chronologies with the Canadian Forest Fire index, and more specifically the Drought Code, should be attempted. With these comparisons, one could define the range of variability in climate associated with 20th century fires and those fire events dated in this study.

More effort should be directed towards long-term vegetation and fire history studies which utilize sediment cores from lakes and bogs. These long-term records of climate and vegetation change are crucial to understanding past and current global change processes. One could address such questions as whether or not the current warming and drying observed across the Kenai Peninsula is an unusual event, or merely part of a longer-term cycle. Longer-term fire history records can be developed from sediment cores and can provide insights into the role of fire over thousands of years. Important questions such as, 'how long has fire been a dominant disturbance mechanism in Kenai Peninsula forests?', can be addressed by long sedimentological fire history records.

The stage has been set for a change in the disturbance and fire regime on the Kenai Peninsula. Conditions are changing each year, and without knowledge of past disturbance regimes we have no reference point for the future. Increasing summer temperatures will have many more consequences than increasing the fire hazard in Kenai Peninsula forests. Spruce bark beetles are influenced by warm early summer temperatures and under ideal conditions can complete their life cycle in one growing season, instead of two. With increasing summer temperatures, spruce bark beetle outbreaks may accelerate and become more common within Kenai Peninsula white spruce forests. If this happens, the structure of tens of thousands of hectares of white spruce forests will be altered, changing habitat conditions for many ecologically and economically important wildlife species. An increase in summer thunderstorm activity and lightning may occur with an increase in summer temperatures. The absence of a concomitant increase in precipitation (or even a decrease), coupled with thousands of hectares of beetle-killed forests, may increase fire hazard across the Kenai Peninsula. Comparison of past periods of spruce bark beetle outbreaks with past fire activity could reveal whether or not past beetle outbreaks have been associated with increased fire activity.

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