Determinants of fire regime variability in lower elevation forests of the northern Greater Yellowstone Ecosystem

by Jeremy Scott Littell

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Science
Montana State University

Abstract:
Understanding how multivariate influences on fire regime cause changes in the spatio-temporal distribution of fire regimes and fire events is critical to the management of forest ecosystems. Climatic change, land-use change, and changes in vegetation patterns during the 20th century in the Greater Yellowstone Ecosystem have been documented, and understanding the past fire history of the ecosystem is necessary to gauge uncertainty and opportunity surrounding management decisions. Previous research in Greater Yellowstone has primarily focused on slow-growing forests with fire return intervals of approximately 200-400 years. Relatively little research has focused on lower elevation forests with shorter fire return intervals. I produced three 400-year dendrochronologically precise fire histories in biophysically similar but geographically separate watersheds in northern Greater Yellowstone. The watersheds are primarily composed of lower elevation Douglas-fir (.Pseudotsuga menziesii) forests with smaller components of lodgepole pine {Pirns contortd), subalpine fir {Abies lasiocarpa), Engelmann spruce {Picea engelmannii), and limber pine {Pirns flexilis). I correlated site-specific and regional fire regime with climatic variability using a variety of multi-taper and bootstrapping time series analysis techniques. At one of the three watersheds, I also related spatial fire regime variability to spatial and topographic variables that influence soil moisture using partial Mantel analysis. Results suggest fire regimes in northern Greater Yellowstone lower elevation forests are defined as much by their variability as the mean fire interval (20-35 years) and that this variability is related to multi-decadal and sub-decadal synoptic Pacific climate phenomena that affect local climate. In addition, these forests exhibit mixed-severity fire regimes throughout the fire history record. Spatial variability in fire regimes is primarily related to elevation. Given the variability in fire return interval and the mixed-severity classification of these fire regimes, it is doubtful that any significant differentiation between current forest structure and the natural range of variability- in forest structure can be made. Instead, the current and predicted future ecological and climatological environment must be considered a proximate driver of fire regime in these systems and management scenarios must be crafted with this uncertainty in mind.

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MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2002

APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGEMENTS

I offer thanks to everyone who helped with this project. I thank Lisa Graumlich for inspiring, mentoring and advising me throughout and for teaching me that science is more than just a good hypothesis: it's the execution of will in pursuit of truth. The other members of my committee, Andy Hansen and Bruce Maxwell, contributed invaluable knowledge of the ecology of fire and its effects in the Greater Yellowstone Ecosystem. The United States Department of Agriculture NRI program funded most of this work, and Gallatin National Forest and Yellowstone National Park made fieldwork possible with sampling permits. To my parents, one of whom taught me to love science early on and the other of whom taught me to organize the ensuing thoughts in my head, I thank you both. Duncan Patten and Don Despain provided insight into the changes in Greater Yellowstone in the last few decades. To all those who accompanied me in the field or who worked on samples in the lab, for a few hours or a few months, I extend immense thanks; this research could not approach what it is without your strong backs and wills: Sean Hill, Gabe Bellante, Lindsey Waggoner, Brian Peters, Andy Bunn, John King, Chris Caruso, Greg Pederson, Tim Sharac, Derek Sonderegger, Todd Kipfer, Katie Brown, Scott Powell, and Doug. I owe special thanks to Jeanette Goodwin for keeping financial disarray at bay despite my best efforts. The evolution of this thesis was substantially expedited by encouragement and/or ideas from Emily Heyerdahl, Mike Pisaric, Dean Urban, Rick Lawrence, and Peter Brown. Finally, I owe no small debt of the soul to my wife, Allene Whitney, who encouraged me to pursue this work with all the intensity that I could muster and was waiting with the Silver Bus when I most needed it.

TABLE OF CONTENTS

TABLE OF CONTENTS – CONTINUED

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES – CONTINUED

ABSTRACT

Understanding how multivariate influences on fire regime cause changes in the spatio-temporal distribution of fire regimes and fire events is critical to the management of forest ecosystems. Climatic change, land-use change, and changes in vegetation patterns during the 20th century in the Greater Yellowstone Ecosystem have been documented, and understanding the past fire history of the ecosystem is necessary to gauge uncertainty and opportunity surrounding management decisions. Previous research in Greater Yellowstone has primarily focused on slow-growing forests with fire return intervals of approximately 200-400 years. Relatively little research has focused on lower elevation forests with shorter fire return intervals. I produced three 400-year dendrochronologically precise fire histories in biophysically similar but geographically separate watersheds in northern Greater Yellowstone. The watersheds are primarily composed of lower elevation Douglas-fir (*Pseudotsuga menziesii*) forests with smaller components of lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and limber pine (*Pinus flexilis*). I correlated site-specific and regional fire regime with climatic variability using a variety of multi-taper and bootstrapping time series analysis techniques. At one of the three watersheds, I also related spatial fire regime variability to spatial and topographic variables that influence soil moisture using partial Mantel analysis. Results suggest fire regimes in northern Greater Yellowstone lower elevation forests are defined as much by their variability as the mean fire interval (20-35 years) and that this variability is related to multi-decadal and sub-decadal synoptic Pacific climate phenomena that affect local climate. In addition, these forests exhibit mixed-severity fire regimes throughout the fire history record. Spatial variability in fire regimes is primarily related to elevation. Given the variability in fire return interval and the mixed-severity classification of these fire regimes, it is doubtful that any significant differentiation between current forest structure and the natural range of variability in forest structure can be made. Instead, the current and predicted future ecological and climatological environment must be considered a proximate driver of fire regime in these systems and management scenarios must be crafted with this uncertainty in mind.

CHAPTER 1

INTRODUCTION

Fire Regime

Fires have fundamentally structured forested ecosystems since the evolution of terrestrial progymnosperm communities in the mid to late Devonian period of the Paleozoic era (Scott 2000, Shear 1991). The effects of these fires were presumably important both to the immediate structure and distribution of early forests and to the evolutionary trajectory of tree-like species into the modern era. However, evidence permitting the precise reconstruction of the frequency, size, and intensity of fire events so far back in the geological record is spatially and temporally sparse, and thus understanding the exact role of fire in early plant ecosystems is difficult. Studying the role of fire in extant forest ecosystems is comparatively tractable, and revolves primarily around description of the effects and causes of fire regime.

Combinations of temporal frequency, spatial size, and relative severity or intensity of fires in forested ecosystems are referred to as fire regimes (Figure 1), although sub-components of seasonality, predictability, and effect have been proposed (Agee 1993). The components of fire regime are not independent, and the relationships between the components are determined by statistical distributions of fire events at a given place through time. The temporal axis of fire regime is described by the fire return interval, or how often fire returns to a given area. The size axis of fire regime is described

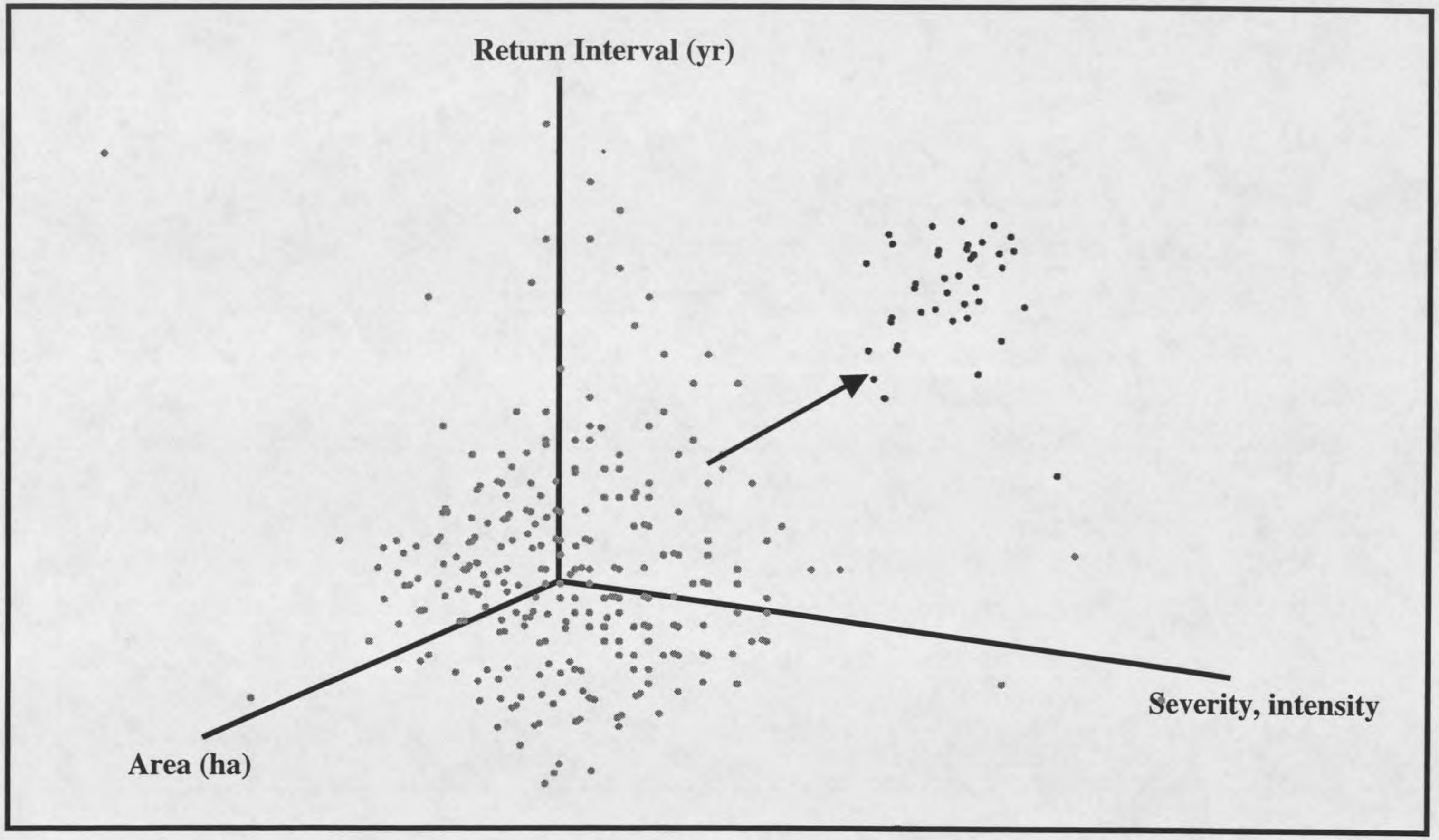

Figure 1. Three-axis Conceptual Diagram of Fire Regime. Fire regime is the scatter of points described by a statistical distribution of events through time (light points). A change in management practices, climate, or vegetation cover can produce a shift in fire regime towards a fundamentally different pattern of fire events through time (after Wallin, personal communication)

by the distribution of fire sizes through time. Finally, the severity axis of fire regime describes the effect of the fire on forest structure in terms of the relative percentage of trees killed in a given area through time. All three axes thus influence each other, and while plotting a given fire event in the fire regime space described by the three axes is fairly simple, describing the multivariate distribution of fire regime is not trivial. Despite this difficulty, it is critical in human-influenced and human-managed forested ecosystems to describe the distributions that comprise fire regime, variability in that regime, and its proximate causes.

Understanding fire regime, its variability, and its causes is critical to the management of forested ecosystems (Arno 1980) because fire is such an integral and prevalent determinant of forest structure (Pickett and White 1985) in the ecosystems humans rely on for forest products, home sites, biological preserves, and ecosystem services. Putting historical fire regime in the context of global change, including changes in climate and human demography, is also critical because future decisions regarding the management of public land in the National Park Service system (NPS), the United States Forest Service system (USFS), and the Bureau of Land Management System (BLM) will depend fundamentally on understanding historical fire regime and how it is likely to change given predicted changes in its proximate drivers (Agee 1997).

Fire-regime Determinants in Forested Ecosystems

Several factors are commonly implicated as important determinants of fire regime. Chief among these is the long-term pattern of temperature and precipitation because, over decades to centuries, they produce a strong regional deterministic effect on the distribution of forest types (Walter 1973) and, over weeks to seasons, determine the relative moisture content in such fuels (Agee 1997). However, any factor that influences the amount of soil moisture available to trees over long periods can exert a controlling factor on fire regime (Renkin and Despain 1992). At the spatial scale of a third-order watershed, geological substrate (Despain 1990), sub-regional precipitation variability (Clark 1989), forest type and other factors may influence fire regime. Assuming ignition sources are not limiting, fire regime is therefore a function of the interaction between abiotic conditions (climate, topography, substrate) and biological/ecological structure (forest cover, community type, ecological history).

Long-term climate influences fire regime at the scale of centuries to millennia via its controlling influence on the distribution of major vegetation types (Fall 1997, Walter 1973, Weaver 1980) and the frequency of events that dry out fuels in those vegetation types (Bray 1971, Swetnam and Betancourt 1998). At temporal scales of years to decades, fire return intervals in the western United States are statistically correlated with long-term quasi-periodic (2-7 years) synoptic climate phenomena such as the El Niño Southern Oscillation (ENSO or SO) (Grissino-Mayer and Swetnam 2000, Swetnam and Betancourt 1990). Finally long-term climate also influences the frequency of short-term (weekly to annual) drought events conducive to the ignition and spread of fire. Thus climate affects fire regime at a variety of temporal scales. Understanding the distribution of fire return intervals in relation to anomalies at one or more temporal scales is critical to predicting fire events but also to future changes in the potential fire regime at a given place.

Spatial variability in geological substrate, elevation, and topography also influence fire regime by affecting soil moisture availability, barriers to fire spread, and growth rates and continuity of fuels (Despain 1990). The grain size, relative mineral composition, and variability of soils interact to influence the potential distribution of tree species, which in turn influences fuel moisture and fire regime distribution (Despain 1990). Similarly, elevation influences precipitation and growing season length and therefore the distribution of tree species (Walter 1973), fuel moisture, and fuel distribution. Finally variation in topography, especially aspect and topographic convergence, influence forest type and fire regime (Taylor 2000, Taylor and Skinner 1998).

Climate, substrate, elevation, and topography all interact to produce the abiotic template which determines the structure and composition of forests at longer time scales as well as fuel moisture at shorter time scales. Thus, statistically characterizing the influence of regional and site-specific factors on fire regimes is critical to forecasting the effects of land-use and climatic change on fire regime.

Effects of Fire Regime in Forested Ecosystems

Prior to Euro-American settlement of the western United States, forest fires were prevalent disturbance mechanisms (Covington 1992, Brown et al. 1994, Wallin et al, 1996) and produced a strong deterministic effect on the structure and function of western forest ecosystems. The manner in which fire influenced those ecosystems was probably directly dependent on its frequency, and contrasting types of fire regime are typically associated with contrasting types of forest structure. In theory, forests where fire was relatively frequent (return intervals of years to decades) tended towards relatively open, savanna-like "parks" which burned primarily in the understory (Weaver 1943). Where fire was infrequent (return intervals of several decades to centuries), forest structure tended towards closed canopy, continuous forests that were consumed in large patches by crown fires, resulting in stand-replacing events (e.g. Romme 1982, Romme and Knight 1981). Increasingly, it is recognized that mixed-severity fire regimes, characterized by fires that burn at multiple intensities (e.g. Barrett 1994, Heyerdahl 1997), are the best description of fire regimes in some locations. The effects of fire in pre-Euro-American settlement forests are most easily described hierarchically according to levels of ecological organization: ecosystem, landscape, community, and population.

Ecosystem properties influenced by fire depend on the geographical location of the ecosystem in question, but in the Intermountain West, rates of nutrient cycling are influenced locally and ecosystem wide by fire. Fire releases carbon through direct biomass burning. Nitrogen, potassium and trace minerals from burned tree tissues, ash, and soil mineralization can produce ecologically significant fluxes of nutrients in the years immediately following a fire (Woodmansee and Wallach 1981). Fire in terrestrial ecosystems can influence aquatic ecosystems via post fire down-gradient sediment transport (Meyer et al. 1995). The magnitudes of peaks in nutrient availability and carbon flux are therefore partially a function of fire regime.

Landscape structure is directly affected by fire regime (Baker 1992, Baker 1993, Romme 1982, Turner and Romme 1994, Turner et al. 1994). The relative patchiness of forests, the sharpness of forest ecotones (Floyd et al. 2000), and the diversity of composition in the forest mosaic are a function of fire regime. Patterns of post-fire regeneration and the variability of fire return across a landscape also have a reciprocal influence on other ecological processes (Shankman 1984).

Fire regime influences both canopy and understory community assemblages by limiting species distributions and influencing the outcome of competition between other species (Heinselman 1981). Tree species with adaptations to frequent fire intervals are especially "favored" in competition because they tend to survive fire events that kill competing species (Habeck and Mutch 1973). Many understory vascular plant species and fungi are fire tolerant or dependent.

Finally, fire regime affects the population dynamics of multiple species by influencing mortality and establishment rates of different tree species (Van Wagner 1978, Clark 1996). Some species, such as Lodgepole pine (*Pinus contorta*), have a higher proportion of seedling establishment after fire events and tend to replace themselves in succession. Other species, such as Engelmann spruce (*Picea engelmanii*) are less fire adapted and undergo local population declines that persist long after fire events due to *Picea* dependence on late-successional stages.

Clearly, in fire-adapted ecosystems of the Intermountain West, fire regime is an important driver of ecosystem, landscape, community, and population processes. Fire exclusion and suppression, to the degree to which they have been successful since the late 19th century, have altered the structure and function of ecological assemblages at a variety of hierarchical levels. Understanding the variability in fire regimes of the past is key to hypothesizing how much forests have changed since fire suppression began, and perhaps even more critically, in understanding how future changes in the drivers of fire regime will likely affect forest ecosystems in the Intermountain West.

Fire Regime Evidence in Forested Ecosystems.

Low intensity fires, which burn primarily understory fuels and less in the forest canopy, leave behind fire scar evidence (Houston 1973, Swetnam 1990, Barrett 1994) at the base of some tree boles in the stand. Fire scars are the result of repeated super-heating of the cambium and subsequent dieback of live tissue (Gill 1974, Dietrich and Swetnam 1984). Scars are easily detected through visual searches conducted along stratified, multiple transects through a site (Arno and Sneck 1977), but are imperfect estimators of fire because (1) not every tree that "witnesses" a given fire produces a scar, (2) some evidence is necessarily lost when trees (or scars) are consumed by fire, and (3) some scars can be buried in trees without outwardly visible injury. Higher intensity crown fires typically kill most or all contiguous trees and "reset" the successional progression of stands, thus producing stands with temporally coherent age classes (Romme and Knight 1981). Stands composed of trees with multiple fire scars are evidence of higher frequency, lower intensity events and stands with coherent age classes but few or no scars are evidence of higher intensity, lower frequency events. Thus one fire regime leaves point pattern evidence (scars), another leaves multiple patches with diffuse edges. Completely enumerating the spatial patterns of such processes, much less analyzing mixtures of data types would be extremely difficult for meaningful areas of mixed-conifer northern Yellowstone forests. However, since the environmental controls of fire regime are continuous, and since fire is a continuous process relative to the scale of an individual tree, it stands to reason that stand age class sampling and fire scarred trees are both reasonable estimators of the type of fire regime at some spatial scale larger than an individual stand.

Rationale: Local, Regional, and Global Change

A critical element in the Intermountain West's successful adaptation to the legacy of its history and the changes it will undergo in the future is understanding past fire history and how current land use changes and future environmental changes are likely to influence fire regime. Managing public lands in accordance with the missions of the NPS, USFS, and BLM requires understanding the drivers of disturbance (*sensu* Pickett and White 1985, Perry and Amaranthus 1997) in the context such change, not merely the mean conditions or range of past variability (Landres et al. 1999). In order to make land-use decisions that accommodate the multiple uses and multiple missions of these agencies, factors that have the potential to alter disturbance patterns and their effects on ecosystem structure and function must be considered. The rationale for this research is thus more than scientific curiosity about how fire regimes have changed in the past. Rather it is also motivated by the necessity of considering the past and future effects and causes of fire regime when calculating the uncertainty of current land use decisions that have effects reaching decades or centuries into the future (Cissel et al 1999).

This thesis documents the results of three exploratory studies of fire regime in lower elevation (approximately 1750-2650m), Douglas-fir (*Pseudotsuga menziesii*) dominated forests of the northern Greater Yellowstone Region (GYR). The purpose of the first study is to describe the most recent 500 years of fire regime for three watersheds in Yellowstone National Park, WY and Gallatin National Forest, MT, U.S.A. The purpose of the second study is to relate these fire regimes to proxy regional precipitation variability and the synoptic climate drivers of that variability. The purpose of the third study is to determine the influence of local factors such as elevation and topography on fire regime. All three studies, when taken together, provide a picture of past fire regime and the scaling of some of its major driving factors in space and time for lower elevation forests of the GYR.

CHAPTER 2

FIRE HISTORY OF LOWER ELEVATION FORESTS IN THE NORTHERN GREATER YELLOWSTONE ECOSYSTEM

Introduction

Understanding the past variability of fire regime is crucial to modern forest management (Cissel et al. 1999, Landres et al. 1999), especially in national parks and national forests in Intermountain West ecosystems where fire is a prevalent agent that determines structure and function throughout the ecological hierarchy. Changes in several factors including declining Native American populations (Barrett and Arno 1982), increasing Euro-American populations, active fire exclusion (through grazing) and suppression (Houston 1973), and precipitation patterns have potentially altered the forest fire frequency in forests of the Greater Yellowstone Region. If land management interventions such as prescribed burning are to produce appropriate community and landscape structures as well as ecosystem functions, fire histories must document the natural range of variability as precisely and extensively as possible (Swetnam et al. 1999).

Methods for documenting fire history in forests of the Intermountain West are still evolving (Arno and Sneck 1977, Mandany et al. 1982, Baker and Ehle 2001). As with any ecosystem process governed by multivariate drivers, fire regime over large regional areas is probably better described as a gradient of regimes than as several classes or categories. It has long been recognized that fire scarred trees allow reconstruction of fire events because fires leave detectable evidence within the tree-ring record by repeatedly injuring and/or charring the cambium and outermost rings (Houston 1973, Dietrich and Swetnam 1984).. By crossdating the fire scarred trees with local or regional tree-ring chronologies, precise reconstruction of fire events is possible. This method is ideal in ecosystems where relatively frequent, low intensity fires leave some trees injured but alive because fire scarred trees are likely to scar in subsequent fire events and preserve at least a partial record of fire events (Grissino-Mayer 1994). In ponderosa pine forests of the Southwestern U.S., for example, reconstructions of frequent surface fires over the last several centuries are based almost entirely on the dendrochronological reconstruction of fire events from fire scarred trees (Kipfmueller and Swetnam 2001). In contrast, ecosystems such as boreal forest or Yellowstone lodegpole pine forests typically exhibit stand-replacing fires in which crown fire kills all or nearly all the trees in burned areas (Romme 1982, Turner and Romme 1994). At moderate return intervals, these forests tend to result in pulses of post-fire recruitment that produce relatively even age-class stands. Thus stand replacing fire regimes usually do not leave fire scars on living trees and are reconstructable only from stand age class data derived from tree-rings.

While the evidence left by these apparently contrasting types of fire regime are quite different and demand different sampling methods, not all forest types clearly fall into one type of regime or the other (Heyerdahl 1997). There is a growing consensus among fire history researchers that mixed fire regimes, in which a given forest exhibits elements of both stand replacing and surface fires in close spatial proximity (Heyerdahl 1997, Barrett, pers. comm.). However, the degree to which spatial variability and temporal variability in types of fire regime contribute to the classification of mixed fire regimes is still subject to a great deal of uncertainty. The Greater Yellowstone Region (GYR) of southwestern Montana, southeastern Idaho, and northwestern Wyoming consists of vast tracts of lodgepole pine forests as well as lower elevation forests dominated primarily by Douglas-fir. Fire research in the GYR has primarily focused on fire return intervals and fire effects in the extensive lodgepole pine forests that persist on rhyolite flows in the region (Romme and Knight 1982, Turner and Romme 1994). This body of research estimated fire return intervals of large scale, infrequent, stand-replacing fires at around 300-450 years, which suggests in turn that the large-scale, intense fires of 1988 were not an unprecedented event in lodgepople pine forests of the region. The fire return interval estimated for lodgepole pine forests on andesitic substrate, which provides better growing conditions, was 200 years (Barrett 1994), indicating that geological parent material can influence vegetation, which in turn can have a strong deterministic influence on fire regimes in Greater Yellowstone (Despain 1990). In contrast, relatively little fire research in Greater Yellowstone has focused on lower elevation, Douglas-fir dominated forests. Fire histories derived from visual ring counts of cross-sections of fire-scarred Douglas-firs at the forest/grassland ecotone in drainages of the Northern Range of Yellowstone National Park described a completely different fire regime with a return interval between 25 and 50 years (Houston 1973). Other fire histories sampled in Douglas-fir forests of Gallatin National Forest suggested a rough return interval of 11 years (Losensky 1993). However, lower elevation forests of the Greater Yellowstone Region have thus far never been subjected to an exhaustively sampled, dendrochronologically based reconstruction of past fire history employing methods to detect both types of fire regime. The use of precise cross-dating affords the opportunity to determine exactly what year a fire occurred; only with such precise information can the relationship between climate and fire be deduced.

The main goal of this paper is to describe the fire history of three geographically distinct but biophysically similar watersheds in northern Yellowstone National Park and Gallatin National forest. This information will allow conclusions about the nature of fire regime in lower elevation forests of the GYR. Specifically, I seek to characterize the spatial and temporal variation of fire regime within and between the three sites. In addition, one of the sites was used to document the degree to which lower elevation forests in the GYR may exhibit mixed fire regimes. To this end, I evaluate three hypotheses:

H0: There is no detectable temporal or spatial pattern in fire regimes within and between watersheds; distribution of fire events in time and space is essentially random.

HA1: Fire regimes are consistent in space and time: there are detectable spatial and temporal patterns in fire regimes within and between watersheds and this regime does not vary substantially in time or space.

HA2: Fire regimes are not consistent in space and time: detectable temporal and spatial patterns of fire events exist within and between watersheds, but vary through time and across space.

The null hypothesis is intended to allow for the possibility that the controls of fire regime are so variable that fire regime does not exist in any meaningful sense at the sites chosen for this study; regime implies repeated mechanistic factors determine when, where, and how fires burn. Evidence leading to failure to reject the null hypothesis would be the lack of coherence of dates of fire events from fire scarred trees; evidence leading to rejection of the null hypothesis would be temporally coherent fire events in and between watersheds.

The two alternative hypotheses concern the variability of fire regime, or more precisely, how adequately the concepts of mean fire return interval and fire regime describe past fire history. The first alternative hypothesis is intended to address the proposition that mean fire return interval describes the distribution of the temporal component of fire regime and that fire regime does not vary substantially within a watershed. Under this hypothesis, I would expect similar fire frequencies in all watersheds with similar forest types, although local differences and the variability of ignitions might produce different fire years in each watershed when compared to its neighbors. Evidence leading to the failure to reject this hypothesis would be consistent with past characterizations of fire regime in Greater Yellowstone without much variation through time or across space. Evidence leading to the rejection of this hypothesis would be substantial variation in fire return interval and differences across years in how fire burns at a given site. The second alternative hypothesis is intended to test whether the methods employed in this study detect different spatiotemporal distributions of fire evidence. Under this hypothesis, I would expect substantial similarity in spatial and temporal patterns as in the first alternative hypothesis, but I would also expect variability in fire regime both within and between watersheds that does not suggest fire regime is stationary in time or space. Reasons to expect this are (1) fires are a function of drivers and feedbacks that create a nonlinear, non-normal multivariate distribution in size and frequency and thus not all watersheds in a region will be synchronous for a given fire event and (2) stand history sometimes has a large influence on the contagion of dominant tree stand structure of the landscape which produces different constraints on the spread of fire in different watersheds. Evidence leading to the failure to reject this hypothesis would be large variance in mean fire return interval and the size of fires through time. Evidence leading to the rejection of this fire regime would be consistent fire return intervals and spatial patterns of fire through time.

Methods

Site Selection

To evaluate these hypotheses, I selected three watersheds in Yellowstone National Park, MT and WY, and Gallatin National Forest, MT, (Figure 2) each of which met four general criteria. First, I searched for watersheds with an appropriate density of fire scarred trees to allow for approximate spatial reconstruction of fire events. Observational fire records since the establishment of Yellowstone National Park suggest a strongly nonlinear distribution of fire event sizes (Despain, personal communication, Taylor 1974). This distribution in turn implies a relatively fine spatial sampling effort must be employed to reconstruct fire because there are many more small fires than large fires. I assumed an average of one scar per 30 ha (40 scars per 1200 hectares) would allow coarse reconstruction of approximate fire perimeters for large fire events. Second, I avoided topographically homogeneous watersheds to maximize the likelihood of sampling the entire spectrum of types of fire events in a given area. Third, I sought watersheds encompassing the local elevation range of Douglas-fir in order to sample fire

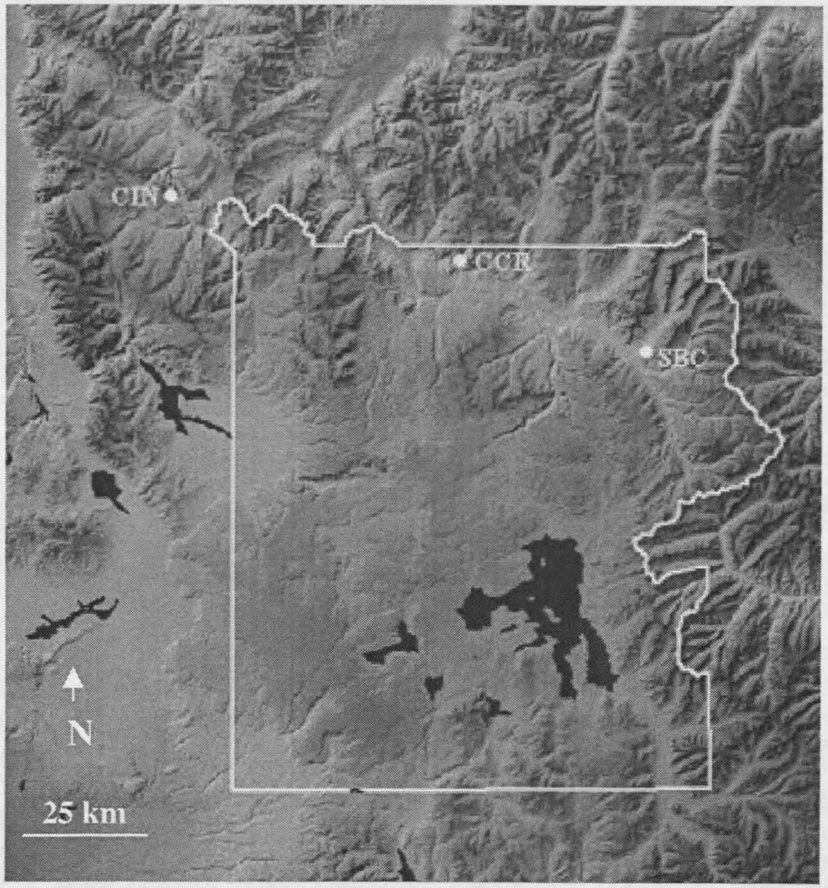

Figure 2. Three Sites in the Northern Greater Yellowstone Region Were Selected for Fire History Studies. Cinnamon Creek (CIN), northwest of Yellowstone National Park, is in Gallatin National Forest. Crevice Creek (CCR) and Soda Butte Creek (SBC) are in Yellowstone National Park (white boundary).

scars along the full elevation gradient of Douglas-fir dominated stands when possible. Finally, given the influence of geological substrate on fire regimes in the GYR, I chose sites with andesitic or sedimentary substrate to avoid the influence of rhyolite on forest composition and fire regime. Selected watersheds were delineated by barriers to fire spread including local ridges and watercourses.

Sampling

In all three watersheds, fire scarred trees were sampled to document the fire history of non-stand replacing events. In one of the watersheds, Soda Butte Creek, a series of plots were sampled to determine if stand-replacing fires could be detected in the watershed.

Fire Scarred Trees. I sampled each watershed in the spring or summer of 2001 by first walking nearly the entire area of each site (Arno and Sneck 1977) and using a Global Positioning System (GPS) to record the latitude, longitude, elevation, species, and number of fire scars of every fire scarred tree, snag, and stump within the borders of the site. From these, I selected approximately 40 trees at each site (total n = 126) to be sampled based primarily on the number of scars on the trees but also to achieve adequate spatial coverage of sampling effort across elevation and aspect ranges within the site. Trees with outward evidence of substantial rot or insect damage were avoided in order to preserve the quality of dendrochronological dating of fire events. A partial cross section from each identified fire scarred tree was then sampled with a chainsaw. To minimize damage to living trees, we sampled only the half of the fire scar with most visible fire events recorded on it. Samples were reassembled and photographed at the time of sampling to facilitate mounting and processing in the laboratory. At the location of each fire scar, I recorded species, diameter at breast height (DBH), latitude, longitude, elevation, aspect, and slope as well as a visual estimate of soil development.

Age-class Cohorts. In one watershed, Soda Butte Creek, I also conducted a study of forest patches in other forest types that did not commonly exhibit fire scars. This sampling method allows detection of stand replacing fires. Using a geographic information system (GIS) to analyze digital elevation models (DEM) of the Soda Butte Creek site, I selected 36 sample patches from modeled distributions of geographical points with different combinations of biophysical factors (elevation, aspect, topographical convergence, and slope) that are hypothesized to influence fire regime. I then located these sample patches in the field and cored the 15 trees nearest the center of a roughly circular plot. Using an increment borer, each tree was cored once as low as possible on the tree (≈ 25 cm) unless a second sample was deemed necessary to obtain the pith of the tree or, in two cases, to sample a fire scar present in the plot. Cores were acceptable if the pith was an estimated ≤5 rings away from the innermost ring on the sample. This estimate was based on direct field observation of the ring curvature near the innermost years of the sample. Species, DBH, UTM coordinates, soil development, and altitude were also recorded for each tree.

Sample Processing

Partial Cross Sections. When necessary, partial cross sections were mounted on plywood backing before being processed. Each sample was sanded with progressively finer sandpaper on a belt sander until all cells and fire scars within the tree-ring chronosequence were visible. Established dendrochronology methods (Stokes and Smiley 1968) were used to crossdate the samples. Specifically, rings were then counted with the aid of a microscope between 10 and 50 times magnification, adjusted to render cells within the ring series visible. Live samples were counted back from the first annual ring inside the cambium (year 2000, or sometimes 2001 depending on sample date); dead samples were counted forward from the first clear annual ring past the pith of the sample. Each annual ring on each sample was measured to 0.001 mm accuracy with a Velmex measuring unit and recorded in computer file.

Complete ring sequences were evaluated against a computer-generated skeleton plot from established cross-dated Douglas-fir tree-ring chronology from a site as close to the fire history site as possible but that was also relatively undisturbed by fire. Soda Butte Creek and Crevice Creek samples were cross-dated against a chronology developed at Mount Everts, Yellowstone National Park (Graumlich et al. in prep) and Cinnamon Creek samples were cross-dated against a chronology developed at Yellow Mountain Ridge, Gallatin National Forest (Graumlich et al. in prep). Tree-ring series cross dating was checked with program COFECHA (Holmes 1983) to find cross-dating errors. To minimize the influence of local factors and tree-growth trends on cross dating, I log-transformed the tree-ring measurements and used a flexible 6-year cubic smoothing spline with 50% frequency cutoff. For correlations between cross dated and unknown samples, I used 60 year windows lagged 10 years forward in time for each correlation. I did not use auto-regressive modeling procedures because there is a high probability of overfitting autoregressive models with such a flexible spline. Detected cross-dating errors were then adjusted on the time sequence recorded on the sample. Once samples were accurately cross-dated, the precise year of the fire scars in each sample was determined from the chronosequence. I determined fire scars from other types of injuries to the cambium by locating combinations of at least two of three typical indicators of fire injury: the presence of charcoal, an injury grown over by subsequent rings, and/or a substantial increase or decrease in ring growth (Dietrich and Swetnam 1984). Increases in ring growth following fire typically indicate release from competition with neighbors, whereas decreases in growth indicate injury to the tree sampled. Samples that could not be crossdated were not used in subsequent analyses.

Plot Study Increment Cores. Increment cores from the plot study were mounted in wooden core mounts, sanded until all cells were visible, and viewed under a microscope between 10 and 50 times magnification depending on visible ring width. Rings on live samples were counted back from the cambium; dead (<10% of increment cores) samples were either visually crossdated against skeleton plots of established Douglas-fir chronologies, or in the case of one plot known to have burned in 1988, dated back from 1988. Samples that could not be dated were not included in subsequent analyses. When pith dates were not present in the core, unless there was reason to believe an excessive number of rings were missing from the sample, the pith was estimated using ring curvatures typical of the species and site to estimate the number of added rings necessary to attain the pith.

Analysis

The information in all samples was used to reconstruct the spatial and temporal fire history for each watershed. Each fire scar or homogenous age class plot was considered a point estimate of a dateable fire event. Temporally coherent fires in the same watershed were mapped using GIS representations of the sites and the geo-referenced sample points.

Fire scar events recorded from the partial cross sections were entered into FHX2 software (Grissino-Mayer 1995, 2001), a fire history data archiving and analysis program. A master fire chronology for each site was produced using the software's graphical capabilities. Mean fire return interval $\bar{I}$ for each site was calculated for F, the number of fire events detected in 3 or more places within a watershed:

$$\bar{I} = \frac{\sum_{i=1}^{F} D_{Fi} - D_{Fi-1}}{F-1}$$

where D_{Fi} is the date of fire event F_i. Additionally, the median and standard deviation associated with mean fire return interval were calculated. Finally, Kolmogorov-Smirnov goodness-of fit tests were employed to determine if the mean fire return interval was more appropriately modeled as the median of a Weibull distribution, which has the added advantage of discounting the influence of non-normal, highly skewed distributions associated with temporal evidence (Grission-Mayer 1995).

The median, mode, and standard deviation for pith dates from each plot sampled were calculated and used to evaluate whether or not a plot was even age class. If the median approximated the mode (mean difference 10.4 years) of the sample and the standard deviation approximated the margin of error introduced by the combination of time to post-fire establishment, pith-estimation and coring above the root crown (<40 years), I focused on the plot as possible evidence of stand replacing fire. If ≥ 0.67 of the samples in the plot were within 15 years of the center of the distribution described by the median and the mode, the initiation dates of the trees were within a maximum of 40 years standard deviation, and a fire detected elsewhere in the site suggested a possible disturbance event, I counted the plot as strong evidence of stand replacing fire in that plot for that fire year. If no fire detected elsewhere in the site corresponded with these stand initiation dates, I counted the plot as strong evidence of a fire event prior to the stand initiation date but did not attempt to reconstruct minimum fire perimeters. Plots that were temporally coherent with known fires were combined with fire scar dates to produce heuristic maps of minimum estimated fire perimeters for known fire years.

Results

A total of 127 fire-scarred trees were sampled: 43 at Soda Butte Creek, 41 at Crevice Creek, and 43 at Cinnamon Creek. Of the 127 fire scarred samples, 108 cross dated and contained interpretable evidence of fire events. At Soda Butte Creek, I also cored 541 trees in 36 plots. I will first address the site-specific results from the combined partial cross sections and plot study at Soda Butte Creek, then focus on the Crevice Creek and Cinnamon Creek sites, and finally address the summary results from all fire history information in a regional context.

Soda Butte Creek. The summary fire history chart from fire-scarred trees at SBC (Figure 3) shows the results from 35 cross-dated samples. Eight samples either did not cross date well or contained scars that could not be reliably distinguished from other types of injuries. Notable fire events (scarring ≥ 3 recorder trees) occurred in 1584, 1634, 1681, 1693, 1695, 1744, 1756, 1800, 1855, and 1870 (Table 1). Other events occurred in 1774, 1790, 1822, 1855, and 1905. The mean fire interval for the entire 1400 ha SBC site for all events recorded on three or more trees is 35.75 years. The standard deviation is 22.33 years; the minimum fire return interval is 2 years, and the maximum fire return interval is 63 years.

Table 1. Fire history of Soda Butte Creek, Yellowstone National Park

Year	Total Scars	Interval (years)
1584	4	.
1634	7	50
1681	3	47
1693	8	12
1695	4	2
1744	4	49
1756	15	12
1800	19	44
1855	5	55
1870	12	15

A Kolmogorov-Smirnov goodness of fit test was used to evaluate the null hypothesis that the observed distribution of return intervals for fires that scarred three or more trees could be modeled by an empirical distribution, and the test was not significant ($d_i = 0.371$, $n = 8$, $p = 0.22$). Similarly, a Weibull distribution models the fire return interval adequately ($d_i = 0.311$, $n = 8$, $p = 0.42$). The Weibull median fire return interval

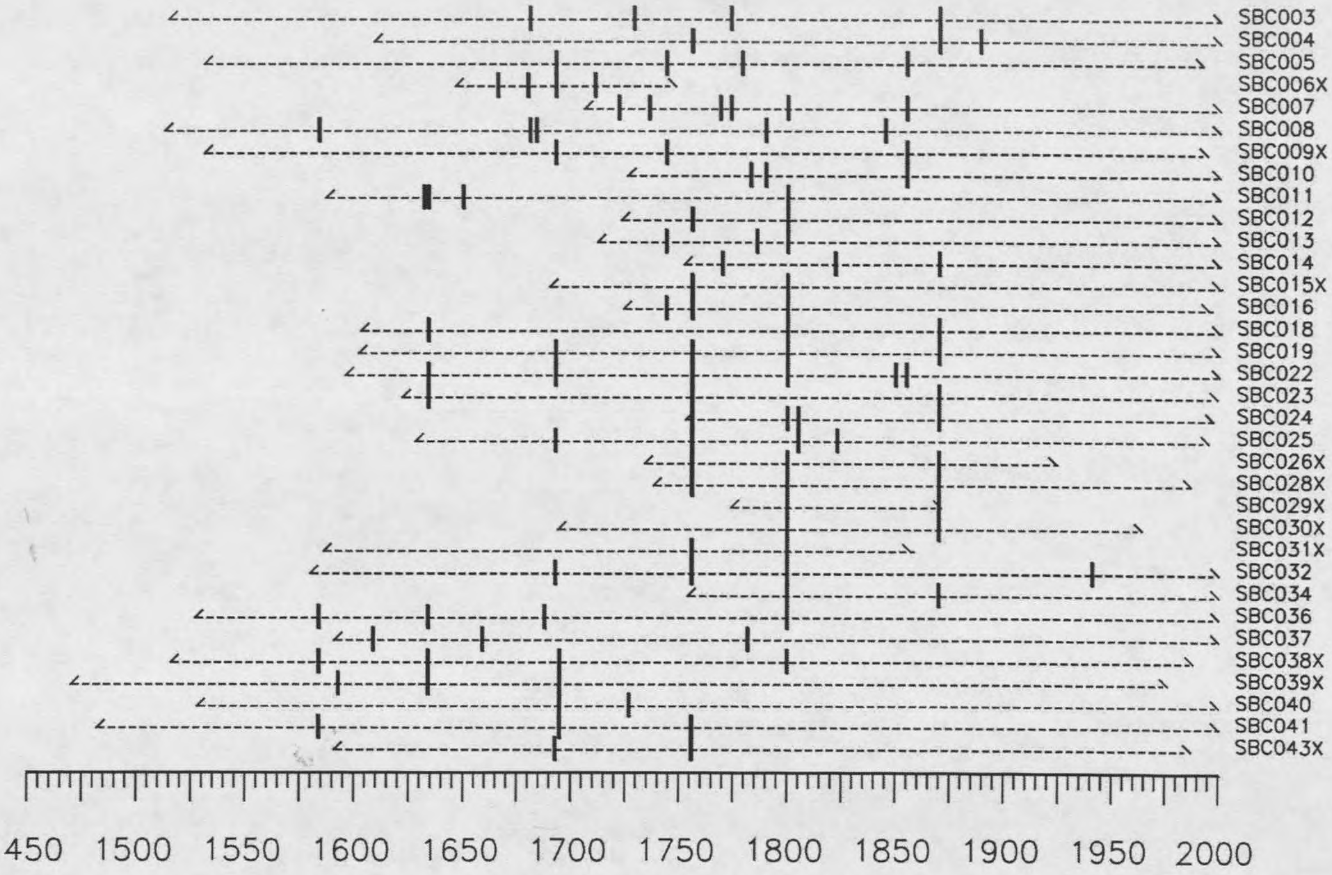

Figure 3. Soda Butte Creek, Yellowstone National Park Master Fire Chart. Each dark vertical bar represents a fire scar detected on the tree sampled on the Y axis on the right hand side of the chart. The dotted lines along the X axis represent the time span of the sample. Prominent fire years recorded on many samples are 1696, 1756, 1800, and 1870.

is 30.33. The significance of the goodness-of fit tests does not change if fires that scarred two trees only are included in the analysis.

Fire evidence in cores from the SBC plots primarily reconfirmed fire dates already established in the fire scar record, but plot evidence suggested the 1822 and 1844 fires were more widespread than indicated by the fire scar record alone. Nine plots met the criteria outlined in the methods section for stand replacing fires. An additional six plots contained trees that yielded fire scars when cored. Fire history information derived from the plot cores is presented in Table 2. Adding these events to the fire chronology for Soda Butte Creek decreases the mean fire return interval to 30 years with a standard deviation of 18.23.

Table 2. Age-class Cohort Plots With Detected Fire Evidence.

Plot	Method of detection	Fire year	Estimated Plot Median	Estimated Plot Mode	Estimated Plot SD
1	age class	1822?	1855	1855	18.01
2	age class	1855	1878	1887	24.76
3	age class	unknown	1938	1946	15.20
4	age class	1870	1899	1883	13.26
6	dated scar	1870	-	-	-
8	dated scar	1870	-	-	-
9	dated scar	1870	-	-	-
10	dated scar	1870	-	-	-
11	documented burn	1988	-	-	-
16	age class	1844	1849	1845	38.89
17	dated scar	1800, 1844	-	-	-
21	age class	unknown	1922	1900	11.13
27	age class	1870	1880	1863	16.76
30	age class	1855	1870	1885	17.54
33	age class	1870	1895	1895	31.90
35	dated scar	1870	-	-	-

Reconstructed fire perimeters (Appendix 1) suggest the relative size of fires varied through time, but there are insufficient fire events to determine the significance of any hypothesized watershed level response through time. There is no evidence to suggest a relationship at the watershed scale between time since fire and estimated area of the fire event.

Crevice Creek. The summary fire chart for Crevice Creek shows the master fire chronology derived from 39 cross dated samples (Figure 4). Two samples did not cross-date. Notable fire events (scarring ≥ 3 recorder trees) occurred in 1696, 1729, 1732, 1740, 1771, 1775, 1784, 1800, and 1867 (Table 3). Other events (2 recorder trees scarred) occurred in 1691, 1705, 1714, 1748, 1751, 1863, and 1875. The mean fire interval for the entire 1400 ha CCR site for all events recorded on three or more trees is 21.38 years. The standard deviation is 21.74 years; the minimum fire return interval is 3 years, and the maximum fire return interval is 67 years.

Table 3. Fire history of Crevice Creek, Yellowstone National Park

Year	Total Scars	Interval (years
1696	12	.
1729	3	33
1732	3	3
1740	3	8
1771	11	31
1775	8	4
1784	4	9
1800	6	16
1867	7	67

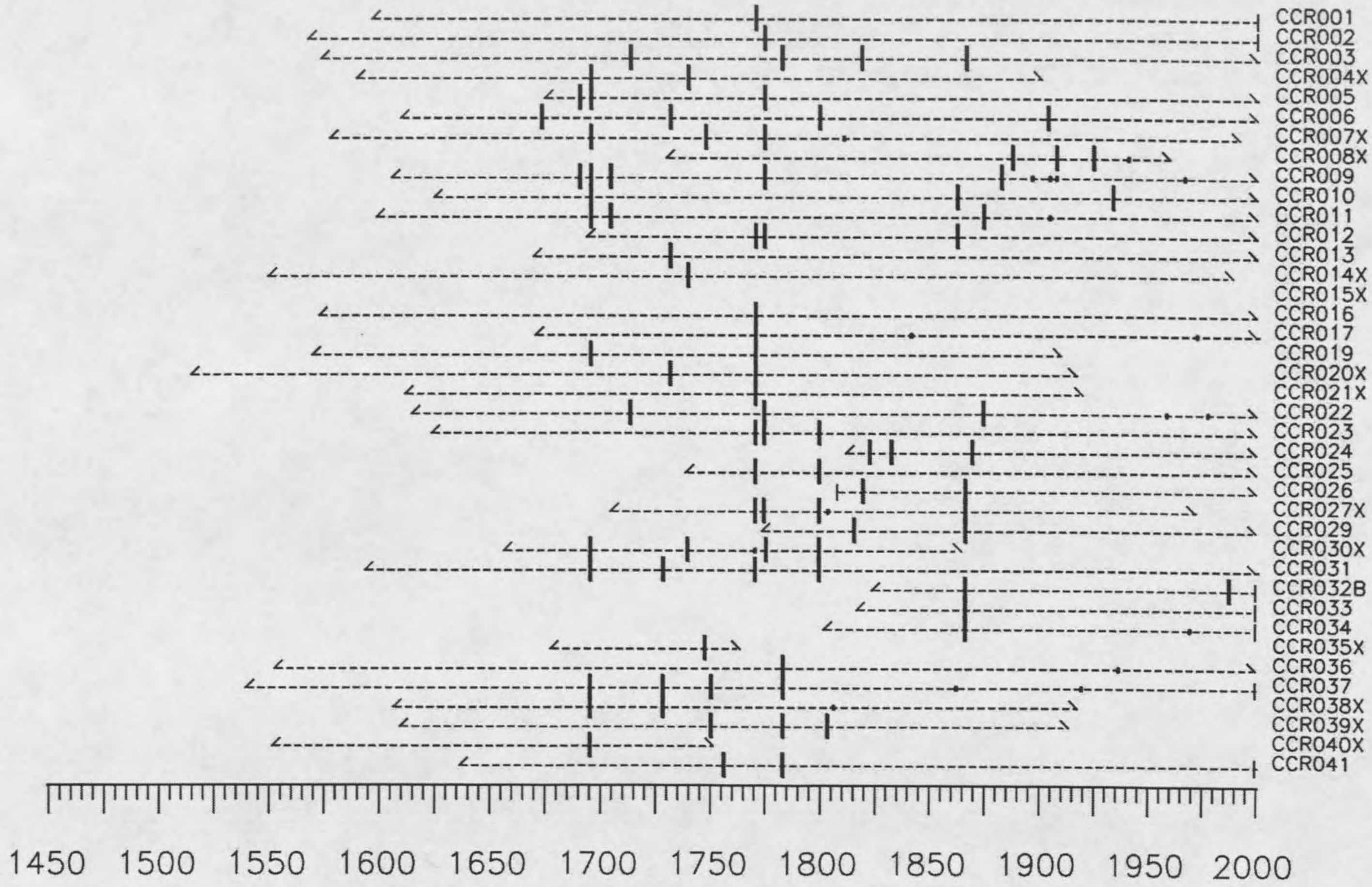

Figure 4. Crevice Creek, Yellowstone National Park Master Fire Chart. Each dark vertical bar represents a fire scar detected on the tree sampled on the Y axis on the right hand side of the chart. The dotted lines along the X axis represent the time span of the sample. Prominent fire years recorded on many samples are 1695, 1771, 1775, 1800, and 1867.

Kolmogorov-Smirnov goodness of fit tests suggested the CCR fire return interval can be adequately modeled by an empirical distribution ($d_i = 0.386$, $n = 8$, $p = 0.18$). A Weibull distribution models the fire return interval adequately ($d_i = 0.182$, $n = 8$, $p = 0.95$). The Weibull median fire return interval is 15.65 years. If fire events scarring only two trees are included in the test, Kolmogorov-Smirnov goodness of fit test suggests the CCR fire return interval are not adequately modeled by an empirical distribution ($d_i = 0.616$, $n = 15$, $p = 0.0001$).

Reconstructed fire perimeters suggest the relative size of fires varied through time, but there are insufficient fire events to determine the significance of any hypothesized watershed level response through time. There is no evidence to suggest a relationship at the watershed scale between time since fire and estimated area of the fire event.

Cinnamon Creek. The summary fire chart for Cinnamon Creek shows the master fire chronology derived from 35 cross dated samples (Figure 5). Eight samples either did not cross-date or contained scars not identifiable as fire scars. Notable fire events (scarring ≥ 3 recorder trees) occurred in 1702, 1734, 1743, 1750, and 1800 (Table 4). Other events (2 recorder trees scarred) occurred in 1715, 1759, 1769, 1805, 1840, an 1870. The mean fire interval for the entire 1400 ha CIN site for all events recorded on three or more trees is 24.50 years. The standard deviation is 20.44 years; the minimum fire return interval is 7 years, and the maximum fire return interval is 50 years.

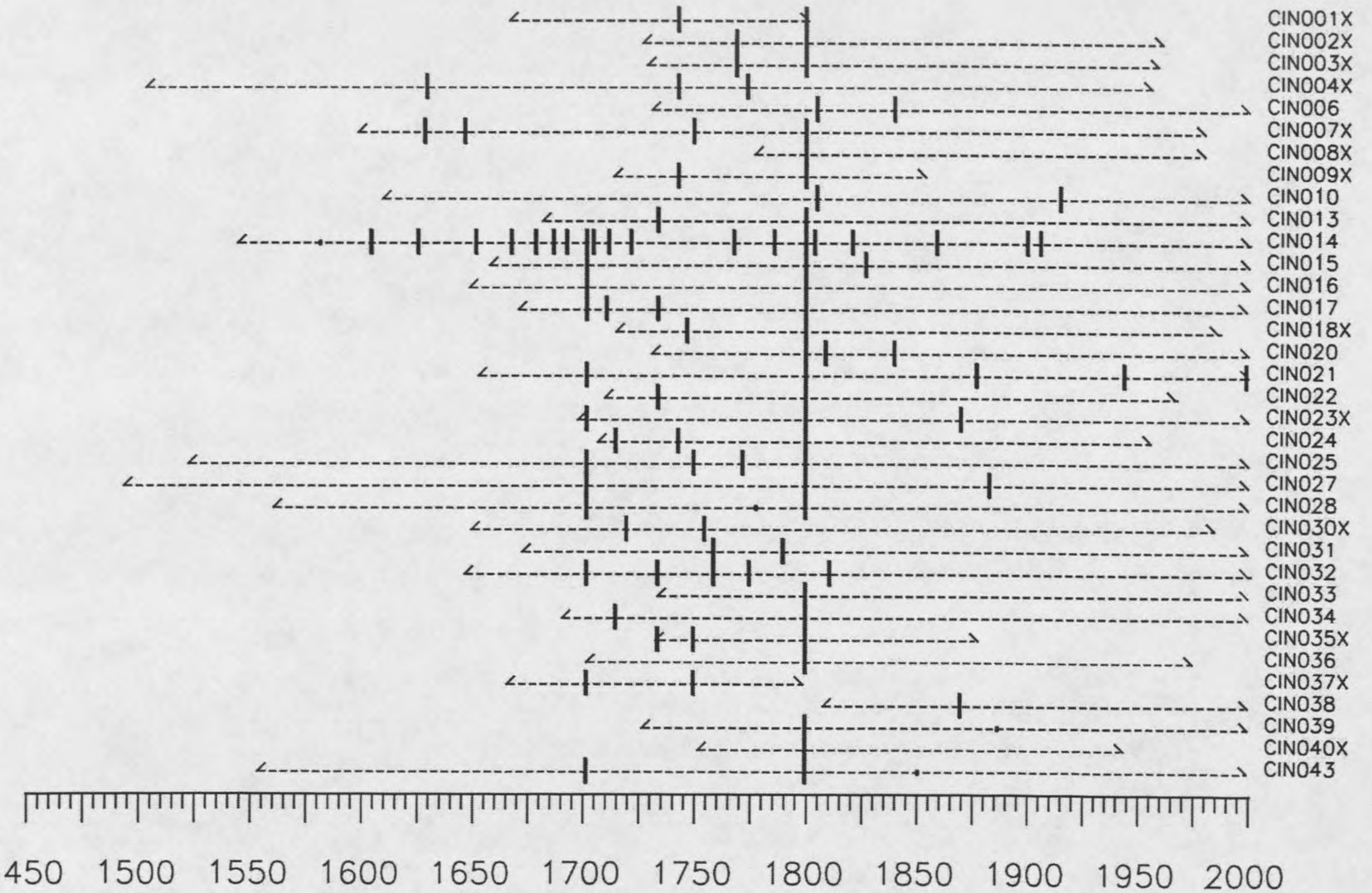

Figure 5. Cinnamon Creek, Gallatin National Forest Master Fire Chart. Each dark vertical bar represents a fire scar detected on the tree sampled on the Y axis on the right hand side of the chart. The dotted lines along the X axis represent the time span of the sample. Prominent fire years recorded on many samples are 1702 and 1800 .

Table 4. Fire history of Cinnamon Creek, Gallatin National Forest

Year	Total Scars	Fire Interval
1702	12	.
1734	5	32
1743	4	9
1750	4	7
1800	27	50

Kolmogorov-Smirnov goodness of fit tests suggested the CCR fire return interval can be adequately modeled by an empirical distribution ($d_i = 0.320$, $n = 4$, $p = 0.81$). A Weibull distribution models the fire return interval adequately ($d_i = 0.304$, $n = 4$, $p = 0.8543$). The Weibull median fire return interval is 20.69 years. The significance of these goodness of fit tests does not change if fires that scarred two trees only are included in the analysis.

Reconstructed fire perimeters (Appendix 1) suggest the relative size of fires varied through time, but there are insufficient fire events to determine the significance of any hypothesized watershed level response through time. There is no evidence to suggest a relationship at the watershed scale between time since fire and estimated area of the fire event.

Regional Fire History. The composite fire history for all three sites indicates only fires in 1800 were synchronous between two or more of the sites. The 1800 fire was detected on 52 of 108 possible fire scarred trees and in one of the SBC coring plots and was represented at all three sites. There is a notable absence of major fires within and between sites past 1870. The sampled fire return intervals are probably not significantly

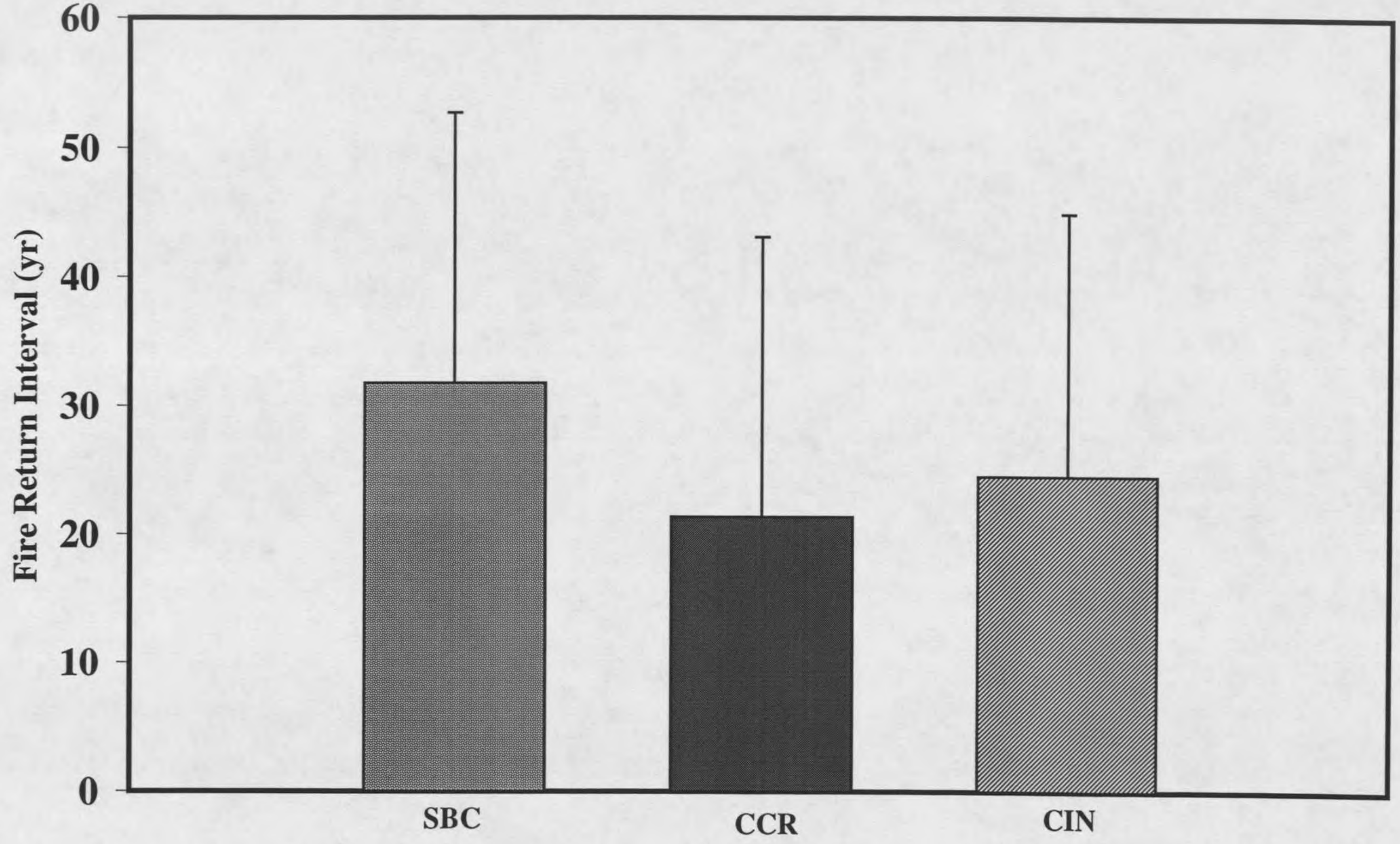

Figure 6. Mean Fire Return Interval Comparisons for 3 Fire History Sites in Northern Greater Yellowstone. Error bars are +1 Standard Deviation from the mean fire return interval, calculated independently for each site. The positive error bar only is shown because fire return intervals are minimum estimates.

different between sites, although low sample sizes preclude hypothesis testing with sufficient power. However, plots of the mean fire return interval and standard deviation for each site suggest the mean fire return intervals are not significantly different across sites (Figure 6).

Discussion

At the Soda Butte Creek site, combined evidence from fire scarred trees and age class plots strongly suggests a mixed severity fire regime. Age class sampling did not significantly augment the temporal component of fire regime, and fire return interval did not change appreciably (decrease of 1 year). However, the intensity component, or characterization of fire type in the watershed, was altered by inclusion of the age class information. Several stands contained evidence of stand replacing fire back to 1855, while other stands contained evidence of multiple, non stand replacing fires dating back to 1744, demonstrating that Soda Butte Creek is best characterized by a mixed fire regime over at least the latter half of the study period. Several plots did not meet the criteria for detecting stand-replacing fire, but often those stands were substantially older than stands where stand-replacing fire was detected. This may serve to demonstrate that as time since fire increases, the relative influence of post-disturbance succession of age classes increases and obscures the fire signal. Without sampling a greater number of plots systematically and including more cores in those plots, it is difficult to confidently establish the full temporal spectrum of stand replacing fires with this methodology. However, the method does appear to adequately detect the variability in fire regime intensity in the recent past. In terms of the spatial component of fire regime at SBC, limited available sample sizes for some time periods suggest limited ability to infer characterization of the variation in fire size through time. The summary conclusion from heuristic fire maps (Appendix 1) derived from Soda Butte Creek fire history information implies that some areas of the site are more likely to burn than others, but the only reliable long term conclusion about spatial variability in fires that there is substantial variation in fire size.

At the Crevice Creek and Cinnamon creek sites, fire return intervals were not significantly different from those established at Soda Butte Creek, and these watersheds exhibit similar variation in biophysical and ecological characteristics. Understory structure and vegetation at Crevice Creek (including Prickly pear and Idaho fescue) suggests a slightly drier local climate than Soda Butte Creek (Ericaceous shrubbery and tree seedling/sapling community), which could explain the numerical difference between the two fire regimes.

Except for the 1800 fire, each watershed reconstruction of fire history produced a unique series of fire events and areas burned. If fire events are deterministically controlled, this suggests either that the conditions necessary for fires to start and carry across the landscape or ignition sources are not usually distributed uniformly in space and time at the scale of the study area. However, the statistical properties of fire return intervals between the sites are quite similar, and fire return interval did not differ significantly in the three watersheds. This common statistical signal in the summary evidence from each watershed implies that the biophysical setting in which fire burns is sufficiently similar over long time periods to produce similar long-term trends in fire regime at all three sites. Thus, the null hypothesis that fire events are essentially random is not supported either at the site or regional scales. There are instead consistent temporal patterns within sites and, in at least one case, between sites. In addition, some parts of the Soda Butte Creek watershed burn more often than others, and fire event maps and the clustering of fire evidence at the Crevice Creek and Cinnamon Creek sites imply non-random spatial fire regimes at both sites. Finally, fire return intervals at all three sites varied considerably with both short (<7 yr) and long (>45 yr) intervals between fires contributing to high standard deviations about the mean fire return intervals. This evidence fits the criteria to reject the first alternative hypothesis and the criteria to fail to reject the second null hypothesis.

Past fire regime research in northern Greater Yellowstone implied that Douglas-fir forests in Gallatin National Forests had relatively short fire return intervals of approximately 11 years (Losensky 1993). Similar forests in the northern range of Yellowstone National Park exhibited fire return intervals of 25 to 50 years (Houston 1973). The results presented here appear to confirm previous research when fire scarred samples alone are included, but when stand age class data is included, fire regimes appear more mixed, even at the local scale (hectares to kilometers) of a single site. The relatively fine scale variation suggested by the combined stand age class and fire scarred tree data implies a blanket fire regime can not be applied over a given forest type at a regional scale. Instead, the heterogeneity at a given site in determinants of forest structure and fuel moisture might have an important influence on the variability of "typical" fire intensities across space. Thus the hypothesis that fire regimes are not equally consistent in space and time best fits the data: detectable temporal and spatial patterns of fire events exist within and between watersheds, but vary through time and across space.

Caveats associated with failure to reject the hypothesis that fire regimes vary in space and time are primarily associated with the evidence I used to reconstruct patterns of fire regime. First and foremost, fire evidence declines in quality as time progresses after a given fire event. This is a function of everything from insect damage of fire-scarred trees to the replacement of stands or trees containing fire regime evidence. In addition, not all fires leave evidence that can be detected 400 years post fire. Thus, reconstructing the perimeter of fire events becomes less certain as time passes. However, the conclusions presented here are derived from evidence that supports the maximum fire return interval for lower elevation forests of the Greater Yellowstone Region is around 25 to 30 years on average, but, more importantly, there is substantial variability about that average. The next chapters of this thesis document the search for mechanisms leading to that variability.

Conclusion

If fire regimes vary substantially between and within biophysically similar sites in a region through time, the utility of the mean fire return interval derived from fire-history research as a management tool must be called into serious question. It is possible that the statistical mean of fire return intervals bisects a bimodal or multimodal distribution of return intervals driven by temporal variation in the most important drivers of fire regime. For example, the existence of multi-decadal periods of anomalously high precipitation as well as the existence of multi-decadal droughts is substantiated by millennial length tree-ring chronologies sampled in the vicinity of these fire history sites (Graumlich et al. in prep, Douglas and Stockton 1975). During multi-decadal drought episodes, regional climate is probably the most important driver of fire regime and thus fire regimes are more likely to be synchronous over large spatial scales. In contrast, during multi-decadal periods with anomalously high precipitation, local factors such as aspect, elevation, topographic convergence and slope probably have a much higher influence on fire regime and regional fire regimes as a result are probably relatively heterogeneous. If this is the case, managing for the mean fire return interval might be the most effective way to impose temporary, artificial homogeneity on forested ecosystems instead of managing for the variation that is suggested by past and present climate trends and disturbance history. Homogeneous systems tending toward equilibrium are almost never found under natural disturbance regimes if long enough temporal scales are examined; apparently stationary systems eventually satisfy the second law of thermodynamics with a large, relatively sudden increase in entropy which results in reorganization of the system's structure and function. For agencies charged with managing for natural resource extraction, preservation of native biodiversity, recreation opportunities and landscape connectivity, or more commonly, some or all of the above, the inherent variability in disturbance drivers and responses demands close scrutiny of the benchmarks used to interpret fire regime and how to mange it.

CHAPTER 3

CLIMATIC DRIVERS OF FIRE REGIME IN THE NORTHERN GREATER YELLOWSTONE ECOSYSTEM

Introduction

Forest fire events are well correlated with dry "fire weather" when fuel moisture drops below critical thresholds and the ignition and spread of fires becomes more likely. The influence of long-term regional climate on the frequency of fire weather has been inferred from contemporary reconstructions of long-term precipitation and fire frequency (Grissino-Mayer 1995, Heyerdahl 1997, Swetnam 1993). Understanding the influence of regional climate on fire regime is critical both in reconstructing the mechanisms leading to past fires but also in forecasting how future climate change will likely affect future fire regime.

In the Greater Yellowstone Ecosystem, global and regional climate models have hypothesized not only different magnitudes of precipitation change under global warming scenarios, but also different directions of change (Bartlein et al. 1997, Romme and Turner 1991, Whitlock and Bartlein 1993). Over the last several hundred years, lower elevation forests of the GYR exhibit mixed fire regimes that, depending on the temporal window and spatial location, have varied between classic surface fire regimes characterized by relatively high-frequency, low intensity fires and mixed fire regimes characterized by lower frequency, higher intensity fires (Chapter 2, Barrett 1994, Houston 1973, Romme 1982). Future changes in precipitation may have a marked influence on the trajectory of

GYR forests and the likely fire frequency, intensity, and scale. Thus it is important to document the strength of the relationship between precipitation variability of known fire events in the GYR and whether that relationship has changed over time.

Variation in long-term climate in the Greater Yellowstone Ecosystem since the last glacial maximum has been documented from analysis of pollen and sediment deposition in lake sediments (Whitlock and Bartlein 1993). However, the annual resolution necessary for reconstructing the past relationship between precipitation anomalies and fire events is not usually present in sediment. Instead, tree-ring based reconstructions of annual precipitation for the last thousand years can be used to model annually resolved estimates of precipitation variability as well as to determine the temporal distribution of fire. Therefore tree-rings provide a good basis for determining the relationship between precipitation variability and fire regime.

The dominant synoptic climate phenomena in a region often have a profound influence on fire regime. Research in the southwestern United States, for example, has documented a significant influence of the El Niño Southern Oscillation (ENSO) on fire events in the southwestern United States (Grissino-Mayer 1995, Swetnam and Betancourt 1993). ENSO is a sub-decadal (2 to 7 years) periodic phenomenon with two dominant phases. In El Niño years, when the Southern Oscillation Index (SOI) is low, the southwestern United States is subject to incursions of moist air from the Pacific Ocean during the spring and fall, which significantly increases precipitation in the region prior to and during the potential fire season. This effect increases fuel moisture, thus decreasing the probability of fire. In La Niña years when SOI is high, the southwestern U.S. usually experiences drier conditions and fires are more probable. In contrast, the

Pacific Northwest experiences a decrease in winter precipitation when the SOI is low (El Niño conditions) and an increase when the SOI is high. The influence of these patterns on the GYR is less dramatic than in the Southwest during the 20th century, but the Yellowstone River basin experiences similar ENSO-driven shifts to the rest of the Pacific Northwest (Dettinger et al. 1993).

ENSO is not the only climate pattern documented to exert an influence on climate in the Greater Yellowstone Ecosystem. The Pacific Decadal Oscillation (Hare and Francis 1995), a multi-decadal climate phenomenon with currently unspecified patterns of sea surface temperature and atmospheric circulation causes, exhibits two multi-decadal phases. Cool-phase PDO (negative values of PDO) typically results in cooler springs and increased winter/early spring precipitation, whereas warm-phase PDO (positive values of PDO) often results in below average October to March precipitation, spring snow pack, and water year stream flow in the northwestern United States (Dettinger et al. 1998). Documented PDO cycles during the 20th century (e.g. Mantua et al. 1997, Minobe 1997) suggest cool PDO (low values) regime from 1890-1924 as well as 1947-1976, while warm PDO (high values) regimes prevailed from 1925-1946 and from 1977 through the mid-1990s.

Thus both ENSO and PDO have been demonstrated to affect precipitation in the Greater Yellowstone Ecosystem during the 20th century. The relative strength of ENSO and PDO have been modeled back in time for several centuries by evaluating the statistical relationship between tree-rings and 20th century climate parameters and then "backcasting" the relationship through time (Stahle et al. 1998, Cook 2000, Biondi et al. 2001). In contrast, the relationship between fire occurrence and long-term climatic variability is difficult to "backcast" empirically because the period of relatively precise climate observation (the 20th century in the GYR) is also the period of active fire exclusion and fire suppression in forests of Greater Yellowstone. Therefore reliable relationships between past fire and climate must be derived from tree-ring based reconstructions of climate and fire regime. I am unaware of any previous attempt to relate long-term precipitation records to an established fire history reconstruction using tree-rings in this region.

The goal of this chapter is to explore the relationships between the regional fire history developed in chapter one and local tree-ring reconstructions of precipitation proxies for the Greater Yellowstone Region. A second goal is to evaluate the relationship between PDO, ENSO, and fire regime in the GYR. To that end, I will evaluate four hypotheses. Note that each alternative hypothesis has an implied null associated with it and that the labeled null hypothesis is an overall null accounting for a "no relationship" scenario.

H0: There are no coherent relationships between regional climate patterns and fire events in the Greater Yellowstone Region; fire events occur during "fire weather".

HA1: Regional fire events are fully explained by the effects of the Pacific Decadal Oscillation (PDO) on climate in the GYR.

HA2: Regional fire events are fully explained by the effects of the Southern Oscillation (ENSO) on climate in the GYR.

HA3: The relationship between regional fire events and climate is a function of both ENSO and PDO.

The null hypothesis is intended to address the possibility that seasonal precipitation anomalies of days to weeks in length that result in fires are the primary manifestation of a fire-climate relationship in the GYR. Evidence leading to the rejection of this hypothesis would include statistically significant relationships between established long-term periodic climate patterns and regional fire events. Evidence leading to a failure to reject the null hypothesis would entail a lack of significant relationships between long-term climate patterns and fire events in the GYR.

The first alternative hypothesis is intended to address the possibility that the Pacific Decadal Oscillation, through its influence on GYR seasonal precipitation, is the primary mechanism behind dry periods that lead to fire. Evidence leading to the rejection of this hypothesis would include lack of a significant relationship between years when PDO values are above normal and the occurrence of fire events. Evidence leading to the failure to reject this hypothesis would be a significant relationship between above average PDO values and fire events.

The second alternative hypothesis is intended to address the possibility that the El Niño Southern Oscillation, through its influence on GYR precipitation, is the primary mechanism behind dry periods that lead to fire. Evidence leading to the rejection of this hypothesis would be lack of a significant relationship between low values of ENSO and fire events. Evidence leading to the failure to reject this hypothesis would be a significant relationship between ENSO and fire events.

The third alternative hypothesis is intended to address the possibility that both PDO and ENSO have a significant influence on GYR climate/fire relationships. Evidence leading to the rejection of this hypothesis would be lack of any significant combination of PDO and ENSO that explained the occurrence of regional fire years. Evidence leading to the failure to reject this hypothesis would be a significant combination of PDO and ENSO that explained the occurrence of regional fire years.

Methods

To test these hypotheses, I first evaluated the relationship between ENSO, PDO, and 20th century precipitation patterns at three meteorological stations near the fire history sites identified in chapter one. Seasonal precipitation variables were assembled from consecutive 4-month precipitation totals at each of the three sites and correlated with 20th century instrumental values of PDO (Mantua et al. 1997, Mantua 2001) and reconstructed values of ENSO (Urban et al. 2000). I also evaluated the relationship between the full timer period of the regional fire chronology developed in chapter two and tree-ring based reconstructions of climate related phenomena: a GYR specific reconstruction of Palmer Drought Severity Index (PDSI) (Pisaric and Graumlich 2002), a PDO reconstruction derived from Southern California and Baja, Mexico (Biondi et al. 2001), and an ENSO reconstruction derived from tree rings in the Southwestern United States, Mexico, and Indonesia (Stahle et al. 1998).

Fire History

A composite regional fire chronology for the northern GYR was reconstructed from fire-scarred trees at three lower elevation forest sites (Chapter 2). The regional fire chronology spans 1550 to 1900, beginning with the period for which there are at least 10% of the trees at any fire history site available to record fires and truncating with the rise of active fire suppression in the early 20th century. Site specific chronologies have different spans, with Soda Butte Creek spanning 1550 to 1900, Crevice Creek and Cinnamon Creek both spanning 1650 to 1900.

Climate Data

PDSI is a composite estimate of the departure of soil water balance from the average. Methods for calculating PDSI vary, but all incorporate monthly temperature, precipitation, and soil recharge rates to evaluate conditions against the long-term mean. PDSI can often be reconstructed from drought-sensitive tree-ring chronologies by comparing instrumentally derived PDSI values for the 20th century with tree-ring variability for the same time period. The relationship between PDSI and tree-rings is then modeled back in time as far as the tree-ring chronology permits. PDSI used in this chapter is derived from two millennial length tree-ring chronologies in the GYR, one at Yellow Mountain Ridge (YMR) near Big Sky, MT, and the other at Mount Everts (MEV) between Gardiner, MT and Mammoth, Yellowstone National Park, WY. The reconstruction was calibrated against 20th century PDSI at gridpoint 36 derived from 20th century climate data in the region centered around 45° N latitude and 110.5° W longitude (Pisaric and Graumlich 2002). The PDO reconstruction used here (Biondi et al 2001b) was derived from Big-cone Douglas-fir and Jeffrey Pine tree-ring chronologies from southern California, U.S., and Baja California, Mexico. 20th century values of instrumentally derived PDO were used to calibrate the relationship and extend it back in time (Biondi et al. 2001). The ENSO reconstruction was derived from factor analysis of a network of tree-ring chronologies in the southwestern United States, northern Mexico, and Java, Indonesia and calibrated against 20th century values of instrumentally derived ENSO (Stahle et al. 1998).

Analysis

To evaluate the relationship between ENSO, PDO, and seasonal 20th century precipitation patterns, I used Pearson correlations. I used three methods to explore the relationship between regional fire history, drought, and global climate phenomena. To explore the relationship between drought and fire, PDO and fire, and ENSO and fire, I used Superposed Epoch Analysis (SEA) (Kelly and Sear 1984, Lough and Fritts 1987, Grissino-Mayer 1995). SEA employs a bootstrapping / re-sampling procedure to estimate statistical confidence intervals for the relationship between an event-based (discrete) response time series and a continuous predictor time series. To evaluate the relative importance of PDO and ENSO through time, I used multi-taper spectral analysis (MTM) (Thomson 1982) and evolutive multi-taper spectral analysis (EMTM) (e.g. Mann and Lees 1996). Multi-taper methods utilize multiple numerical filters to evaluate power spectra for time series that violate stationarity assumptions required by traditional spectral analysis techniques. Finally, to provide confirmation of the SEA results given low sample sizes of fires and the potential spuriousness of SEA for climate phenomena with periodicities as long as PDO, I used a bootstrapping and resampling procedure.

Relationships between fire years and unusually dry years were evaluated with Superposed Epoch Analysis (SEA) to determine if there was a statistically significant relationship between Palmer Drought Severity Index and regional fire events. 1000 SEA iterations were run for the 30-year period surrounding each fire event for the fire chronology period between 1550 and 1900. This analysis was repeated for the common period of PDO, ENSO, and fire history reconstructions between 1661 and 1900 with the same SEA parameters.

Next, to determine the relative importance of PDO and ENSO to the distribution of dry years and to evaluate how likely a combined PDO-ENSO signal was, I used multi-taper time series methods to examine the power spectrum distribution of the reconstructed PDSI chronology. I also used evolutive multi-taper analysis to determine how stationary the PDSI power spectrum is over time. For the multi-taper power spectrum density analysis, I used a value of $p_i = 3$ resulting in $k=2(p_i)-1= 5$ adaptive tapers, which is an appropriate value for a chronology the length of the PDSI reconstruction. I used a spectrum-derived red noise modeling procedure to filter the power spectrum density. For the evolutive multi-taper procedure, I retained the above parameters and used 250-year windows stepped forward 5 years for each iteration of the evolutive procedure. 250-year windows are approximately five to ten times the wavelength expected for PDO-type climate signals, so this window should be sufficient. Significance for the power spectra were determined by 95% confidence intervals calculated by an f-test of chi-square values determined by the multi-taper software used to produce the power spectrum density.

SEA was then run on subsets of the regional fire chronology against PDO and ENSO to determine the relative importance of each phenomenon to distinct classes of fire events. Specifically, the regional fire data were split into bins of events that occurred during warm phase PDO or cool phase PDO and El Niño or La Niña ENSO events. These groups were then evaluated separately to partial out the potentially interacting effects of PDO and ENSO in the GYR.

Because of the relatively long fire return intervals described by the fire chronology, this procedure resulted in groups of fire events that were fairly small. Therefore, in order to substantiate the SEA results, I used a bootstrapping and resampling procedure to evaluate the probability of selecting at random groups of years equal to the sizes of the groups of fire years with means lower than the means of the climate phenomena for the fire years. This expands on the SEA analysis by testing more than the local context for a given fire event year; groups of years are sampled iteratively from the distribution of all years to determine whether the fire years sampled are significantly different from random groups of years. Specifically, I evaluated the mean PDO value for 15 warm-phase PDO fire events against 1000 random means of samples of 15 PDO values taken from the entire PDO distribution and the mean of the 6 El Niño-phase SOI events against 1000 means of random samples of 6 SOI values taken from the entire SOI distribution.

Results

Table 5 shows the results of correlation analysis of 20th century precipitation at 3 meteorological stations near fire history sites with independent 20th century PDO and ENSO values. Figure 7 illustrates the relationship between the summary regional fire chronology and PDSI. Fire year relationships at the regional scale are plotted on the SOI reconstruction (Figure 8) and the PDO reconstruction (Figure 9).

Table 5. Best Fire History Site Seasonal Meteorological Relationships With PDO and ENSO for the 20th Century. Abbreviated months (DJFM = December January February March) indicate time spans of best correlation

	Meteorological Site (Associated Fire History Site)		
	West Yellowstone (Cinnamon Creek) 1926-1998	Gardiner (Crevice Creek) 1956-1998	Lamar Ranger Station (Soda Butte Creek) 1940-1998
Dec/Jan/Feb PDO (Mantua 2001)	DJFM $r = -0.447$; $p = 0.002$	DJFMA $r = -0.388$; $p = 0.018$	DJFM $r = -0.536$; $p < 0.001$
Winter ENSO (Urban et al. 2000)	JFMA $r = 0.441$; $p = 0.001$	DJFM $r = 0.512$; $p = 0.002$	JFMA $r = 0.500$; $p = 0.001$

Superposed Epoch Analysis

Site-specific Superposed Epoch Analysis suggested a relationship between PDSI and fire events at two of the three sites. At Soda Butte Creek, the year of fire has a significantly lower PDSI value than simulated years ($p \leq 0.05$) (Figure 10). SEA did not detect any significant relationship between fire events and PDSI at Crevice Creek (Figure 11). At Cinnamon Creek, the year prior to fire had a significantly higher PDSI value than simulated years ($p \leq 0.05$) (Figure 12). When all the site-specific fire chronologies were combined into a single regional chronology, none of the implied site-specific relationships were significant (Figure 13). However, both relationships are close to the 10

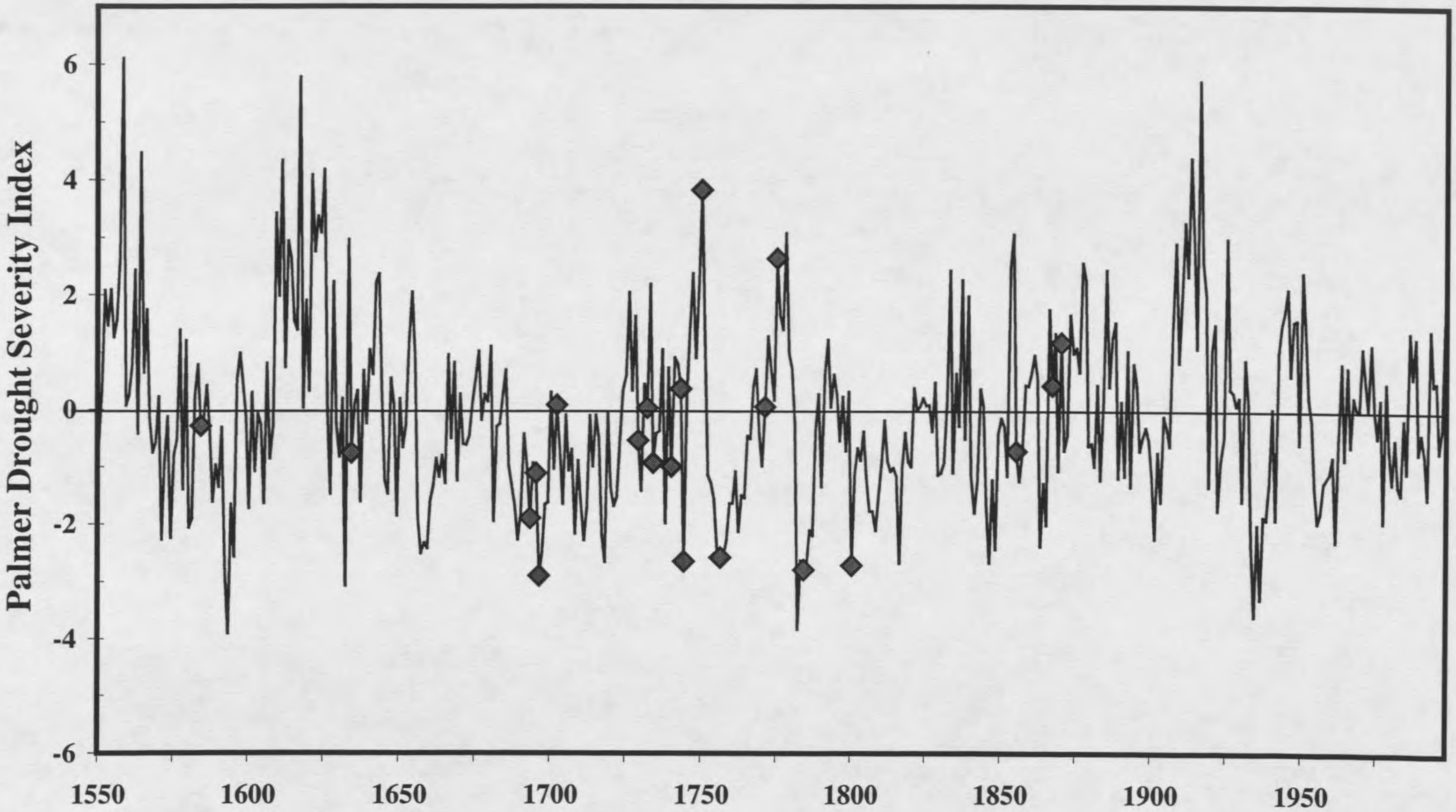

Figure 7. Fire Event Years plotted on a Time Series of Reconstructed PDSI (Pisaric and Graumlich 2002). The time series is composed of annual values. Fire events occur during low PDSI years, but also occur in years when PDSI is high.

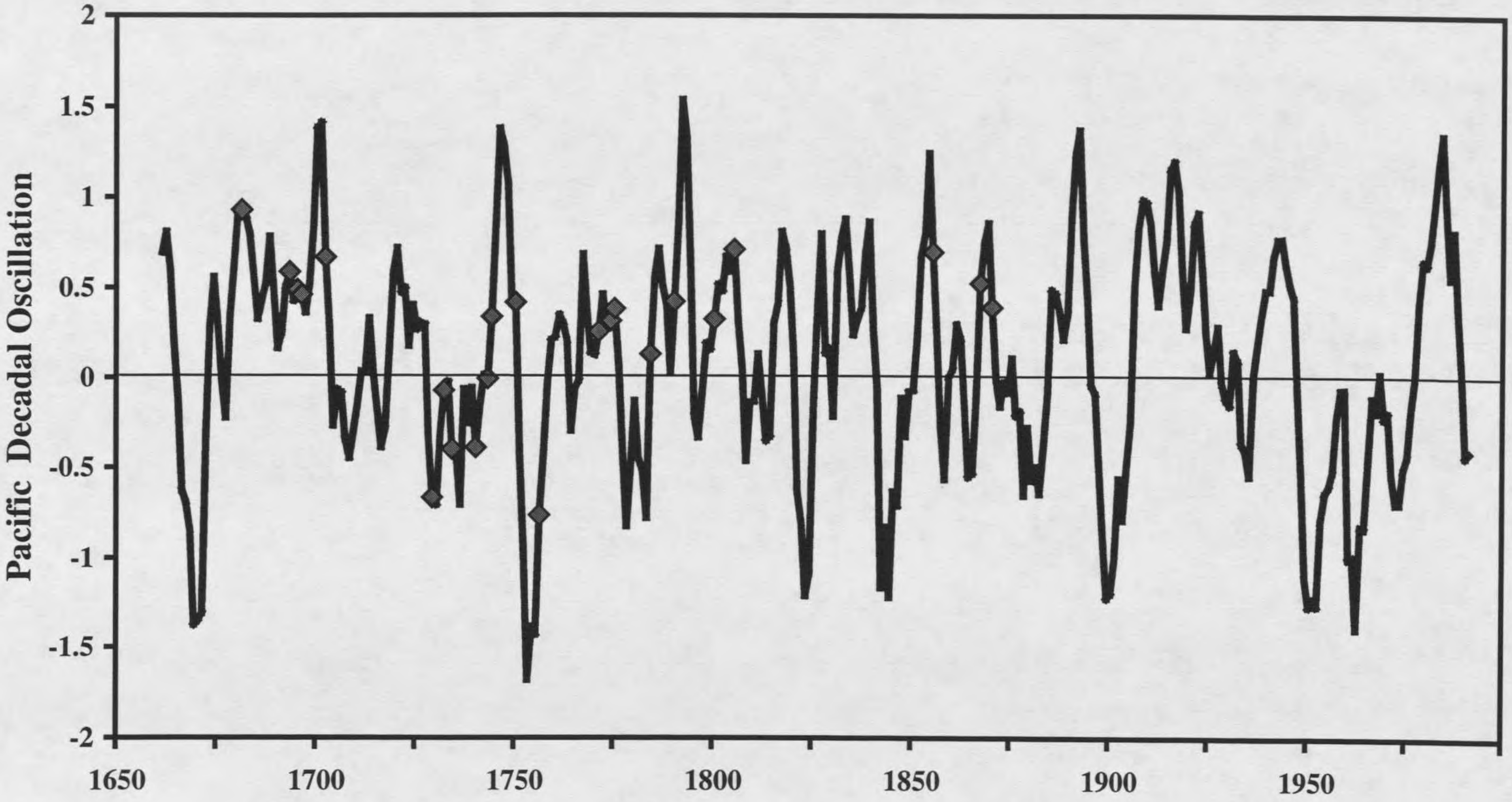

Figure 8. Fire Event Years Plotted on a Time Series of Reconstructed PDO (Biondi et al. 2001). The dark time series is composed of reconstructed annual PDO values. Fire events occur more often during warm phase (positive) PDO, but some events occur during cool phase PDO.

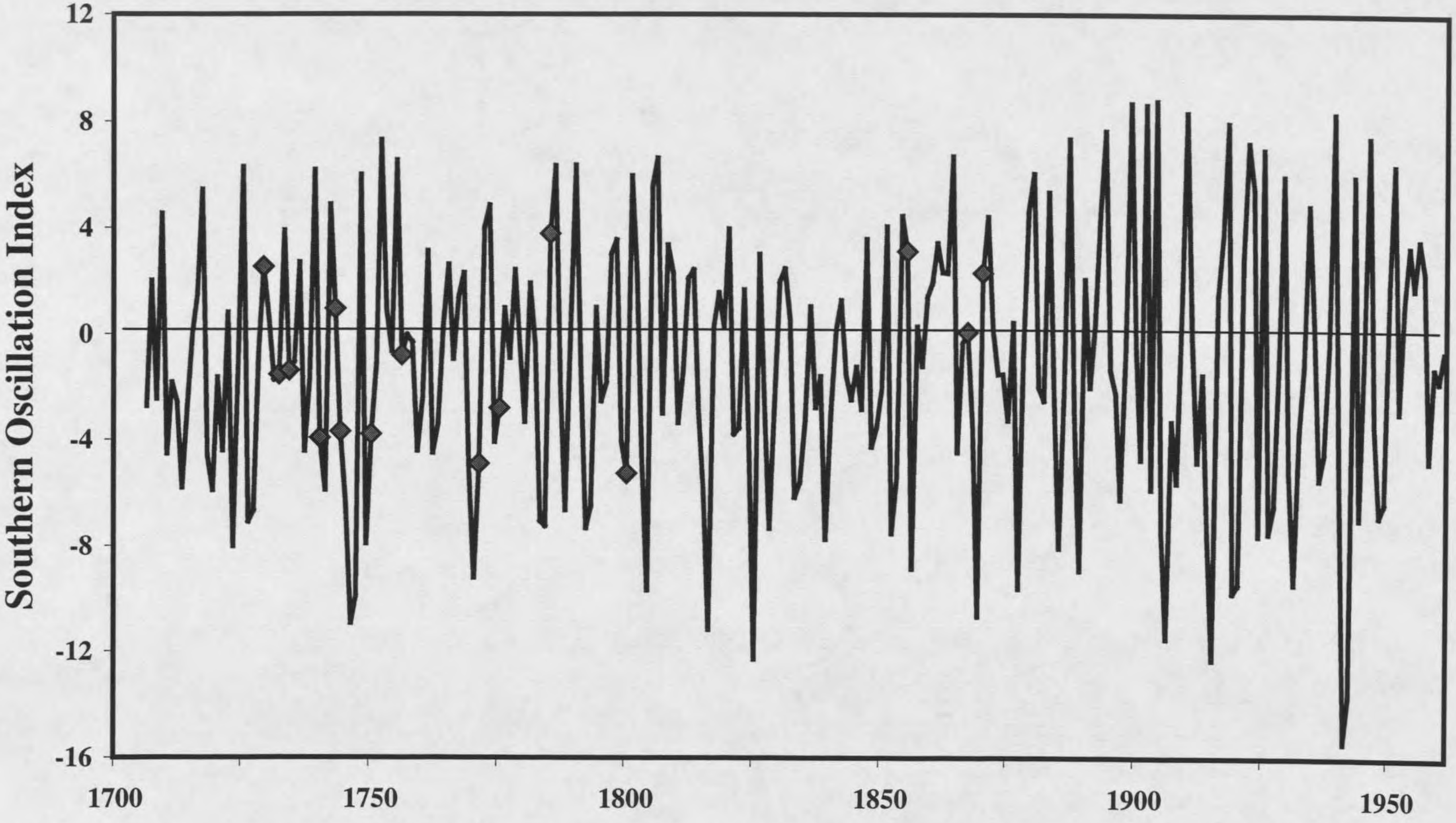

Figure 9. Fire Event Years Plotted on a Time Series of Reconstructed SOI (Stahle et al. 2000). The dark time series is composed of annual values of ENSO. Fire events occur during both El Niño (low SOI values) and La Niña (high SOI values).

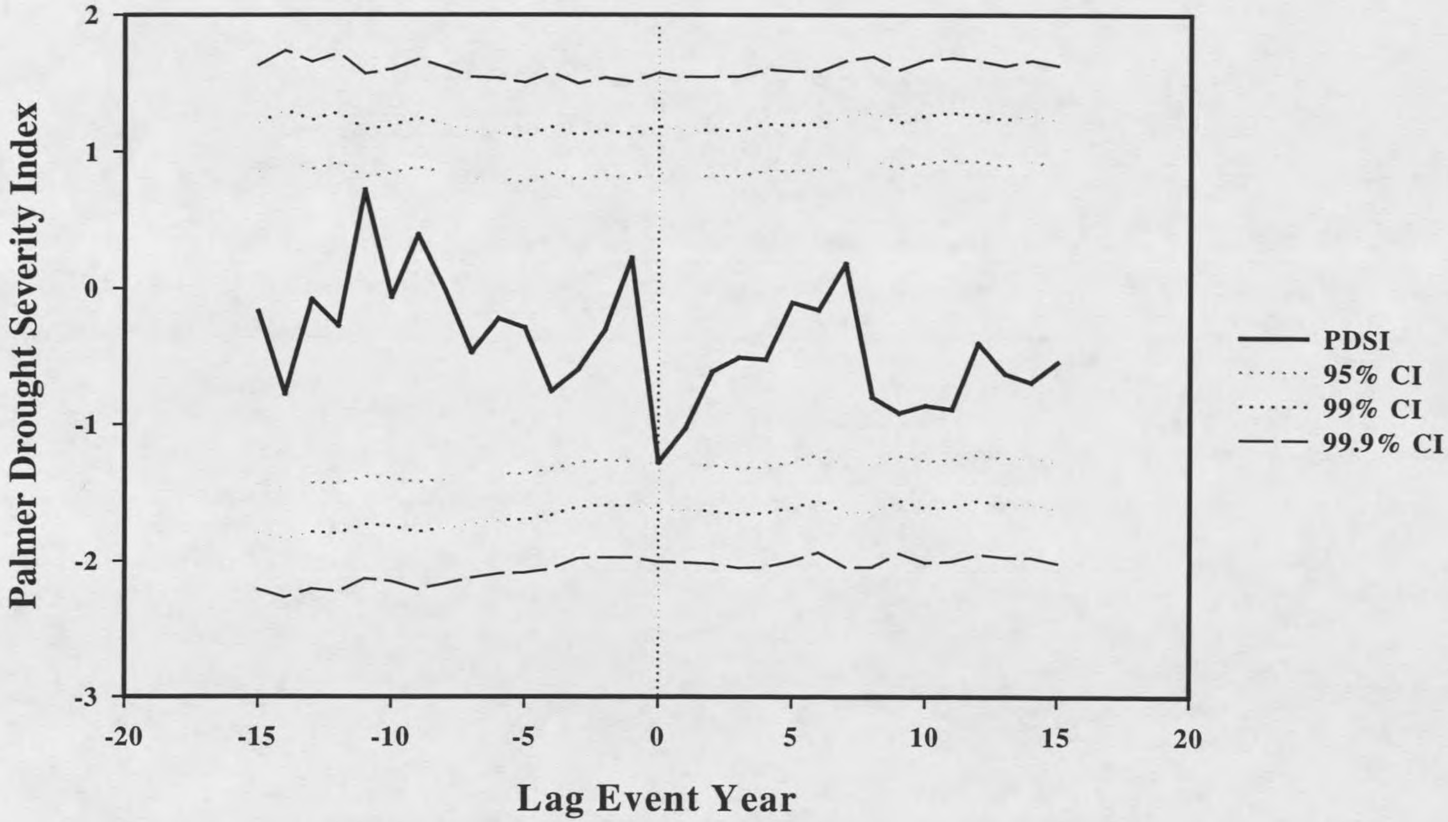

Figure 10. Superposed Epoch Analysis Simulation Results for SBC Fire Years Versus PDSI 1550-1900. The year of fire is significantly drier than expected at random.

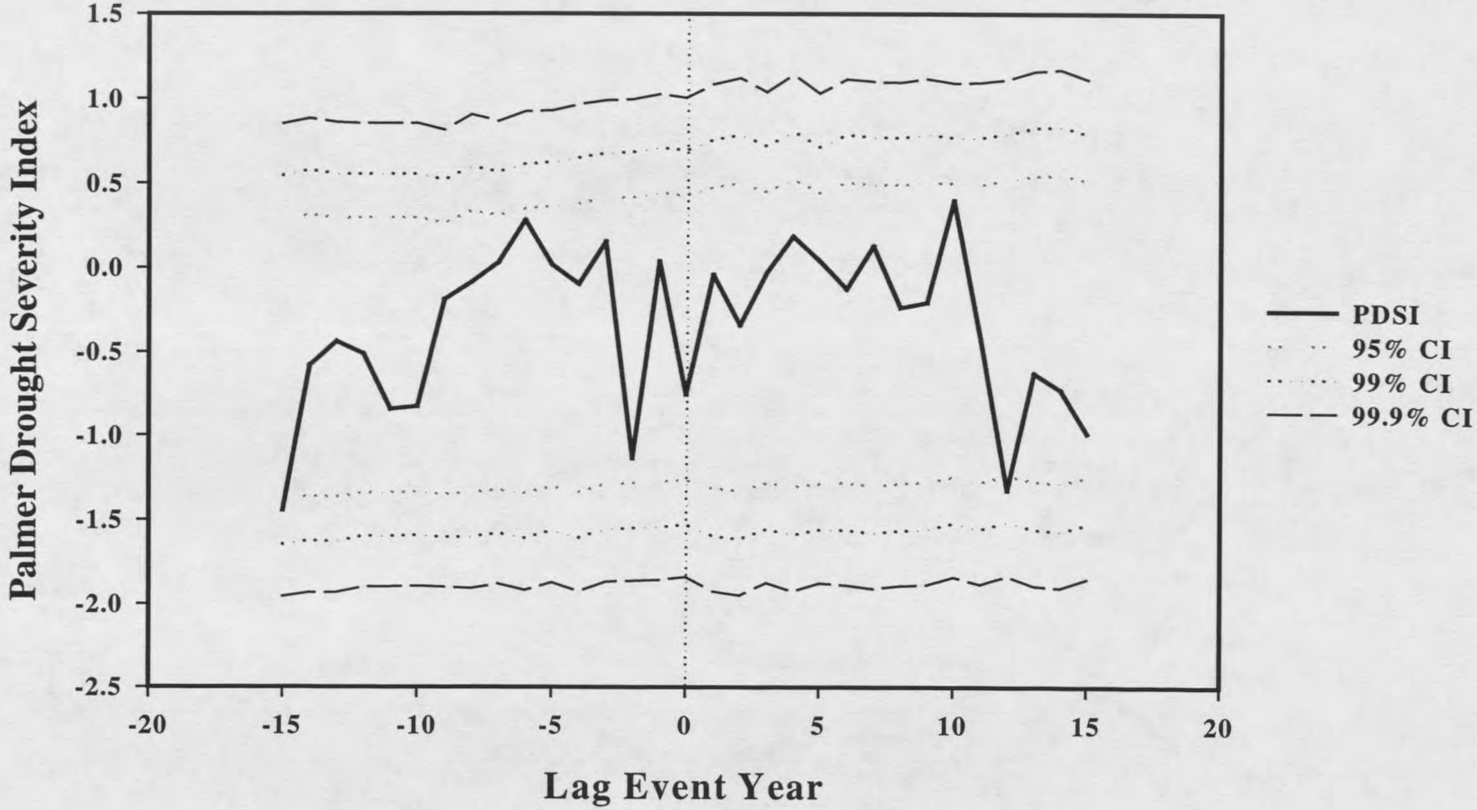

Figure 11. Superposed Epoch Analysis Simulation Results for CCR Fire Years Versus PDSI 1650-1900. The year of fire is not significantly drier than expected at random.

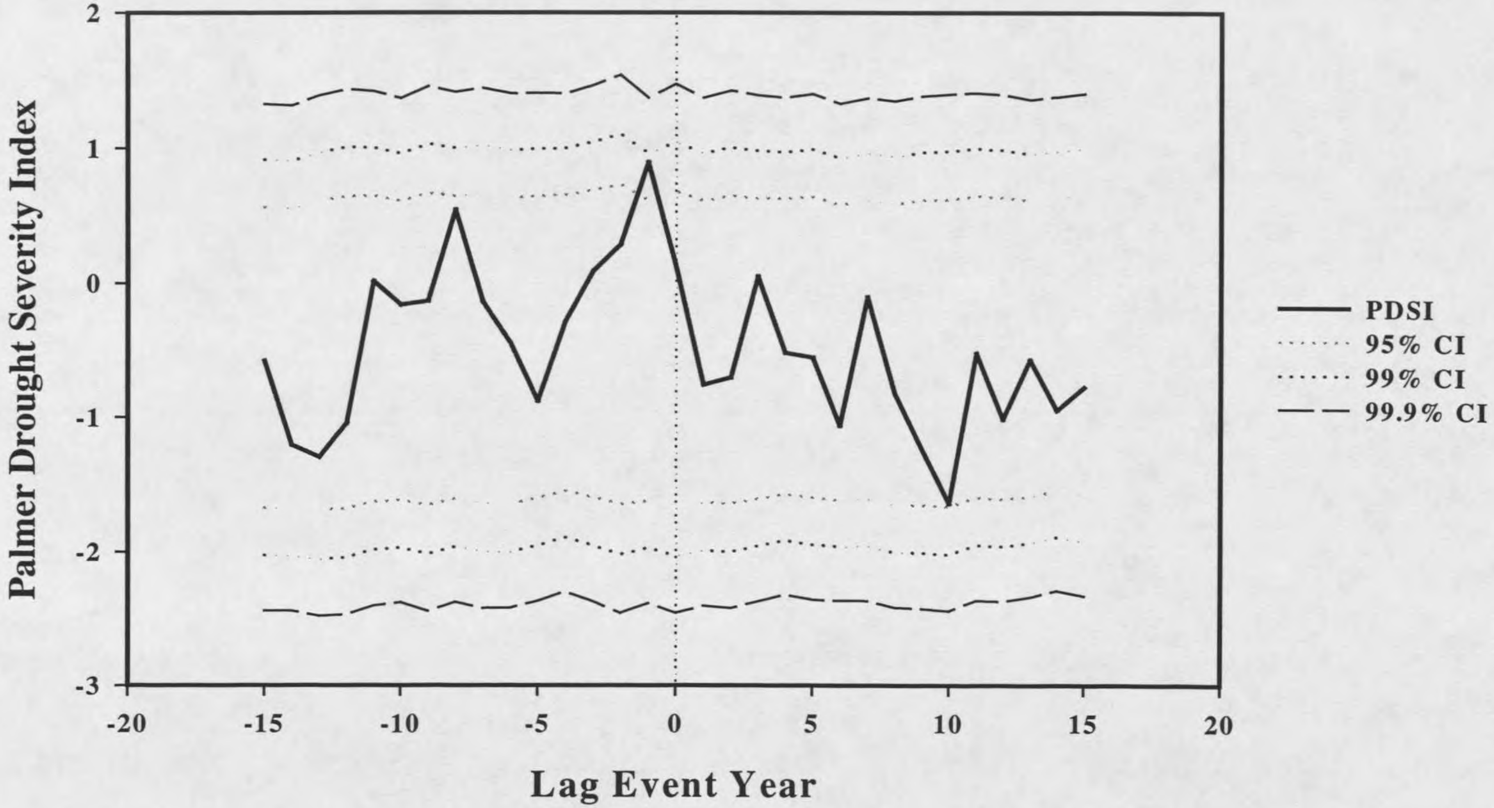

Figure 12. Superposed Epoch Analysis Simulation Results for CIN Fire Years Versus PDSI 1650-1900. The year of fire is not significantly drier than expected at random, but the year prior is significantly wetter than expected at random.

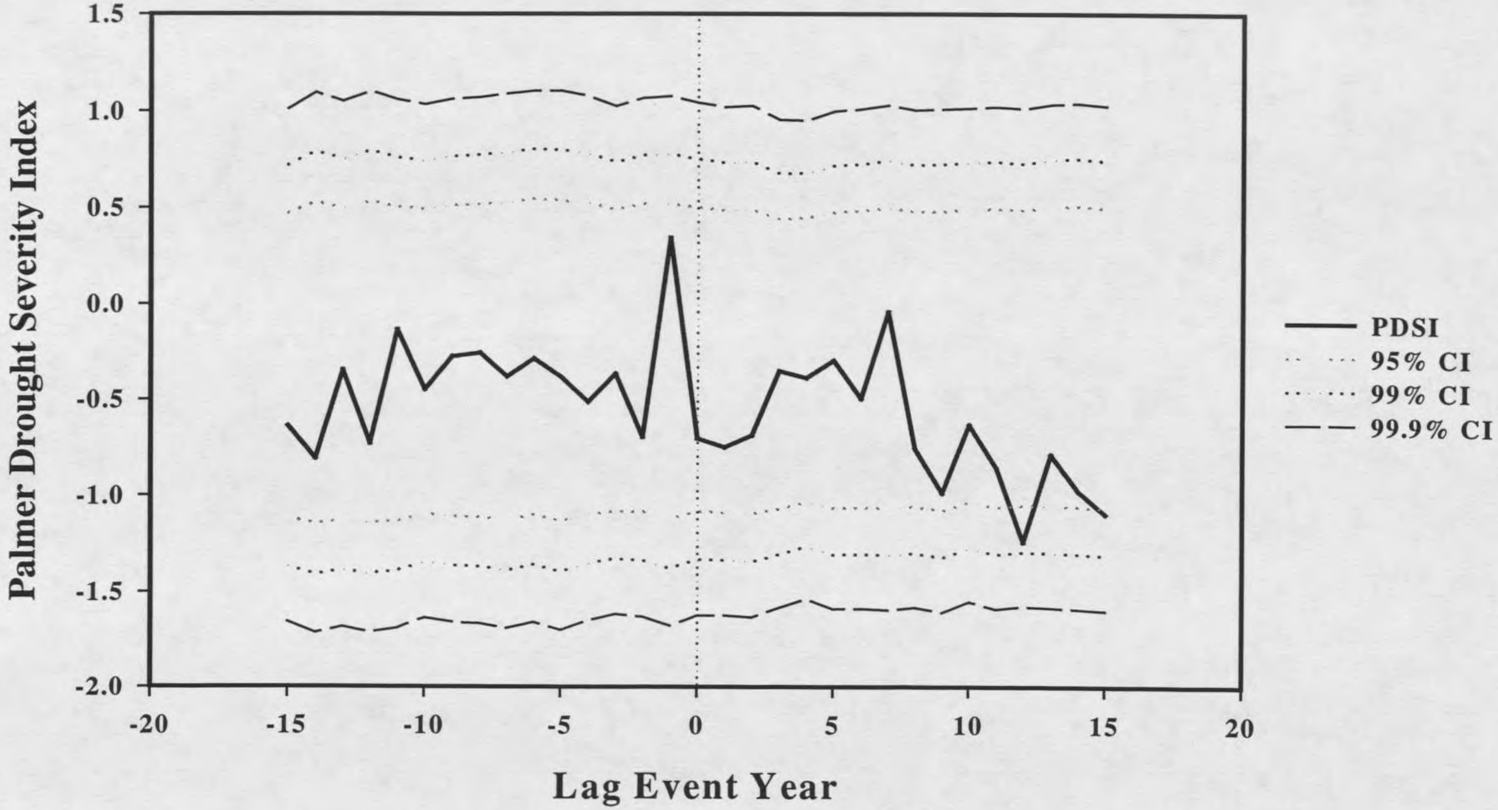

Figure 13. Superposed Epoch Analysis Simulation Results For Regional Fire Years Versus PDSI 1550-1900. The year of fire is not significantly drier than expected at random, nor is the year prior significantly wetter than expected at random.

and 90% confidence intervals for the regional chronology, which suggests the possibility of a relationship not detected by this method.

The relationship between the complete regional fire chronology and the PDO reconstruction for the common period between the two series was not significant (Figure 14). The relationship between the fire chronology and ENSO was also not significant (Figure 15). However, heuristic examination of regional fire years plotted on time series of PDO (Figure 8) values and ENSO (Figure 9) values suggests that the relative importance of the two cycles might not be stationary through time.

Adaptive and Evolutive Multi-taper Analysis.

The adaptive multi-taper power spectrum density analysis of the PDSI signal suggested significant power spectrum peaks for wavelengths corresponding to expected peaks for ENSO signals (2-7 years) and significant power spectrum density peaks for wavelengths corresponding to expected peaks for PDO signals (25-40 years) (Figure 16). An evolutive multi-taper analysis of the same period shows that the significance of the mid- and long-wavelength portions of the power spectrum are significant in the early and later portions of the PDSI chronology but that very few frequencies are significant for the windows centered around approximately 1750 (Figure 17).

Superposed Epoch Analysis for the different PDO and ENSO bins of the chronology resulted in significant relationships between high values of PDO and warm phase PDO fire years ($p < 0.05$) (Figure 18). There was also a significant ($p < 0.05$) relationship between the SOI value for the year prior to fire and the cool phase PDO fire year (Figure 19).

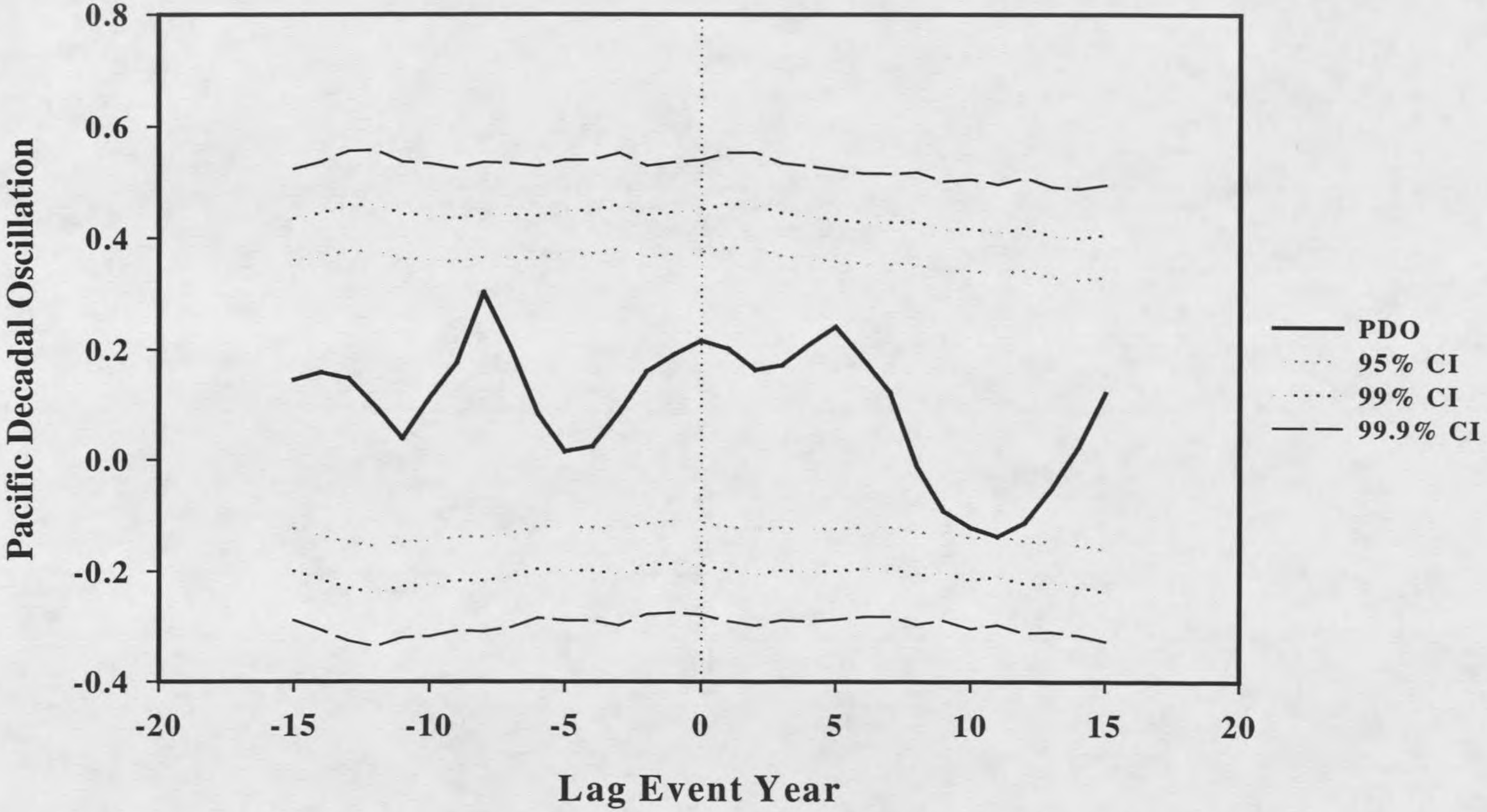

Figure 14. Superposed Epoch Analysis Simulation Results for Regional Fire Years Versus PDO 1661-1900. The year of fire does not exhibit a significant relationship with PDO.

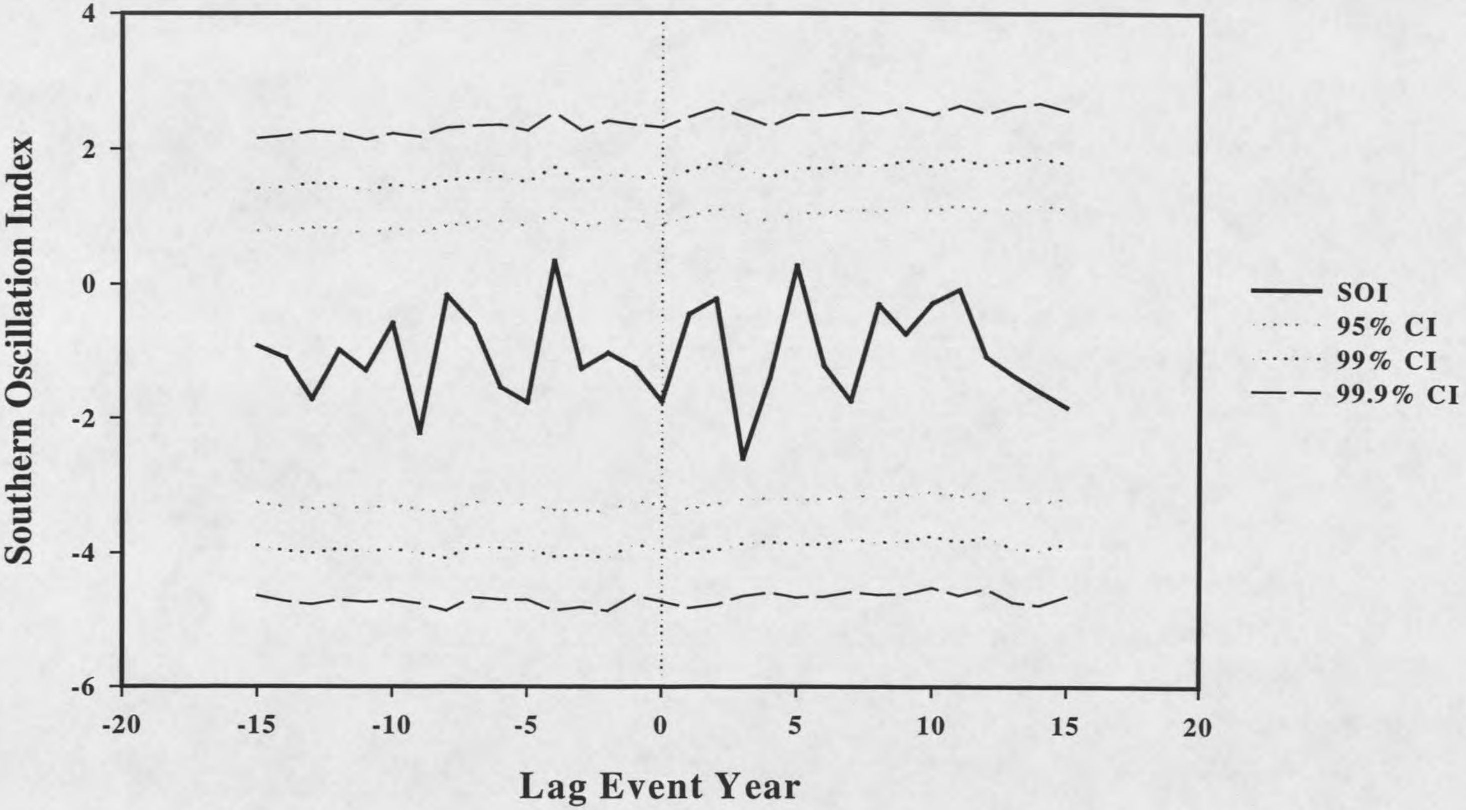

Figure 15. Superposed Epoch Analysis Simulation Results for Regional Fire Years Versus SOI 1706-1900. The year of fire does not exhibit a significant relationship with SOI.

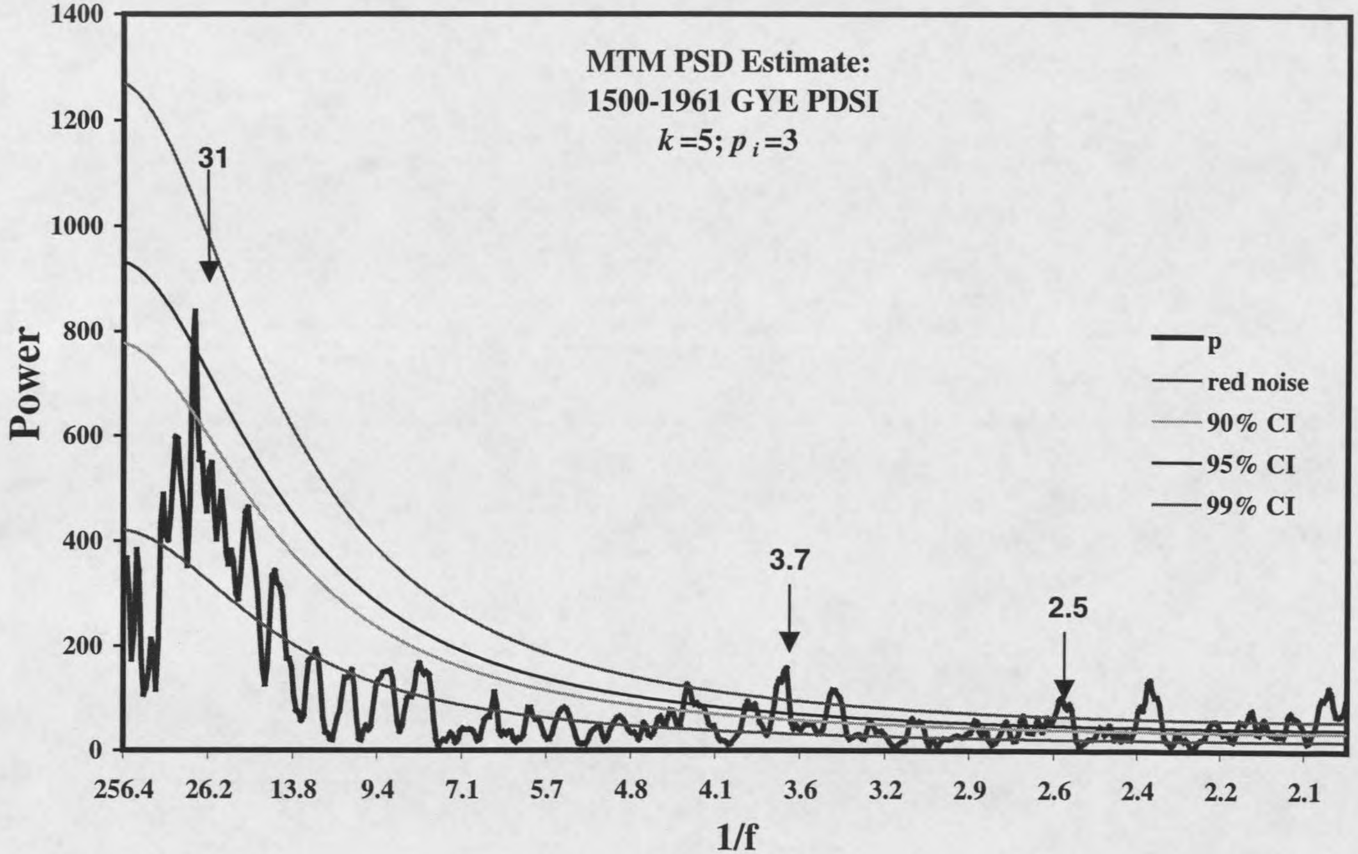

Figure 16. Power Spectrum Density Plot for Reconstructed Greater Yellowstone PDSI (data source: Pisaric and Graumlich 2002). Significant power spectrum peaks associated with SOI and PDO wavelengths are present in the full time series of PDSI values. This suggests an influence of SOI and PDO on GYR precipitation.

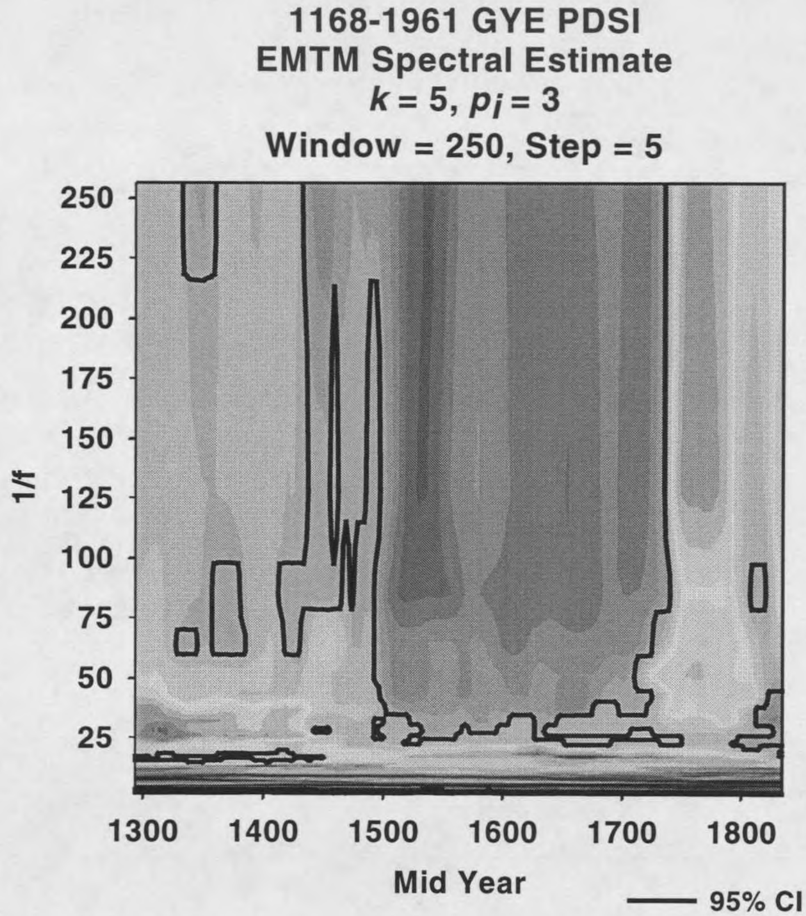

Figure 17. Evolutive Power Spectrum Density Plot for Reconstructed Greater Yellowstone PDSI. Significant power spectra signatures are not stationary through time. A prominent restructuring of power occurs during the mid 1700s when longer wavelength phenomena cease to be as important in the distribution of variance in the power spectrum. Similar restructuring occurred around the 14th century.

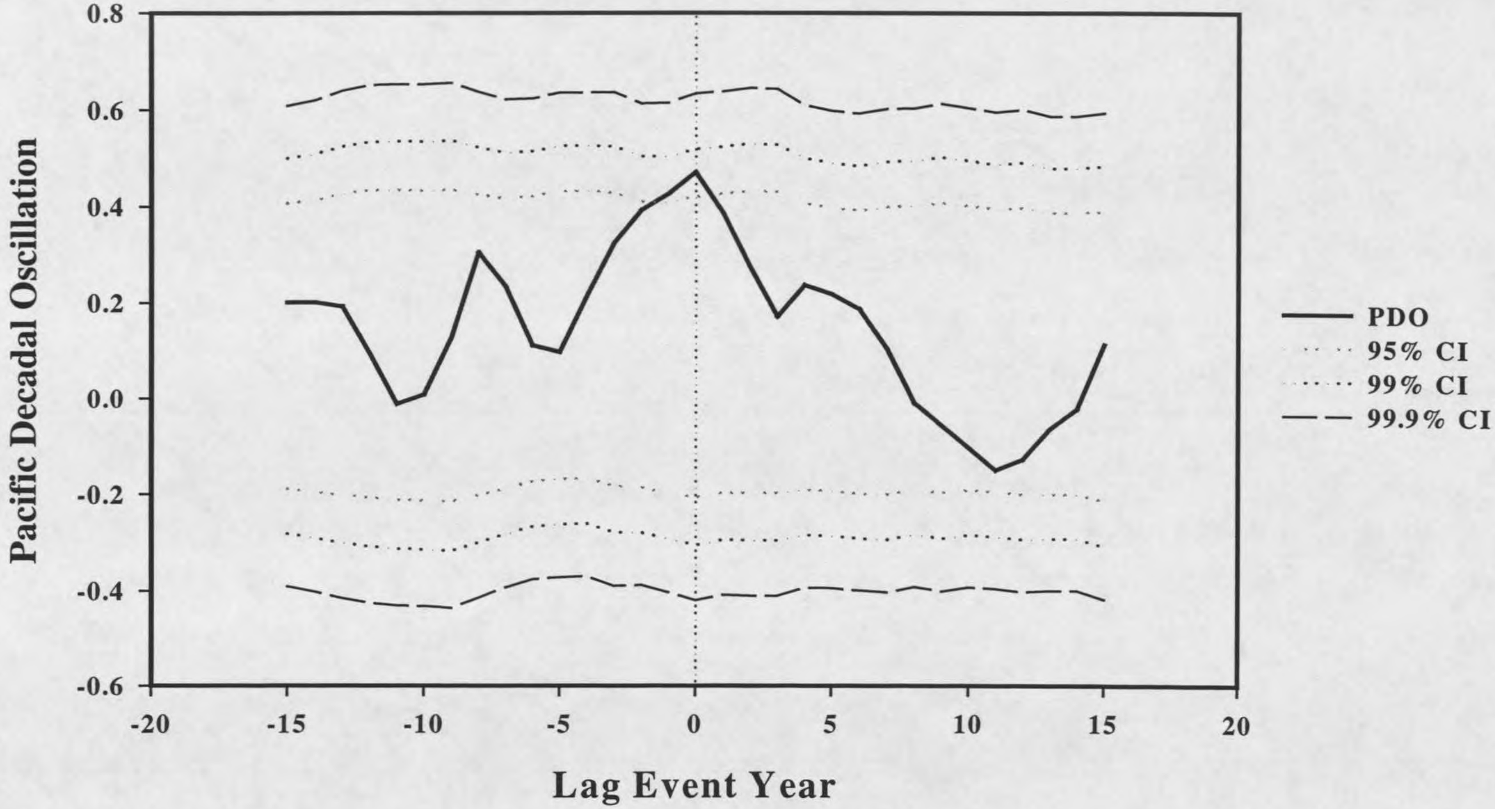

Figure 18. Superposed Epoch Analysis Simulation Results For Warm-phase PDO Regional Fire Years Versus PDO 1661-1900. The years surrounding fire years exhibit a significant relationship with PDO.

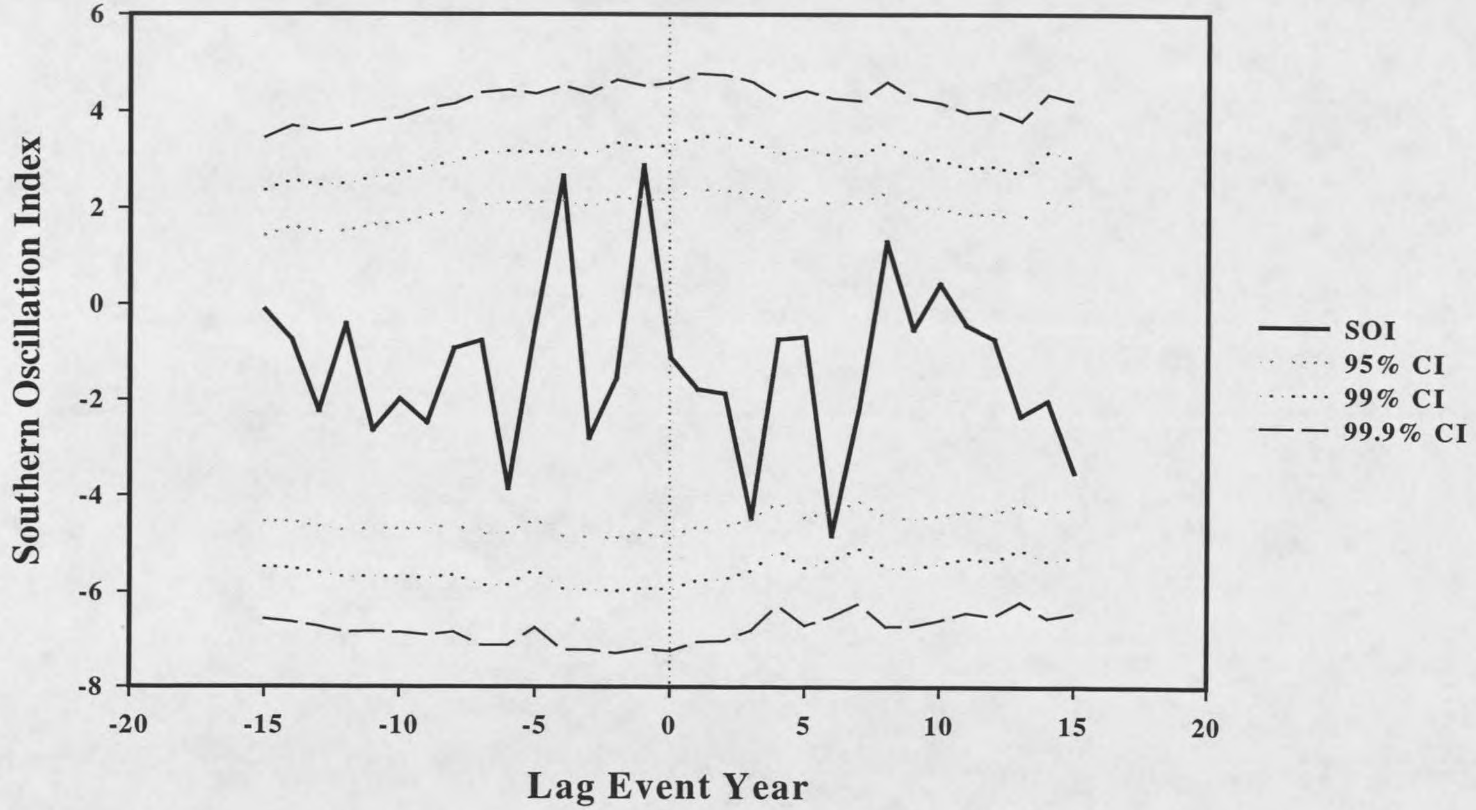

Figure 19. Superposed Epoch Analysis Simulation Results for Cool-phase PDO Regional Fire Years Versus SOI 1706-1900. The year of fire does not exhibit a significant relationship with SOI, but the year prior is significantly high.

Bootstrapping and Resampling

The probability of sampling 15 PDO values greater than the values of the warm-phase PDO fire years was less than 0.05. Similarly, the probability of sampling 6 SOI values less than the values of cool-phase PDO fire years was less than 0.05.

Discussion

Correlations between Pacific synoptic climate phenomena and late winter/early spring precipitation are significant during the 20th century. These patterns imply that drought in the GYR is at least partially influenced by ENSO and PDO. However, superposed epoch analysis suggested no region-wide, period of record relationship between fire events and the Southern Oscillation or the Pacific Decadal Oscillation. Site-site specific patterns were different however, and multi-taper time series analysis procedures revealed that the relative importance of ENSO and PDO length periodic climate phenomena to drought in the GYR varied over time. Thus since the power spectrum density of dry years is not stationary in time, there is no reason to expect stationarity in the influence of the two pacific-centered periodic climate phenomena on fire in the GYR. Instead, when PDO is in the warm phase, it has a demonstrated impact on winter precipitation and could be related to approximately 75% of fires detected in this fire history reconstruction for lower elevation forests of the GYR. However, during a redistribution of power in the spectrum of PDSI in the mid 1700s, PDO was in a cool phase and El Niño-like events may have become a more significant influence on drought. Superposed epoch analysis on the partial groups of fire events indicated fires related to SOI instead of PDO characterized this period. The regional fire frequency for that time period is also substantially higher when considered alone than the fire frequency for the entire period of record or for only the warm-phase PDO portion of the record.

The null hypothesis that there are no coherent relationships between regional climate patterns and fire events in the Greater Yellowstone Region and that fire events occur during "fire weather" is thus not supported by these analyses. The first and second alternative hypotheses, that fire events are explained fully by the Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO) are also not supported. The summary evidence presented here suggests that failing to reject the third alternative hypothesis, that both PDO and ENSO influence fire events, is acceptable. However, the relative influence of the two phenomena does not appear to be consistent through time, and thus forecasting fire events based on one index or the other is not likely to skillfully predict the likelihood of fire events. This lack of stationarity in the temporal domain of the causal relationship between precipitation and fire suggests that a spatial investigation of that relationship is also warranted. The resolution of the fire history produced in the first chapter of this thesis does not permit accurate reconstruction of fire areas so the relationship between annual area burned and Pacific drivers of precipitation cannot be realistically pursued here.

Understanding how climate variability, and in particular how ENSO and PDO, influence fire regime in the Greater Yellowstone Ecosystem, is important to the efficacy of future management decisions in national parks, national forests, and other multiple-use areas. The fact that the relationship between fire and precipitation is not stationary in time suggests that managing fire in terms of the mean fire return interval is not always the best course of action: fire has burned more or less frequently because of different climate influences at different times during the last 500 years. Understanding the potential influence of PDO and ENSO and the combination of the two on the other components of fire regime, intensity and scale, are more difficult than resolving the temporal aspect of fire regime. By incorporating the information from past fire precipitation relationships into the current decision making processes, and by recognizing that the stationarity of these relationships is likely to change in the future, the uncertainty of current decisions can be better evaluated and the flexibility of future decisions retained.

CHAPTER 4

LOCAL SPATIAL AND ENVIRONMENTAL CONTROLS ON FIRE REGIMES IN MIXED-CONIFER FORESTS, YELLOWSTONE NATIONAL PARK

Introduction

Forest fire regimes are a characterization of the fire frequency, intensity, and area at a given place (Heinselman 1973, Houston 1973). Most fire history research attempts to place a local forest fire regime along a gradient between low frequency, high-intensity crown fire events and high frequency, low intensity surface fire events (Barrett 1994). It is sometimes possible to reconstruct the spatial extent of fires from forest age-class (Romme and Knight 1981, Heyerdahl 1997) or fire scar (Heyerdahl 1997) data, but this requires very large sample sizes. Very little research emphasizes the statistical relationships between the spatial distribution of biophysical processes and the spatial distribution of fire regimes across the landscape. Understanding how biophysical variability in space and time influences the spatiotemporal variability of fire regime is critical to landscape forest fire modeling and management of fire on public land. It also has implications for carbon sequestration models and conservation ecology.

The statistical description and analysis of fire regimes has been almost exclusively temporal. Most studies seek primarily to describe the mean frequency of past fire events prior to human intervention in the natural fire cycle (Swetnam 1990, Grissino-Mayer and Swetnam 2000). Some studies also have roughly described the spatial extent of past fire events (Romme and Knight 1981, Turner and Romme 1994, Everett et al.

2000), but relatively little study has focused on the actual spatial structure of fire regimes in the context of the environmental controls on fire regime (McKenzie et al. 2000). The work that has been done correlated fire regime in homogeneous systems to altitude (Agee 1991, Barrett 1994) or forest type (Romme and Knight 1981, Swetnam 1990, Turner and Romme 1994). However, in order to develop a general model of fire regime as a product of environmental variables, spatial structuring of the drivers of fire regime must be studied in heterogeneous systems. For example, it is clear that the fire regime in lodgepole pine forests of greater Yellowstone has a longer return interval than the fire regime in Arizona ponderosa pine forests (Turner and Romme 1994, Swetnam 1990), but it is not clear how the variability of environmental controls of fire regime, especially the spatial structure of the environment, determine fire return interval. In this paper, my objective is to determine what effect the spatial structure of the environment has on fire regime in forests of the Greater Yellowstone Ecosystem.

Establishing the correlation between fire regime and biophysical variables in a spatially structured environment is complicated by several problems that render data intractable for traditional statistical analysis. Different kinds of fires leave behind different kinds of evidence (Agee 1991), and thus sampling protocols necessarily become dual. The biophysical drivers of fire regimes (the “normal” frequency, burn intensity, and scale of fire events at a given place) are those drivers that control fuel moisture and are often collinear (D. Urban, pers. comm.). Finally, both fire regime data and the environmental controls on fire regime are usually spatially auto-correlated (McKenzie et al 2000).

The objective of this study, framed in the hypothetical language of Legendre and Legendre (1998), is to determine whether or not the spatial structure of the environmental variables of fire regime fully explains the spatial structure of the fire history data, or is there a part of the spatial structure of the fire history data which is not explained by the environmental variables I chose to model? The most appropriate method is therefore one where spatial structure, environmental determinants, and the interaction between the two are all accounted for; in order to partition out the main components of variation, it must be assumed that the spatial and environmental components are on equal footing (Legendre and Legendre 1998).

Mantel's Test

Partial Mantel analysis (Smouse et al. 1986, Legendre and Troussellier 1988) provides a method for partialling out spatial/environmental determinants of a spatially explicit ecological process (Leduc et al. 1992, Legendre and Legendre 1998). A classical Mantel's test (Mantel 1967) tests whether the variation in one distance matrix is correlated with the variation in another distance matrix, but it is unique because it is robust to non-independent data (Smouse et al. 1986, Legendre and Legendre 1998). This procedure was adapted to account for the simultaneous effects of multiple matrices by holding one or more constant while evaluating relationship between others (Smouse et al. 1986, Legendre and Troussellier 1988). Partial Mantel analyses have been used to evaluate the importance of spatial structure in boreal seedling response to local abiotic variables (Leduc et al. 1992) and genetic variability and gene flow across landscapes (Smouse et al. 2001). Applications of similar methods (Legendre and Fortin 1989) have been applied to the distributions of ectomycorrhizal fungi (Villeneuve et al. 1991, Nantel and Neumann 1992) and freshwater fishes (Mandrak 1995).

In this case, the partial Mantel process requires a similarity matrix describing response variable (fire regime) structure (**Y**), a Euclidean ecological distance matrix derived from environmental variables (**X**), and a matrix of Euclidean geographic distances computed from all pairs of sampling stations (**W**) (Legendre and Legendre 1998). The matrices are then used in a partial Mantel analysis (e.g. Leduc et al. 1992). The response matrix **Y** in most partial Mantel analyses is either a symmetrical binary coefficients matrix, which is appropriate for presence absence data, or a similarity index such as a Jaccard's or Bray-Curtis similarity (Legendre and Legendre 1998). Different Y matrices are appropriate given the properties of the response variable.

To address the problem of the influence of local spatial variability on fire regime, I evaluate two sets of hypotheses. The first set of hypotheses addresses the distribution of fire evidence across the SBC site:

H_0 : Point estimates of fire regime are distributed randomly across the SBC site.

H_A : Point estimates of fire regime are clustered across the SBC site

The second set of hypotheses address the correlation between the spatial distribution of fire regime and spatial distribution of the biophysical soil moisture proxies they should theoretically (Urban and Miller 2000) be correlated with. The null hypothesis in this case is a blanket null, accounting for the possibility there is no relationship between any of the biophysical variables. The alternative hypotheses below all have associated, implied null hypotheses.

H_0 : There is no correlation between the spatial distribution of point fire regime estimates and the spatial distribution of point biophysical soil moisture proxies: aspect, topographical convergence, and elevation.

H_{A1} : There is a correlation between the spatial distribution of point fire regime estimates and the spatial distribution of individual point topographical convergence.

H_{A2} : There is a correlation between the spatial distribution of point fire regime estimates and the spatial distribution of individual point aspect.

H_{A3} : There is a correlation between the spatial distribution of point fire regime estimates and the spatial distribution of individual point slope.

H_{A4} : There is a correlation between the spatial distribution of point fire regime estimates and the spatial distribution of individual point elevation.

H_{A5} : There is a correlation between the spatial distribution of point fire regime estimates and the spatial distribution of point multivariate biophysical soil moisture proxies: aspect, topographical convergence, slope and elevation.

Methods

Site Description

The site (SBC) is at the confluence of Soda Butte Creek and Cache Creek, Yellowstone National Park, USA, site center = 44° 51' 50", 110° 08' 50". Topography is highly dissected at the site. Vegetation at SBC is forested from the lower tree line (Douglas-fir and lodgepole pine) at about 1750m to upper tree line (whitebark pine, Engelman spruce, and subalpine fire) at about 2700m. Substrate is andesitic and sedimentary.

To test whether the spatial distribution of fire regime is correlated with the spatial distribution of soil moisture proxy variables, I employed two distinct data sets. The first is the response variable fire regime data. This data was collected from SBC between May and November 2001 and includes global positioning system (GPS) NAD 27 Universal Trans-Mercator (UTM) locations of fire history data from 35 fire scarred Douglas fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*) and from 36 variable-diameter stand age plots. Fire scars were extracted from live trees, snags, and stumps with a chainsaw and dated with standard dendrochronology techniques (see Methods, Chapter 2). The variable-diameter plots were chosen from multivariate distributions of soil-moisture proxy variables: aspect, topographic convergence, slope, and elevation. Stand ages in each plot consisted of the estimated pith dates from the closest 15 trees, regardless of species, to the center of the selected plot. Fire return intervals were estimated as the point specific mean of all intervals between detected fires for fire scarred trees or the most probable fire interval detected in plot studies, unless fire scars were dated in the plot. The most probable fire interval for stands with stand replacing fires detected was assigned a 200 year return interval (Barrett 1994) if the stand initiated in the later half of the 1800s or later to avoid the potential influence of 20th century fire suppression on the distribution of fire return intervals.

The second dataset consists of sample point specific aspect, elevation, slope, and topographic convergence index (TCI) extracted from an ARC produced 10m USGS digital elevation model of the SBC site (Figures 1-4). To produce a continuous variable, aspect was transformed using the following equation:

$$tasp = \cos((45\text{-}asp)\pi))/180)(-1)$$

A partial Mantel's test for the data sets I used to address my hypotheses requires three matrices: a Euclidean distance matrix of all pairwise sampling sites (W), a Euclidean distance matrix for each environmental variable (X_{ELEV}, X_{TASP}, X_{SLOPE}, X_{TCI}), and a response distance matrix of fire return intervals estimates.

Data Analysis

To address the spatial randomness of the data values, I first calculated the site wide intensity λ using a kernel estimator. I calculated $\hat{F}$ to examine first-order spatial randomness and Ripley's $\hat{K}$ to examine second-order spatial patterning. For $\hat{K}$, I calculated a bootstrapped confidence interval/simulation envelope using 1000 binary simulations.

The W (spatial point pattern), X_1 (elevation), X_2 (transformed aspect), X_3 (slope), X_4 (topographic convergence), and Y (fire interval) distance matrices were then used to calculate simple and partial Mantel/Pearson correlations (using EcoDist library for S+, Urban and Gosley) between the matrices. The permutations of the correlations calculated are listed in Table 6. Each Mantel run was calculated with 1000 permutation Monte Carlo simulations with a critical probability of 0.9 to establish 95% confidence intervals and p values.

Results

Point Pattern

The point pattern produced by all data points considered together (Figure 20) shows strong evidence of clustering, but there is no obvious first order trend (Figure 20). λ varied across the site, and there are three distinct clusters (Figure 20) driven by fire-scarred trees. $\hat{K}$ was greater than the values of the simulation envelope confidence intervals for all values up to about 1.8 km (Figure 21). $\hat{F}$ nearest neighbor distances are skewed towards shorter distances (Figure 22).

Mantel's Test

Mantel's tests showed significant correlations between the space matrix (W) and both elevation ($r = 0.31$, $p \leq 0.00$) and transformed aspect ($r = 0.12$, $p \leq 0.00$) (Table 6). The fire distance matrix (Y) was significantly correlated with the elevation matrix ($r = 0.15$, $p \leq 0.00$) but not topographical convergence, transformed aspect, or slope (Table 6). No partial Mantel tests demonstrated changes for non-significant simple Mantel's test variables in Mantel r when other, significant variables were held constant. The spatial variability at the site is partially correlated with elevation and aspect, but only the direct correlation between elevation and fire regime is significant (Figure 23).

Table 6. Mantel Correlations, associated p values and confidence intervals. * indicate significant Mantel correlations.

Model	Mantel R	p(r<0)	p(r>0)	p(r=0)	2.5% CI	97.5% CI
fire ~ xy	0.08	0.01*	0.99	0.02	0.04	0.13
fire ~ dem	0.15	0.01*	1	0.01	0.1	0.21
fire ~ slope	0.02	0.33	0.67	0.72	-0.02	0.05
fire ~ tasp	0.03	0.23	0.77	0.53	0	0.06
fire ~ tci	0.01	0.39	0.61	0.84	-0.02	0.03
fire ~ xy + dem	0.04	0.13	0.88	0.25	0	0.08
fire ~ xy + slope	0.08	0.01*	0.99	0.01	0.04	0.13
fire ~ xy + tasp	0.08	0.01*	0.99	0.01	0.04	0.13
fire ~ xy + tci	0.08	0.01*	0.99	0.01	0.04	0.13
fire ~ xy + dem + slope	0.04	0.15	0.85	0.27	0	0.08
fire ~ xy + dem + tasp	0.03	0.13	0.87	0.32	0	0.07
fire ~ xy + dem + tci	0.04	0.14	0.86	0.25	0	0.08
fire ~ xy + slope + tasp	0.08	0.02*	0.98	0.02	0.04	0.12
fire ~ xy + slope + tci	0.08	0.02*	0.98	0.02	0.04	0.13
fire ~ xy + tasp + tci	0.08	0.01*	0.99	0.02	0.04	0.12
fire ~ xy + dem + slope + tasp	0.03	0.14	0.86	0.29	0	0.08
fire ~ xy + dem + slope + tci	0.04	0.14	0.87	0.24	0	0.07
fire ~ xy + slope + tasp + tci	0.03	0.14	0.86	0.29	0	0.08
fire ~ xy + dem + slope + tasp + tci	0.03	0.17	0.83	0.31	0	0.08
fire ~ dem + slope	0.02	0.34	0.66	0.72	-0.02	0.05
fire ~ dem + tasp	0.03	0.22	0.78	0.5	0	0.07
fire ~ dem + tci	0.01	0.35	0.65	0.79	-0.02	0.04
fire ~ slope + tasp	0.01	0.34	0.66	0.8	-0.02	0.05
fire ~ slope + tci	0	0.44	0.57	0.97	-0.02	0.04
fire ~ tasp + tci	0	0.43	0.57	0.97	-0.03	0.03
fire ~ dem + slope + tasp	0.03	0.25	0.75	0.54	0	0.06
fire ~ dem + tasp + tci	0.15	0*	1	0	0.1	0.22
fire ~ dem + slope + tci	0.15	0*	1	0	0.1	0.21
fire ~ dem + slope + tasp + tci	0.03	0.23	0.77	0.53	0	0.07
fire ~ slope + tasp + tci	0.01	0.37	0.63	0.82	-0.03	0.05
xy ~ dem	0.31	0*	1	0	0.28	0.35
xy ~ tasp	0.12	0*	1	0	0.07	0.17
xy ~ tci	0.03	0.2	0.8	0.41	0.01	0.06
xy ~ slope	0	0.46	0.55	0.92	-0.02	0.03
tasp ~ dem	0	0.46	0.54	0.98	-0.04	0.03
tasp ~ tci	0.25	0*	1	0	0.16	0.3
tasp ~ slope	0.22	0*	1	0	0.15	0.26
slope ~ tci	0.43	0*	1	0	0.35	0.53

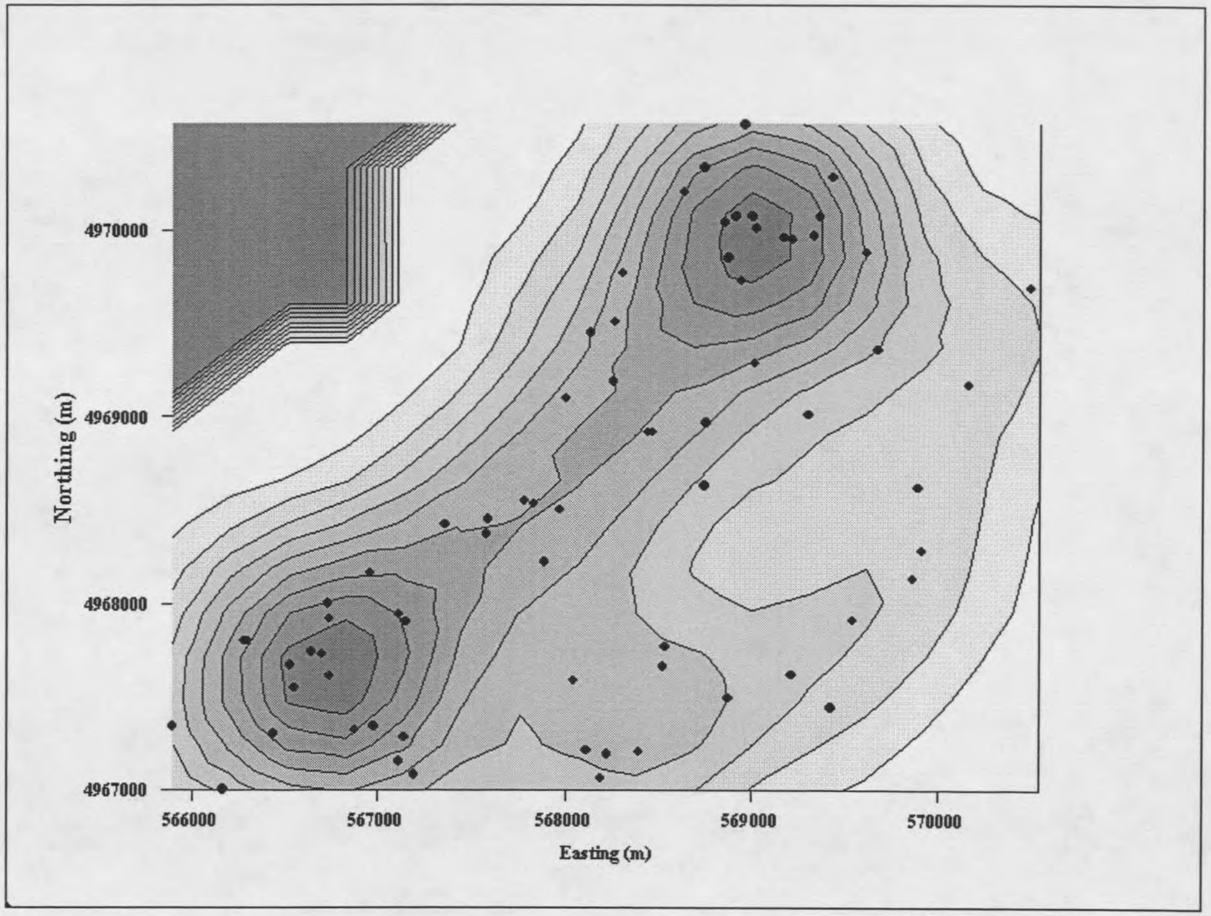

Figure 20. Spatial intensity (λ) of Fire Scarred Trees and Age Class Plots at Soda Butte Creek. Spatial clustering of sample points is strong and driven by the proximity of fire scarred trees to each other.

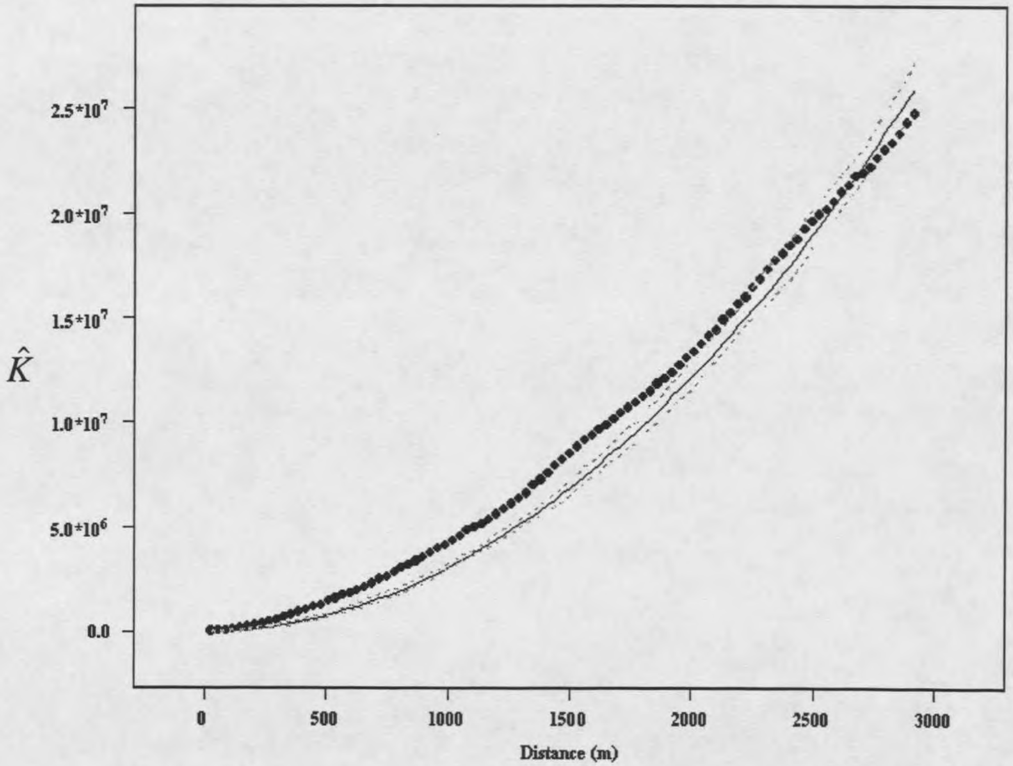

Figure 21. $\hat{K}$ **With Simulation Envelopes for Sampling Points at Soda Butte Creek. Second order spatial patterning is significantly clustered at all distances between 0 and 2300 m. Dark points are values of** $\hat{K}$ **; dashed lines indicate upper and lower simulated 95% confidence intervals; grey line indicates the expected value.**

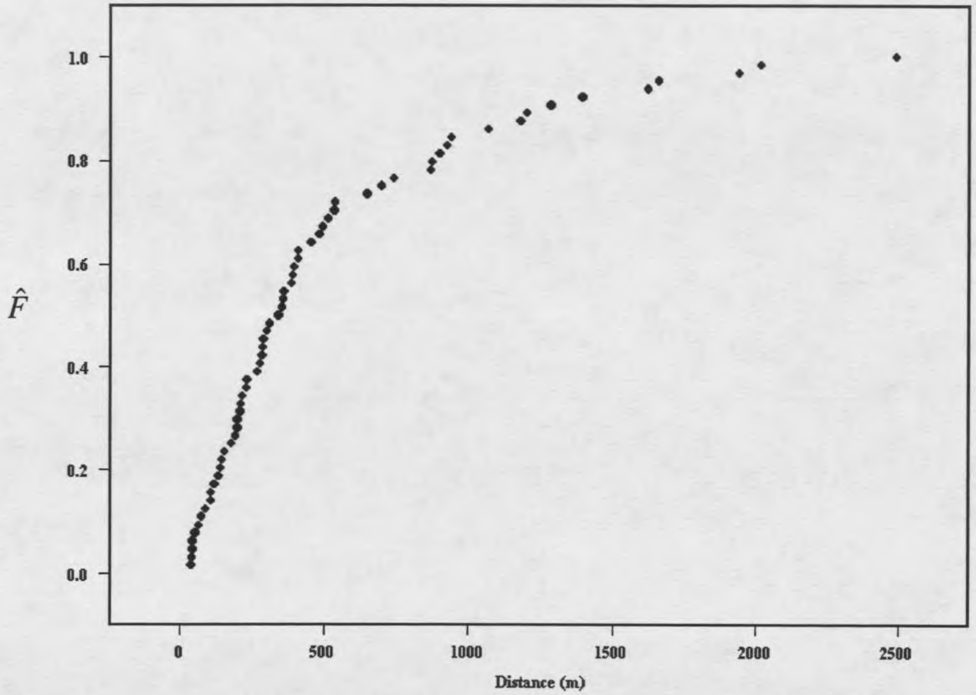

Figure 22. $\hat{F}$ **for Sampling Points at Soda Butte Creek. Nearest neighbors are most clustered at shorter distances. Dark points are values of** $\hat{F}$ **.**

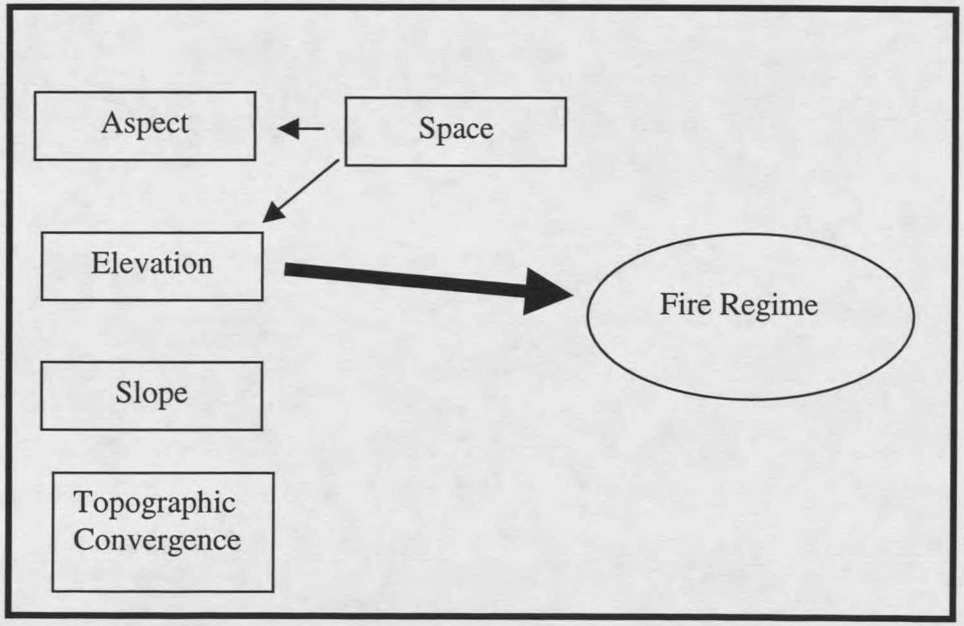

Figure 23. Conceptual Diagram of Mantel's Test Results

Discussion

The clustering demonstrated by Ripley's $\hat{K}$ (Figure 21) combined with λ plots (Figure 20) suggests fire scarred trees are strongly clustered. It should be noted that the site is not square; bounding box changes didn't seem to have much effect on Ripley's $\hat{K}$, but intensity might change if the site better approximated a rectangular grid. Spatial clustering is a pattern observed in fire-history studies globally, and is probably an artifact of the continuous nature of fire and the similar response of similar trees to disturbance. The clustering does suggest that fire regime is not the same everywhere in the sample site.

Simple Mantel's test results suggest that the spatial matrix is significantly correlated with elevation (Table 6). This result is not surprising because even though SBC is topographically dissected, there is an elevation trend from one edge of the site (west) to another edge (east) and this is reflected in the sampling points also. Simple Mantel's tests for fire regime matrix / environmental matrix correlations were dominated by elevation even when space was controlled for. None of the other environmental variables were significant even when space and elevation were controlled for (Table 6).

Thus the null hypothesis that point estimates of fire regime are distributed randomly across the SBC site must be rejected. Mantel's test results, however, suggests that the null hypotheses associated with the first three alternative hypotheses, that topographic convergence, aspect, and slope affect the distribution of fire regime across the site, must not be rejected (Figure 23). Only the implied null for the fourth alternative hypothesis can be rejected; point elevation is correlated with point fire regime once spatial effects have been removed. Combinations of the variables would therefore not be significant.

Thus, environmental controls on fire regime at local scales, if they exist, are masked by elevation. Elevation is commonly spatially autocorrelated with precipitation, temperature, evapotranspiration, and light intensity, all of which could affect fire regime. Without specific biophysical modeling to determine the effects of elevation on the ecophysiological responses at SBC, it is doubtful if I would be able to partial out the effects of elevation on fire regime. This might in turn merely demonstrate that the controls on fire regime operate on scales of kilometers along elevation gradients rather than on scales of meters in response to local biophysical variables. However, if the ultimate application of this work was to inform prescribed fire treatments, the results bolster previous results (Heyerdahl 1997, Swetnam 1990) that suggest elevation is a strong determinant of fire regime in much of the western United Sates.

In summary, although there are hypothetical reasons why soil moisture proxies should be correlated with fire regime type once spatial variability is accounted for, such relationships were not detected here except for the distinct significant relationship between fire regime and elevation. This relationship may be cause for a more detailed mechanism to explain the variation of fire regime at scales of hectares instead of kilometers. However, it is likely that larger scale phenomena that influence climate have a larger impact on local fire regime than local biophysical controls, at least for the period of record for this study.

CHAPTER 5

SUMMARY: FIRE REGIME VARIABILITY IN SPACE AND TIME IN LOWER ELEVATION FORESTS OF THE GREATER YELLOWSTONE REGION

Key Findings

The goal of this thesis was to determine the past fire history of three lower elevation watersheds in the northern Greater Yellowstone Region and relate the variability, if any, in fire regime to the biophysical template of the region. Fire regime differed in its manifestation in three watersheds of the Greater Yellowstone Ecosystem. Each watershed had a unique fire history, and only a few fire years in the past five hundred years were detected at more than one watershed. Fire episodes, however, in which all three sites burned within a few years of each other were not uncommon. In addition, sites cannot necessarily be characterized at the scale of several hundred hectares as having a single fire regime. More intensive, plot based research at Soda Butte Creek in Yellowstone National Park demonstrated that at least some watersheds in low elevation forests of the Greater Yellowstone Region are characterized by a mixed fire regime wherein some fire events burn stand replacing, some burn as understory burns, still other fires burn as both stand replacing and understory fires, and fire frequency varies substantially through time. However, the statistical properties of fire regimes in the three watersheds are quite similar: all three watersheds have fire return intervals between 20 and 30 years, but the standard deviation, minimum and maximum fire return intervals varied substantially between watersheds and through time.

Regional fire years are related to periodic climate phenomena arising in the Pacific Ocean. The Pacific Decadal Oscillation, or PDO, has a significant influence on drought in Greater Yellowstone, but this effect too is non-stationary. During the mid 1700s, the influence of PDO-length periodicities on local precipitation became insignificant, and during that period the El Niño Southern Oscillation became more important to precipitation variability and significantly influenced fire events in the GYR.

Finally, aside from the effect of elevation, the spatial variability in biophysical variables that influence soil moisture was unrelated to the spatial variability in fire regime. This suggests that, although synoptic climate phenomena that influence precipitation have a deterministic effect on when fires occur, the behavior and thus the effects of fire on the ground can vary markedly. Two fires detected at Soda Butte Creek burned both as understory fires in open Douglas-fir forests and as stand replacing fires in lodgepole pine forests with closer fuel continuity. This may be related to the distribution of fuel moisture during fire events; in years that are dry enough, fuel moisture could be homogenously below the threshold needed to burn and fire propagates easily through different forest types. Forecasting when thresholds of fuel moisture are exceeded homogeneously across the landscape may be the single most important predictive effort in determining fire spread and the effects of fire on a variety of ecological processes.

These results suggest that the variability in climate and its relationship to variability in fire regime are more important to the characterization of fire in a spatiotemporal context than mean fire return interval. Fire, like any ecological process with a suite of non-linear interacting drivers that produce feedbacks, does not conform to normal distributions and varies significantly in both space an time. Lower elevation forests of the Greater Yellowstone Region are therefore in a constant state of transition; there is no equilibrium and therefore the mean fire return interval, as well as the concept of natural range of variability, must be evaluated in the context of current ecosystem structure and climate trajectories.

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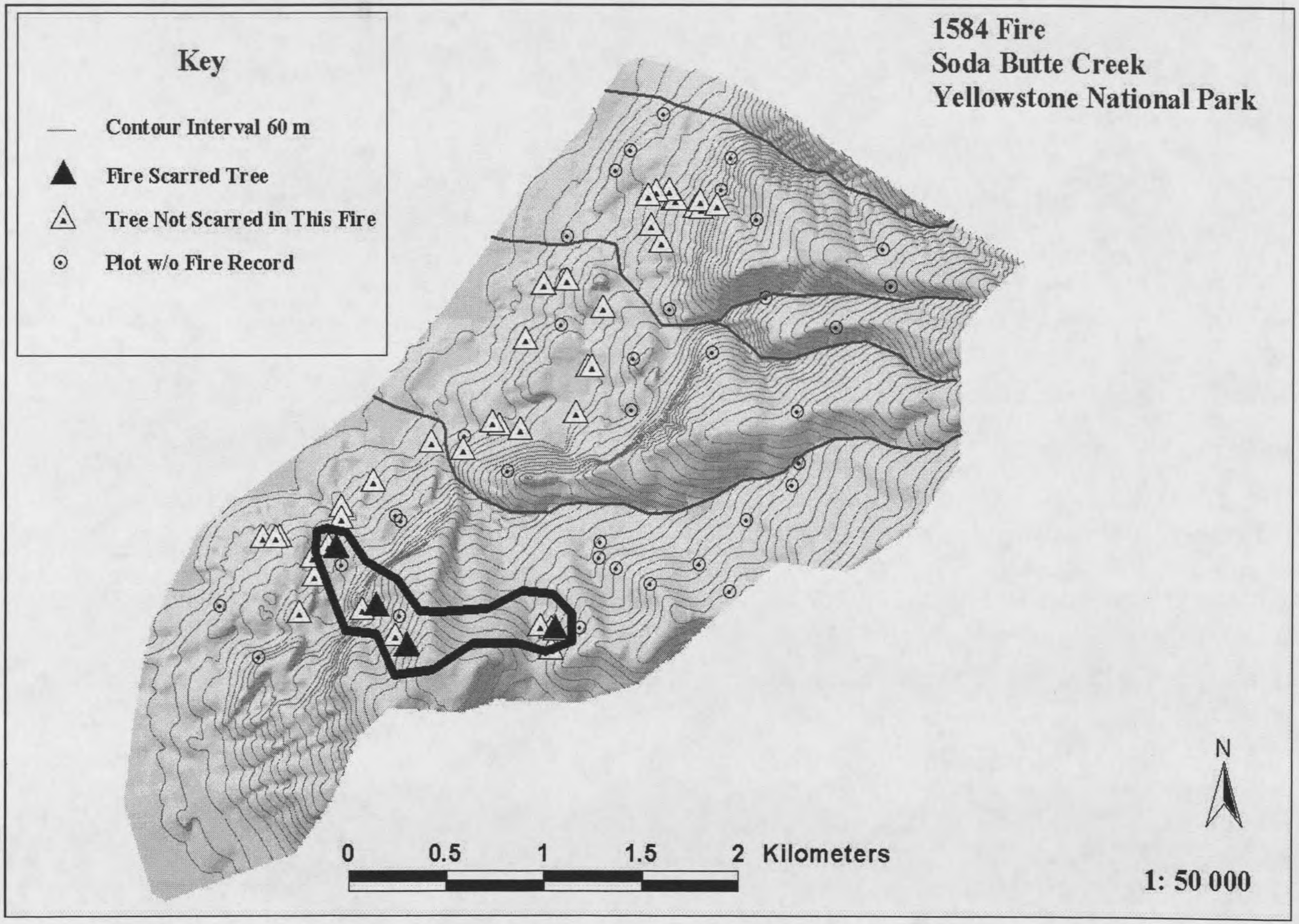
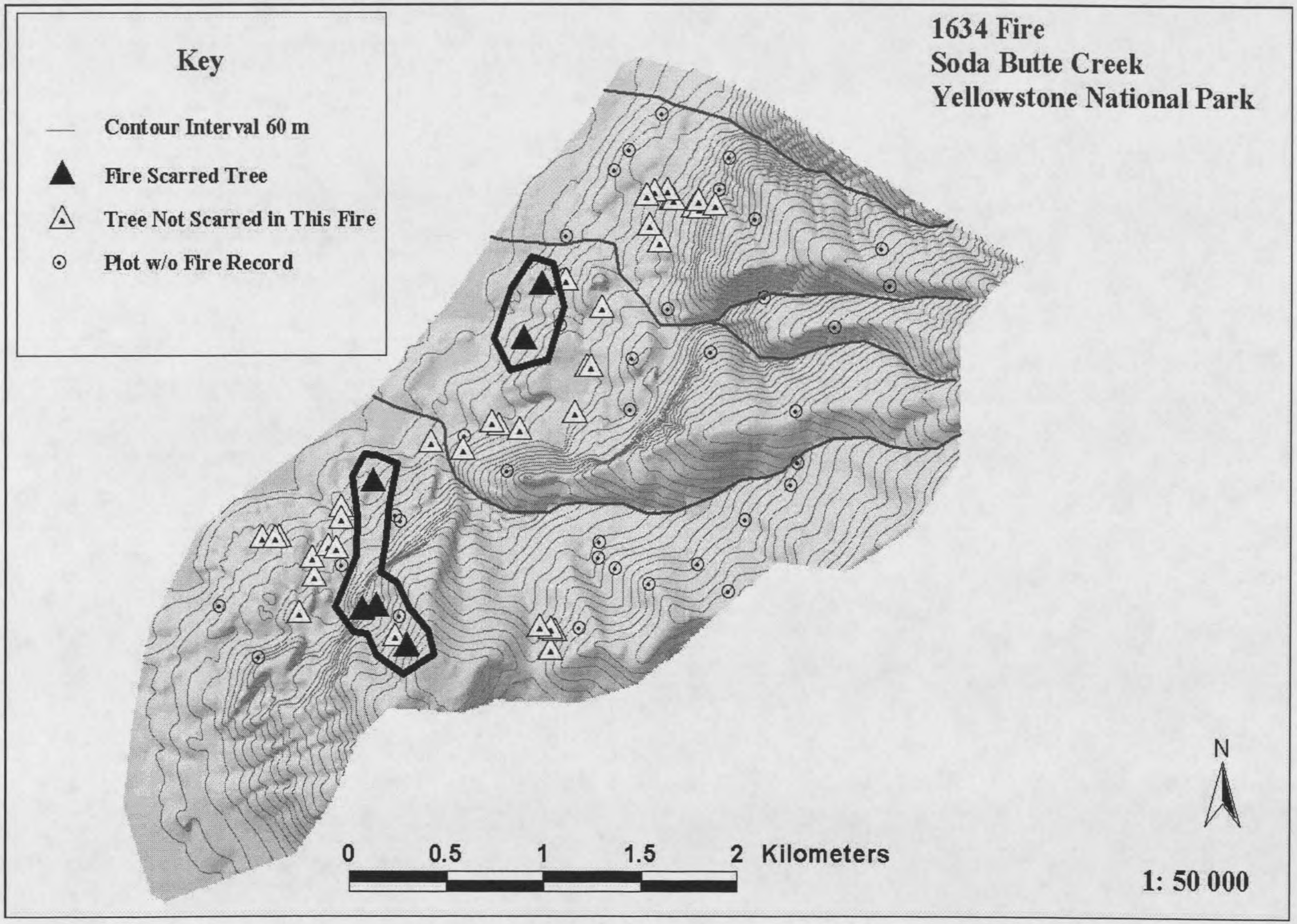
APPENDICES

APPENDIX A

FIRE PERIMETER MAPS


Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
1584 Fire
Soda Butte Creek
Yellowstone National Park
0 0.5 1 1.5 2 Kilometers
N
1: 50 000


1634 Fire
Soda Butte Creek
Yellowstone National Park
Key
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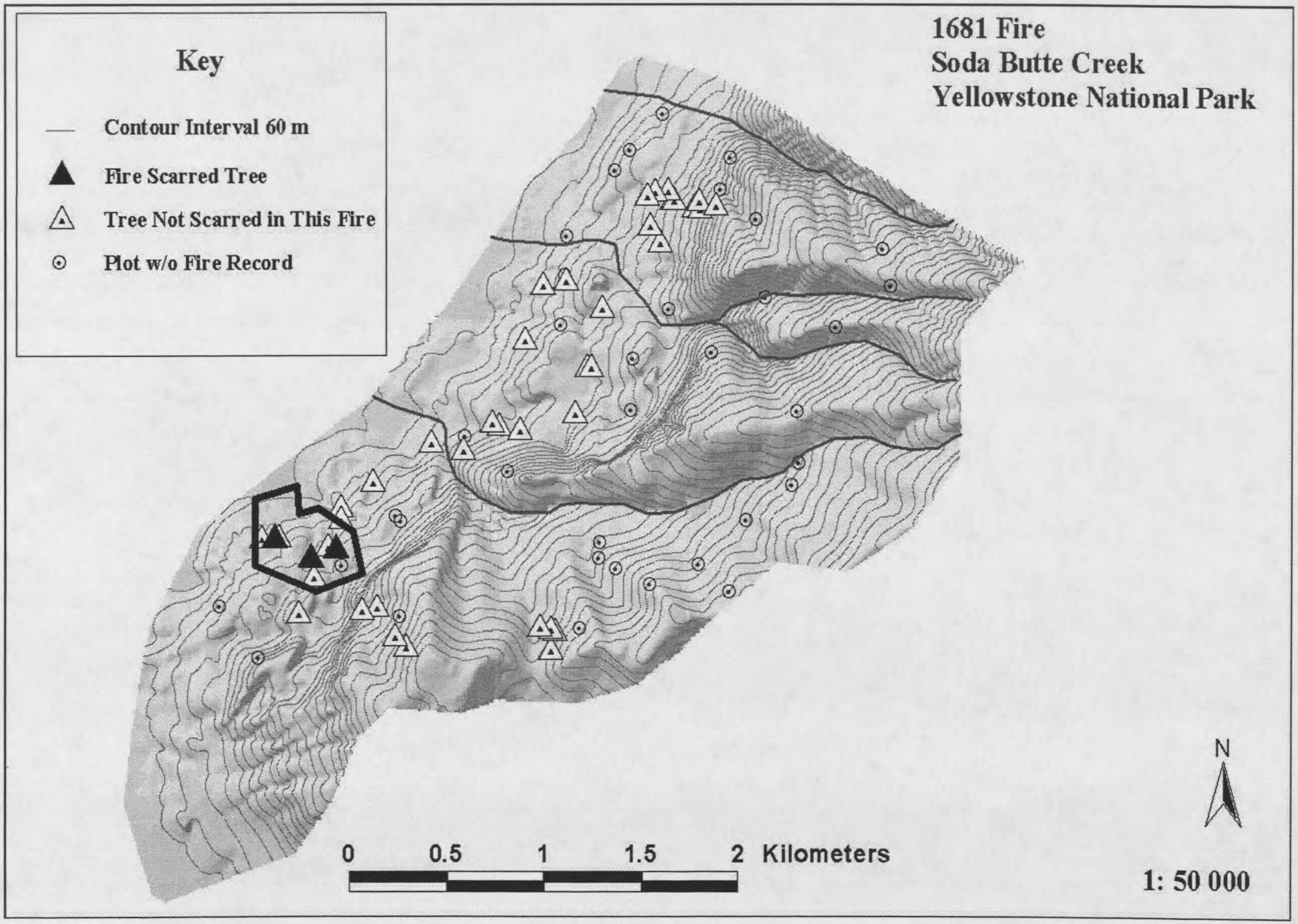
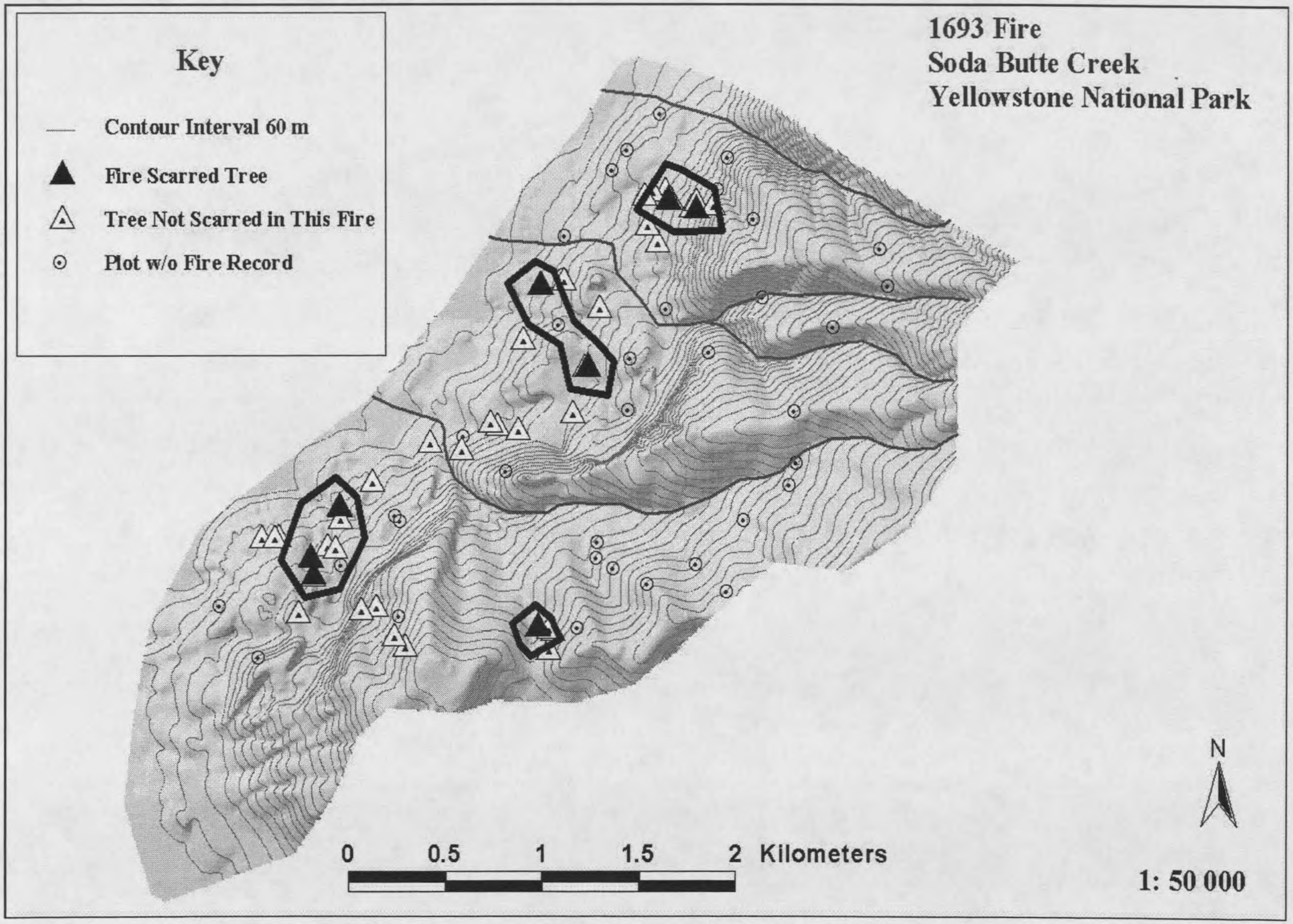
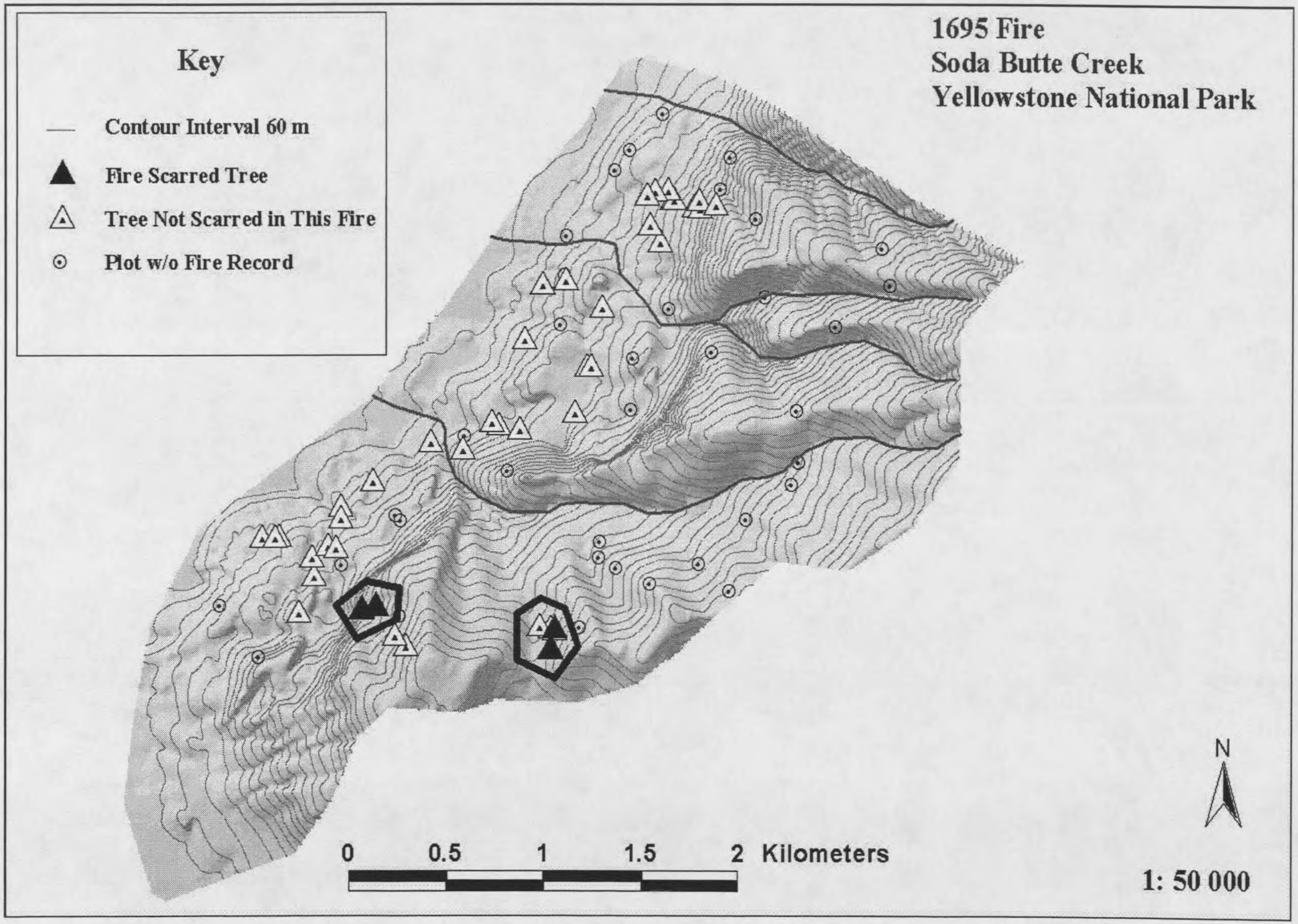
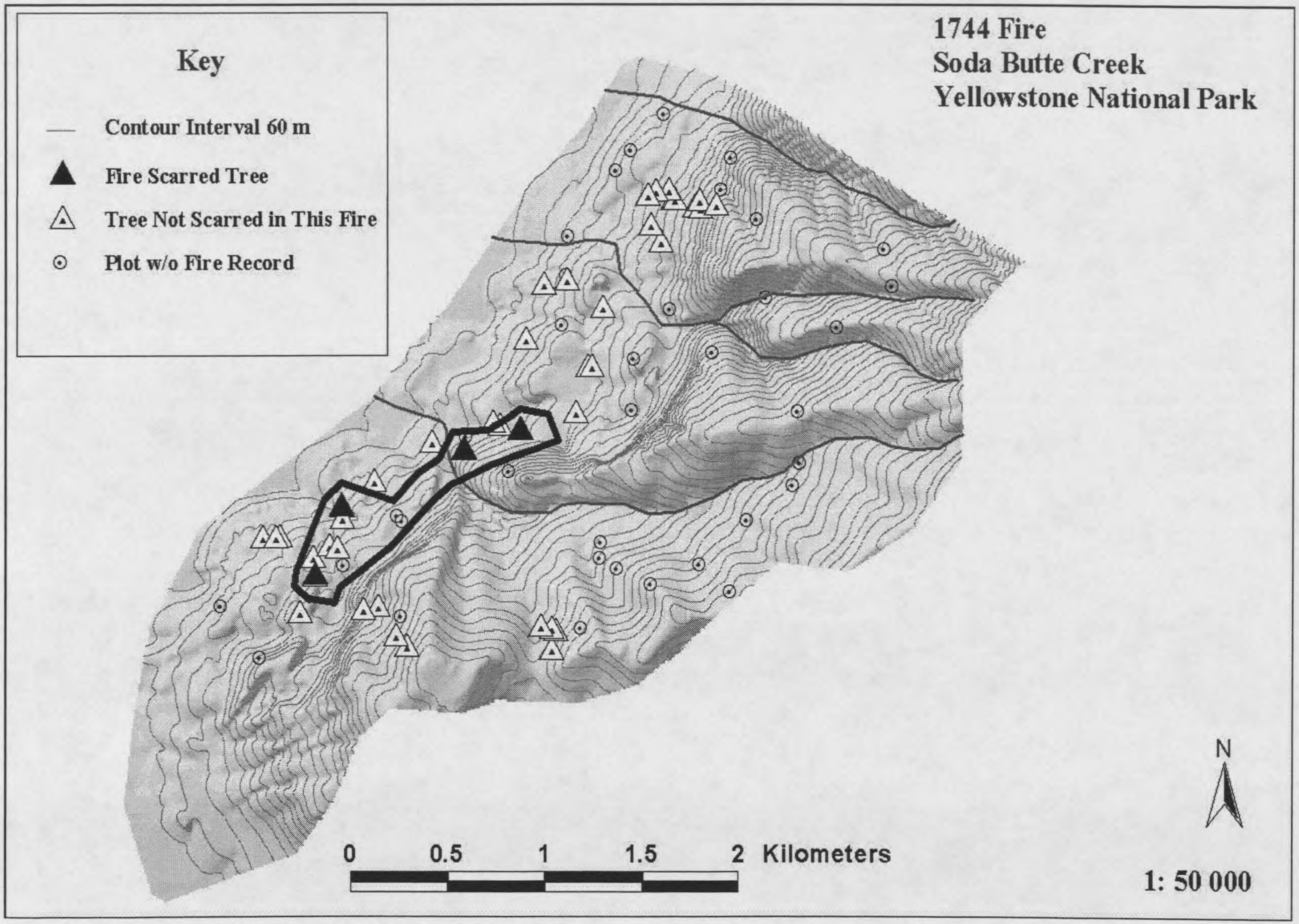
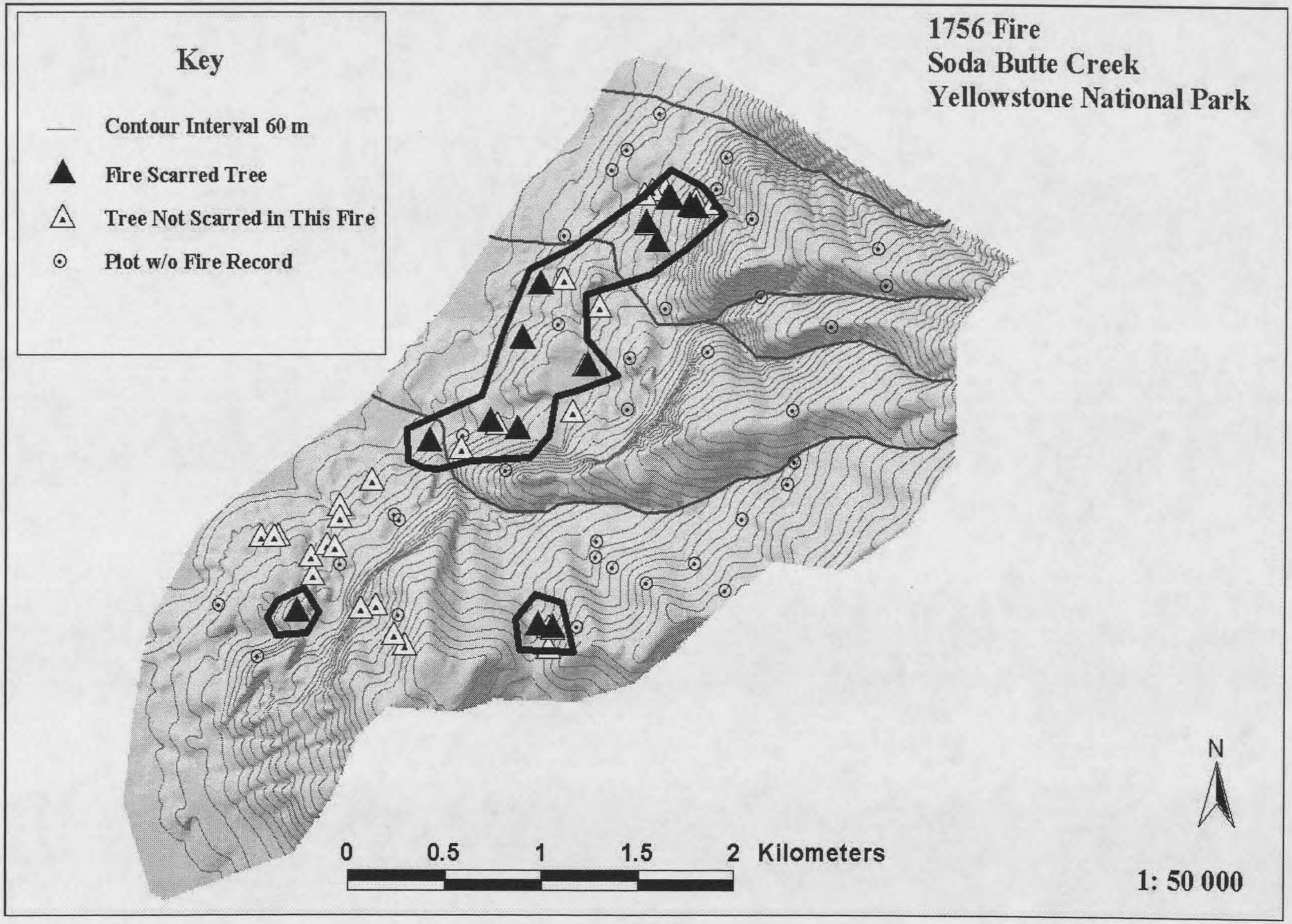
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
0 0.5 1 1.5 2 Kilometers
N
1: 50 000

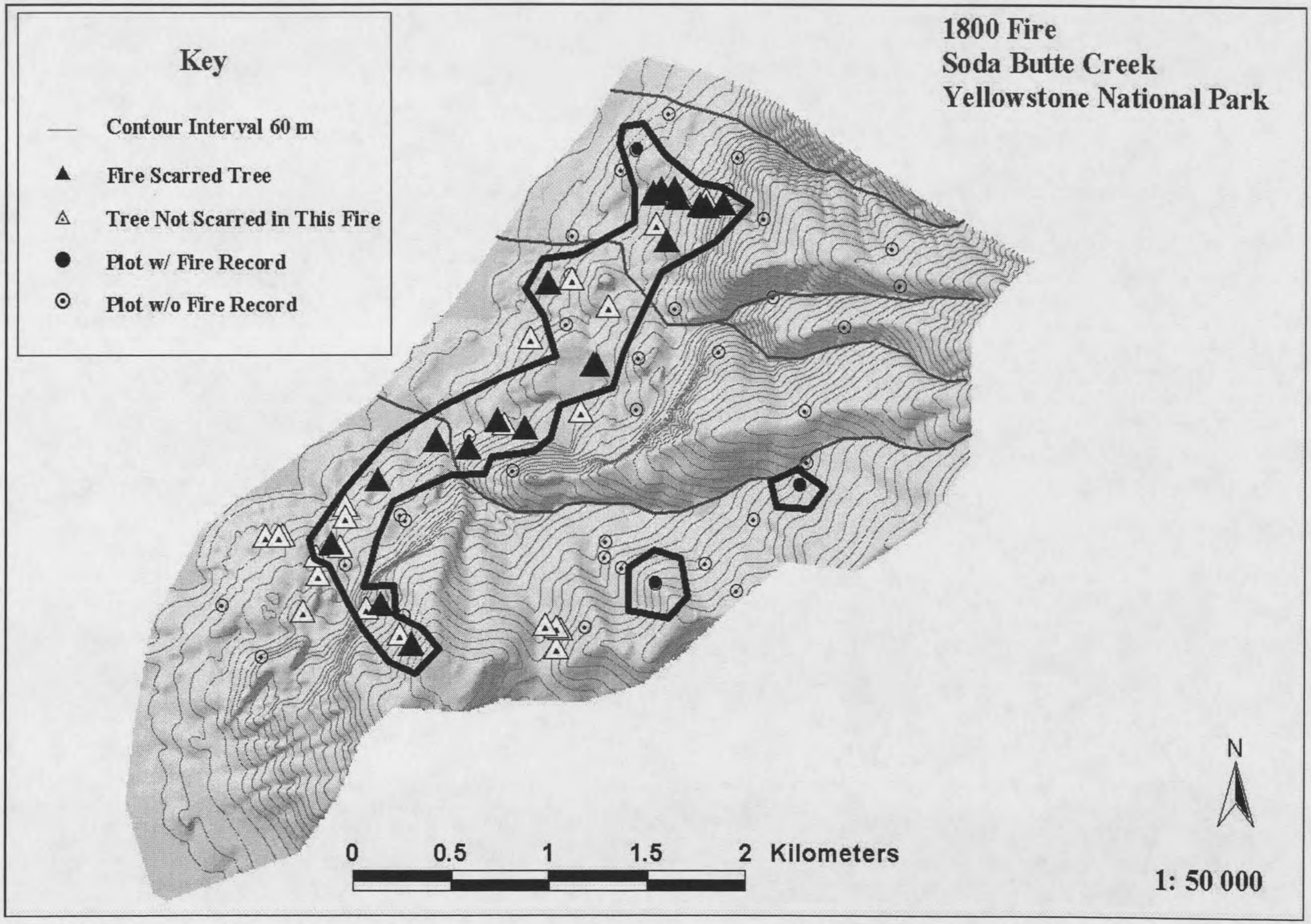

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
1681 Fire
Soda Butte Creek
Yellowstone National Park
N
0 0.5 1 1.5 2 Kilometers
1: 50 000

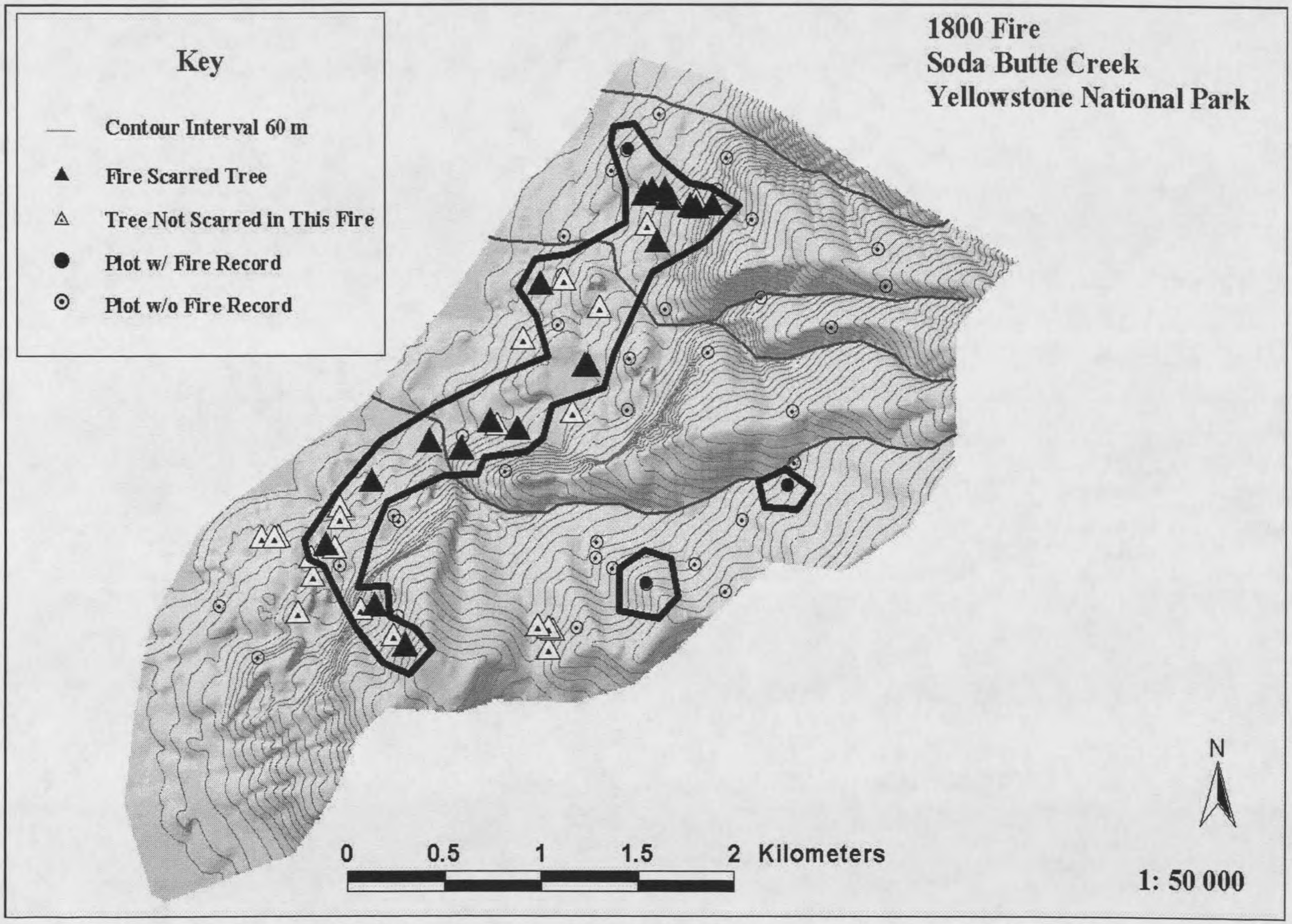

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
1693 Fire
Soda Butte Creek
Yellowstone National Park
0
0.5
1
1.5
2 Kilometers
N
1: 50 000

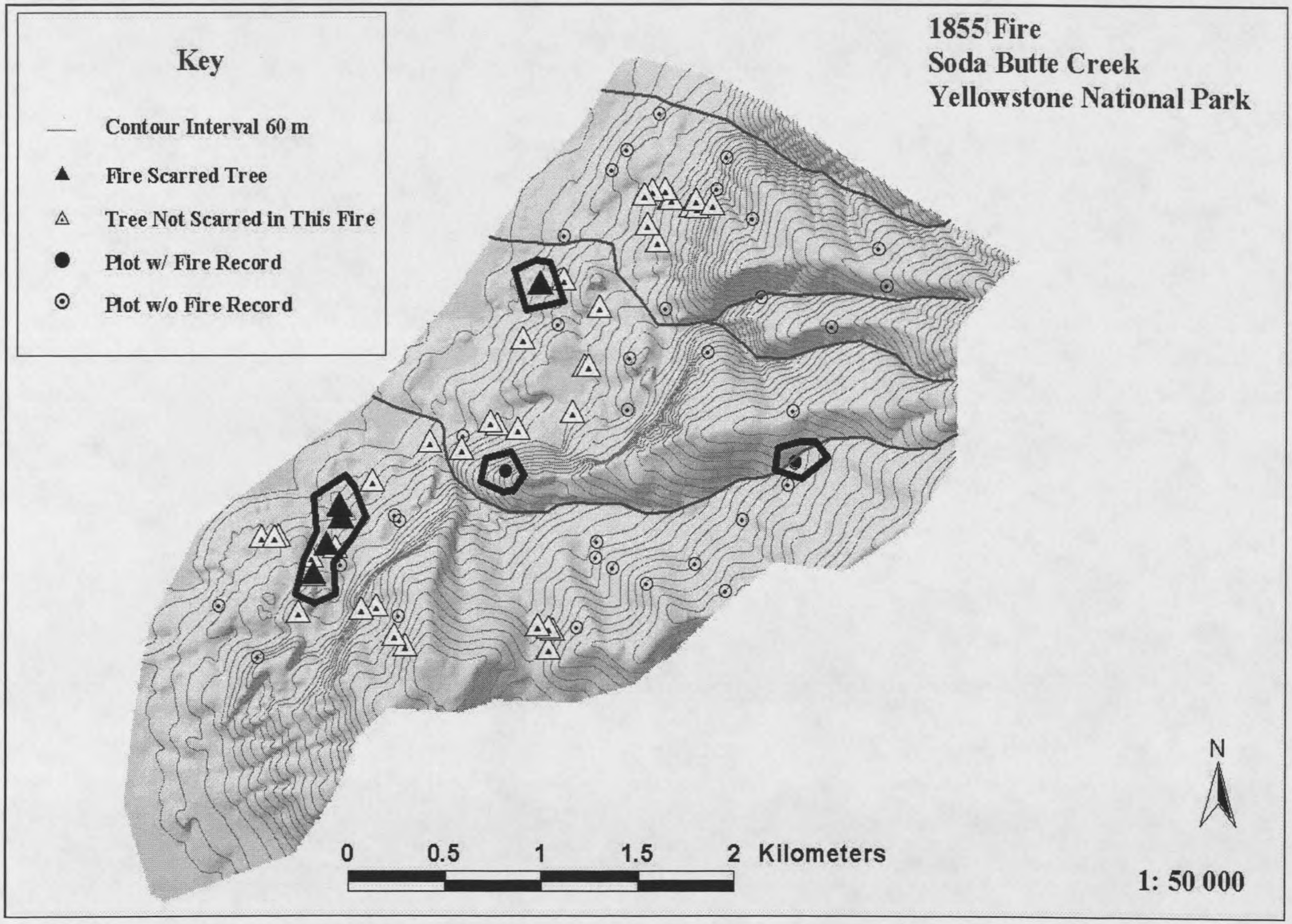

1695 Fire
Soda Butte Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
0 0.5 1 1.5 2 Kilometers
N
1: 50 000

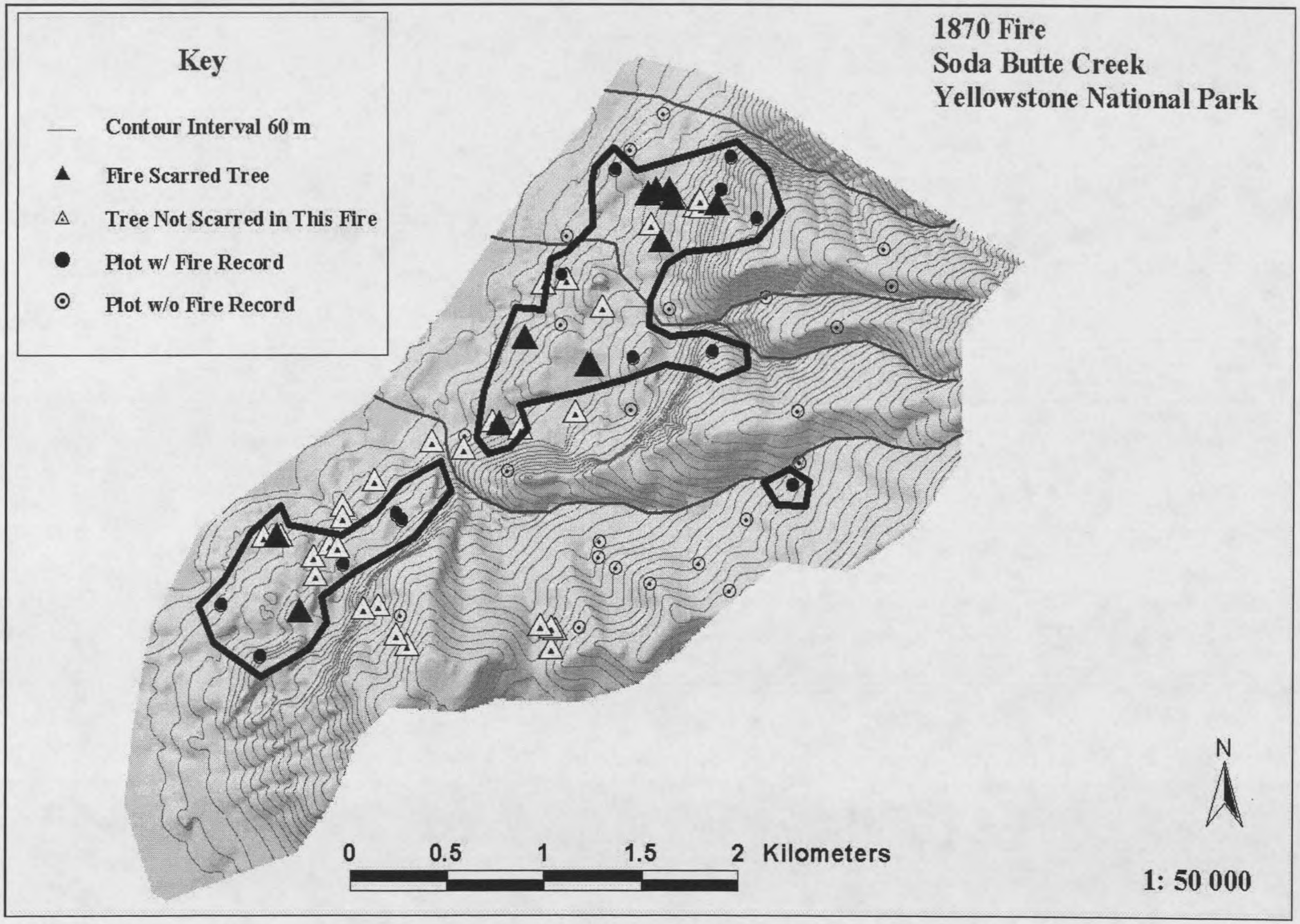

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
1744 Fire
Soda Butte Creek
Yellowstone National Park
N
0 0.5 1 1.5 2 Kilometers
1: 50 000

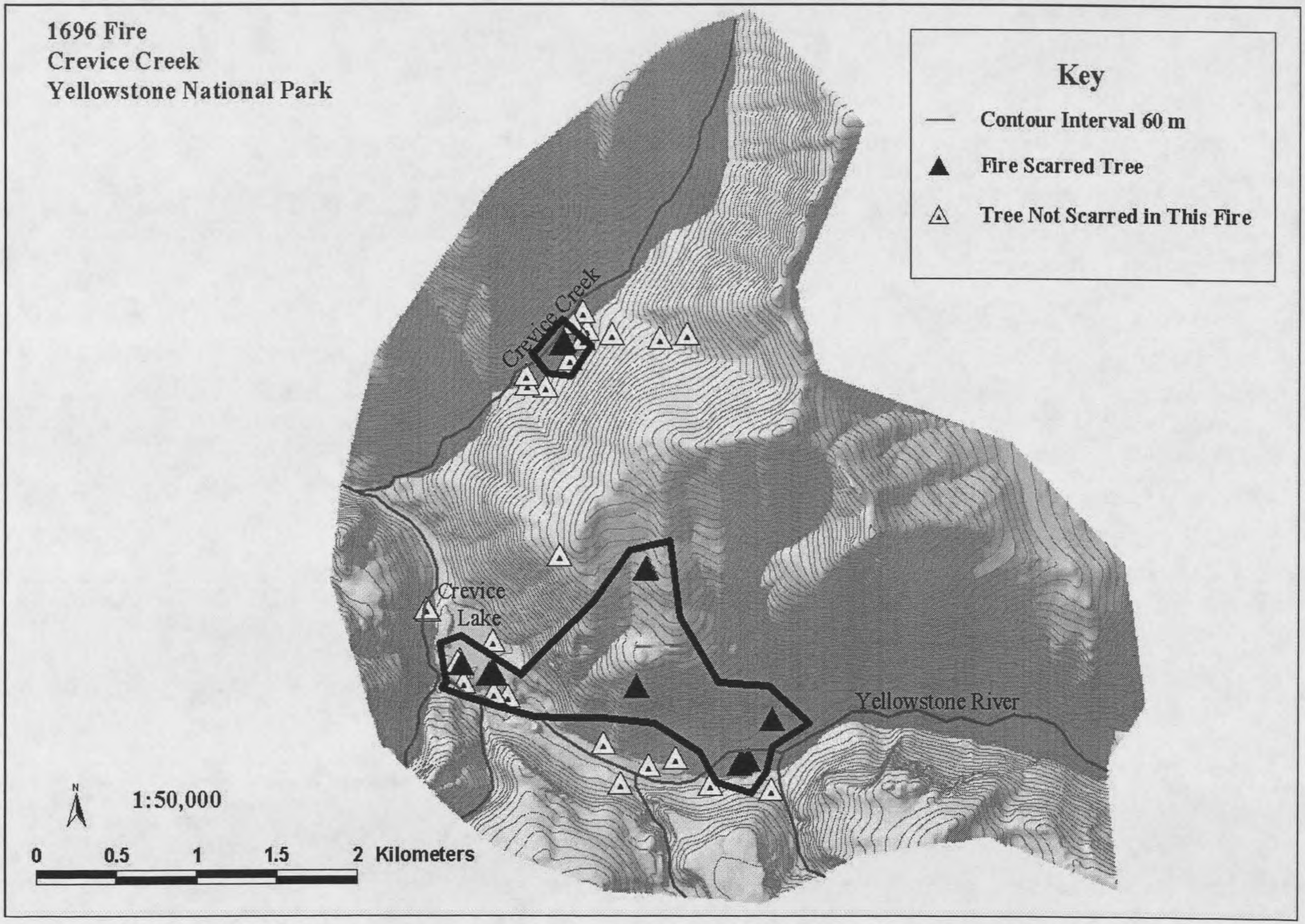

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/o Fire Record
1756 Fire
Soda Butte Creek
Yellowstone National Park
N
0 0.5 1 1.5 2 Kilometers
1: 50 000

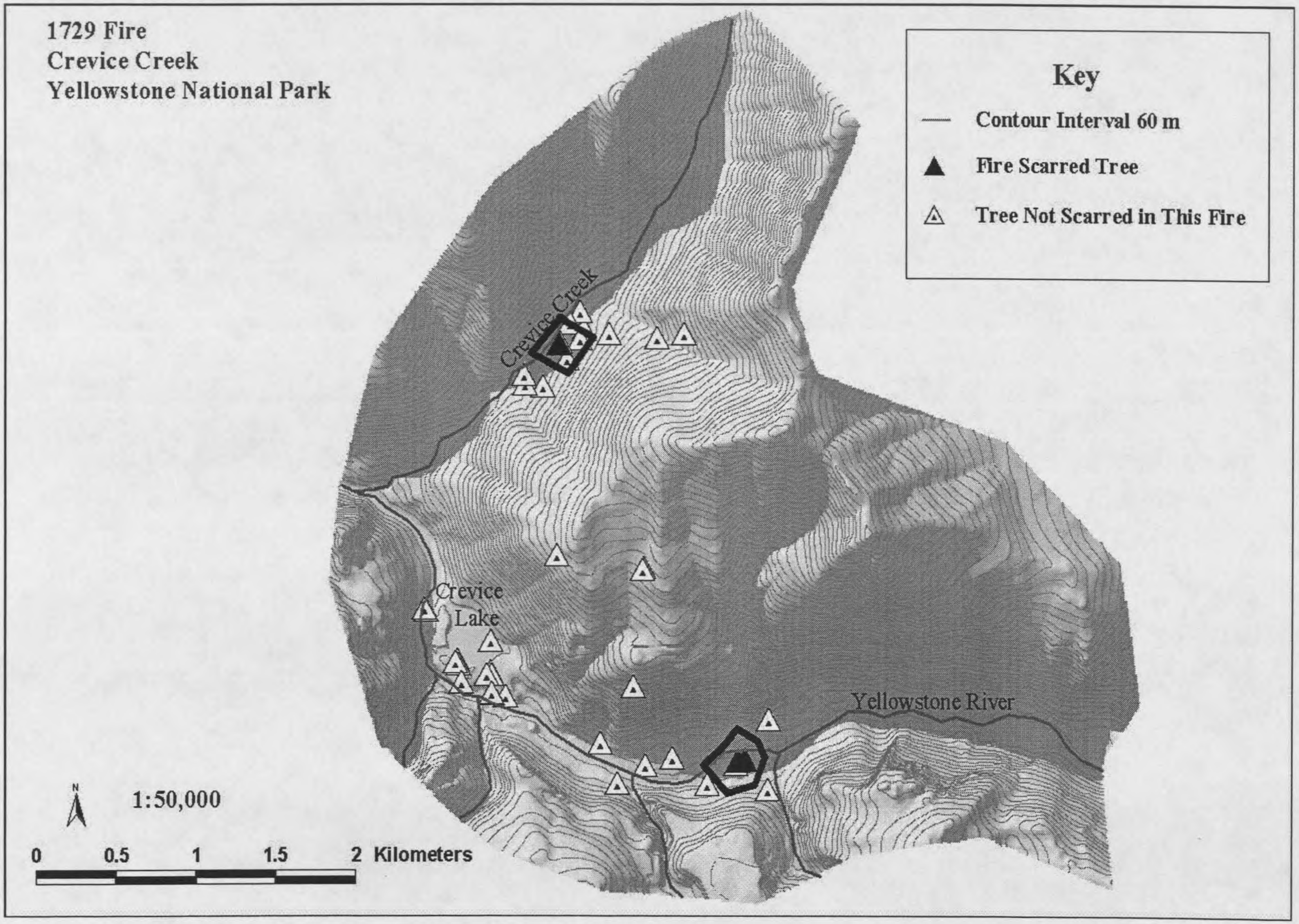

1800 Fire
Soda Butte Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/ Fire Record
Plot w/o Fire Record
N
0
0.5
1
1.5
2 Kilometers
1: 50 000

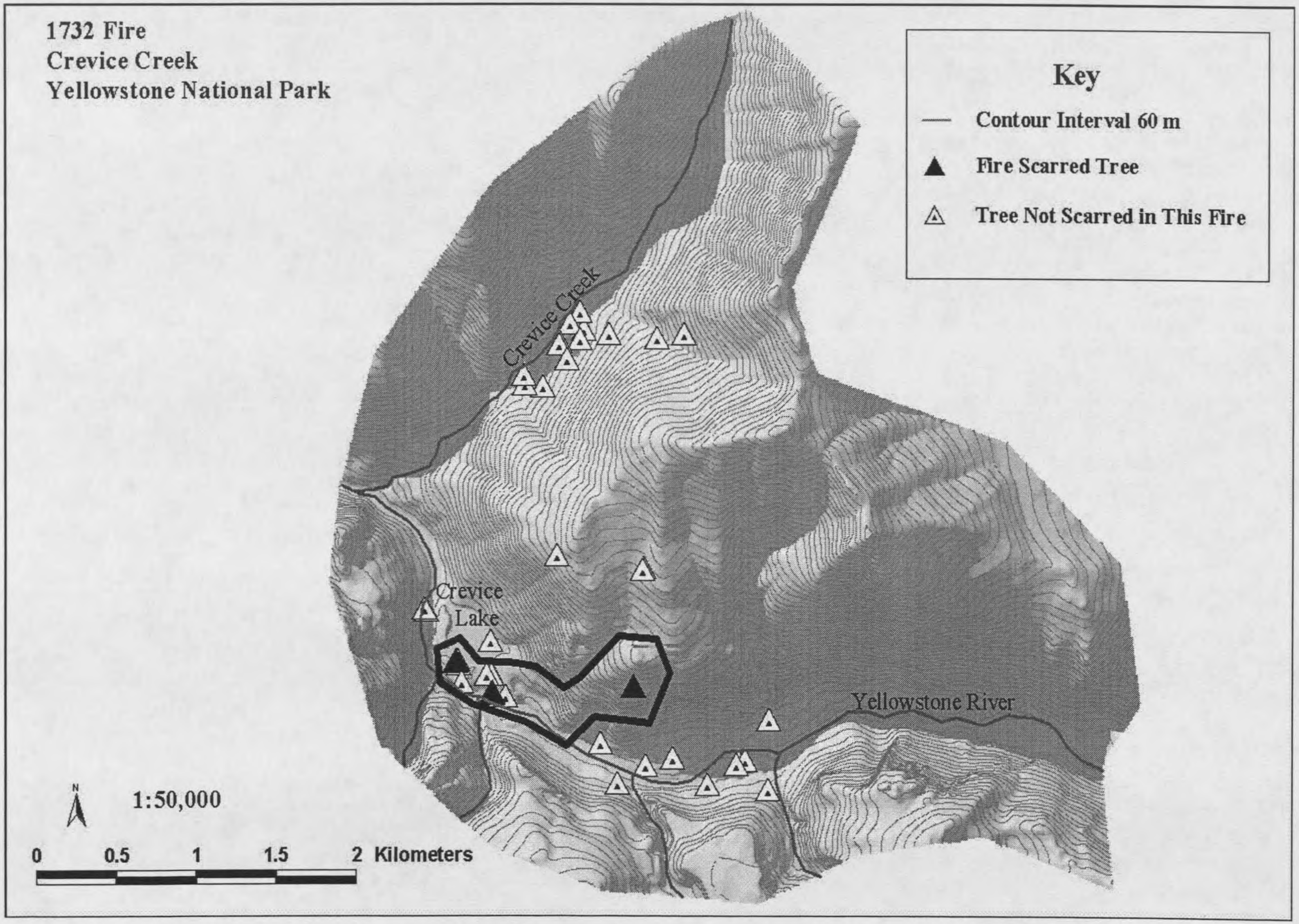

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/ Fire Record
Plot w/o Fire Record
1800 Fire
Soda Butte Creek
Yellowstone National Park
N
0
0.5
1
1.5
2 Kilometers
1: 50 000

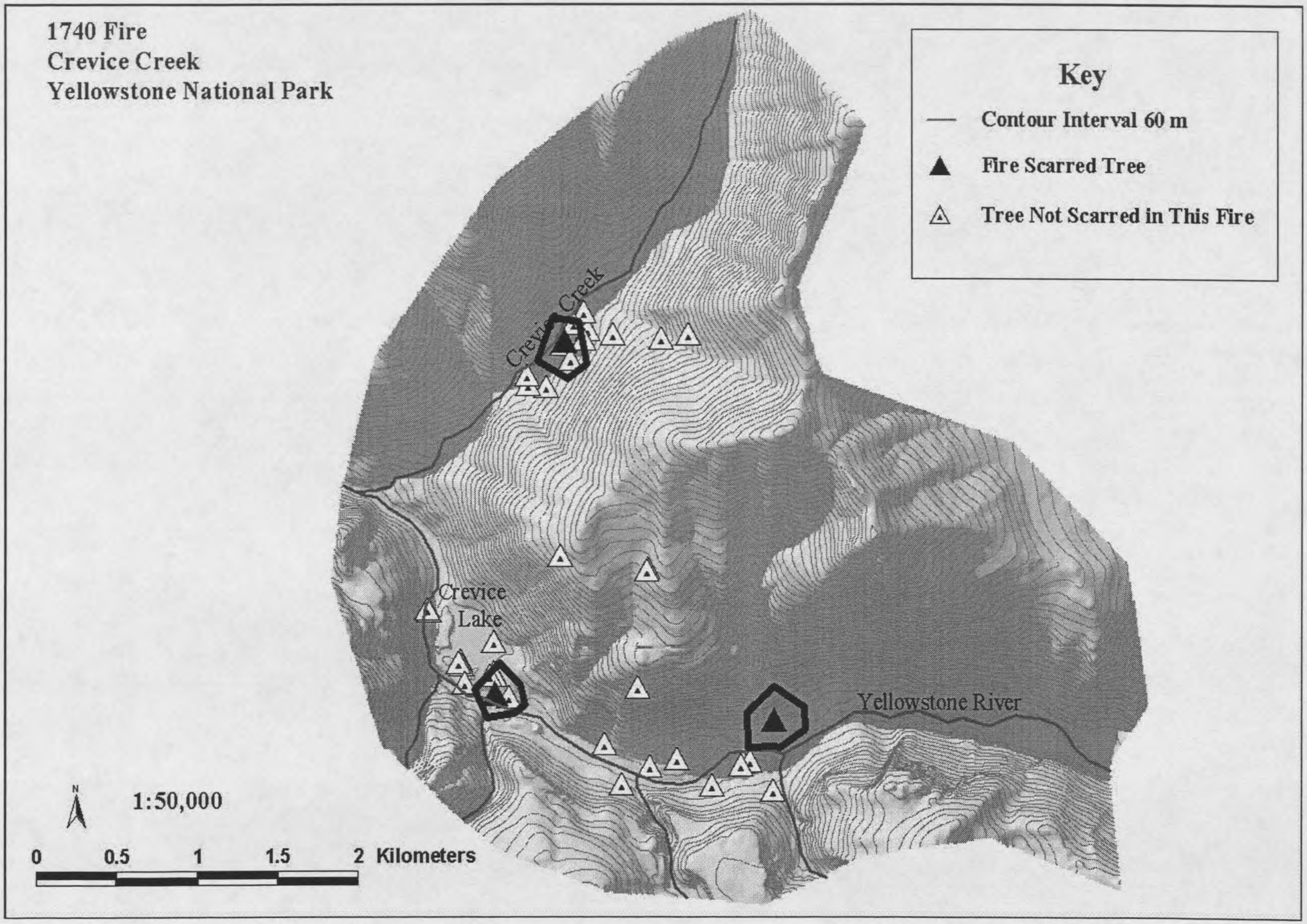

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/ Fire Record
Plot w/o Fire Record
1855 Fire
Soda Butte Creek
Yellowstone National Park
N
0 0.5 1 1.5 2 Kilometers
1: 50 000

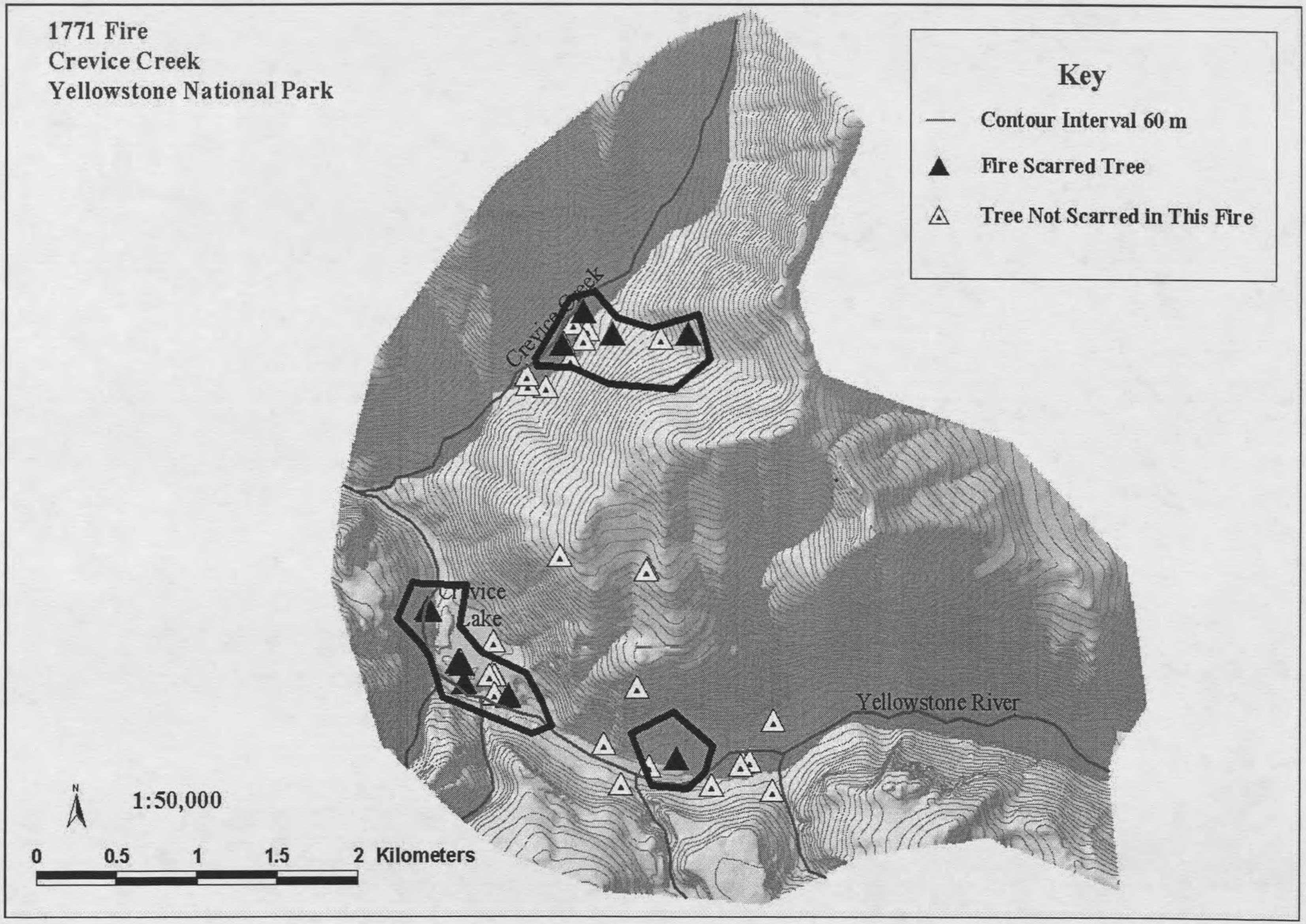

Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Plot w/ Fire Record
Plot w/o Fire Record
1870 Fire
Soda Butte Creek
Yellowstone National Park
0
0.5
1
1.5
2 Kilometers
N
1: 50 000

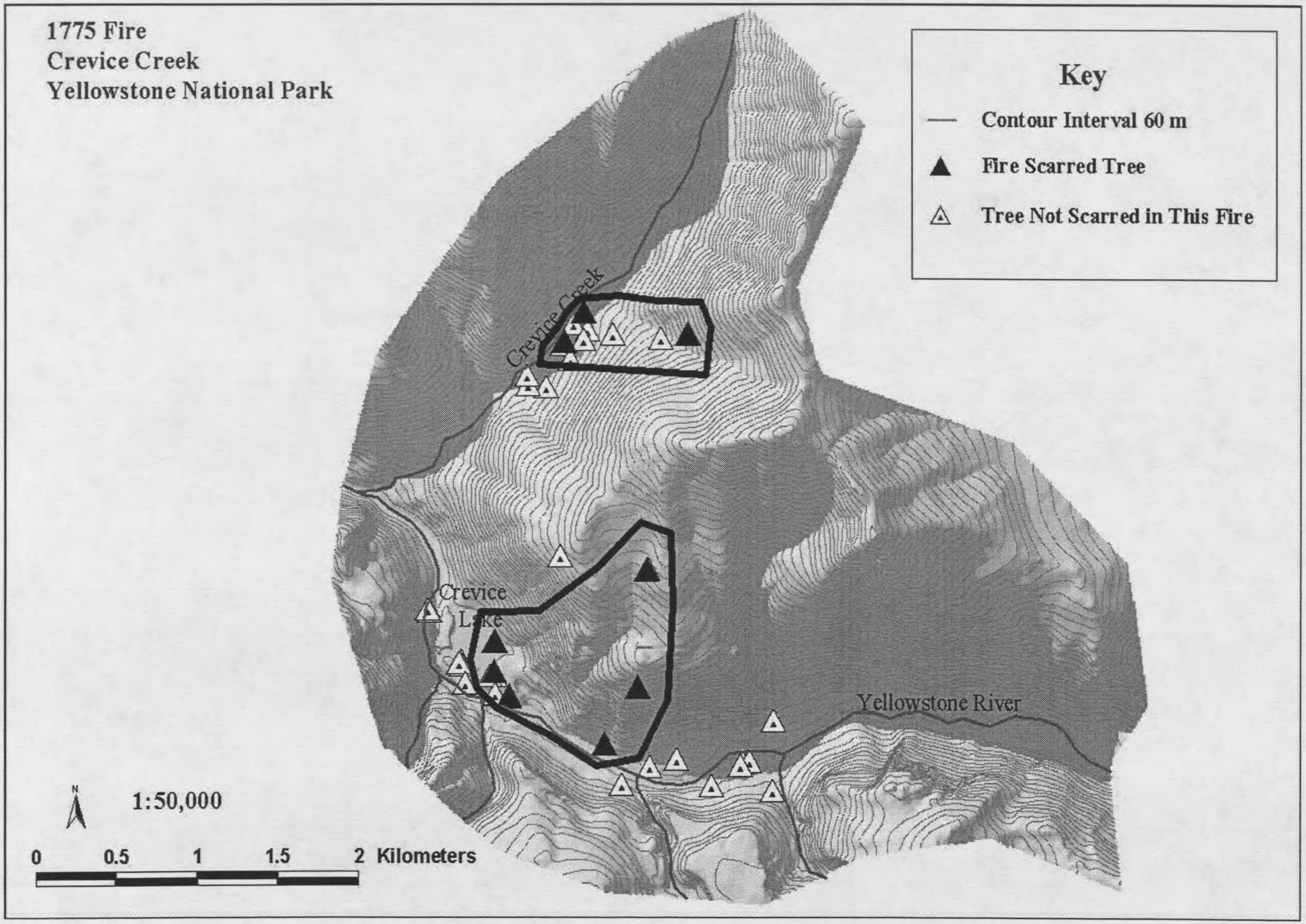

1696 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice
Lake
Yellowstone River
1:50,000
0 0.5 1 1.5 2 Kilometers

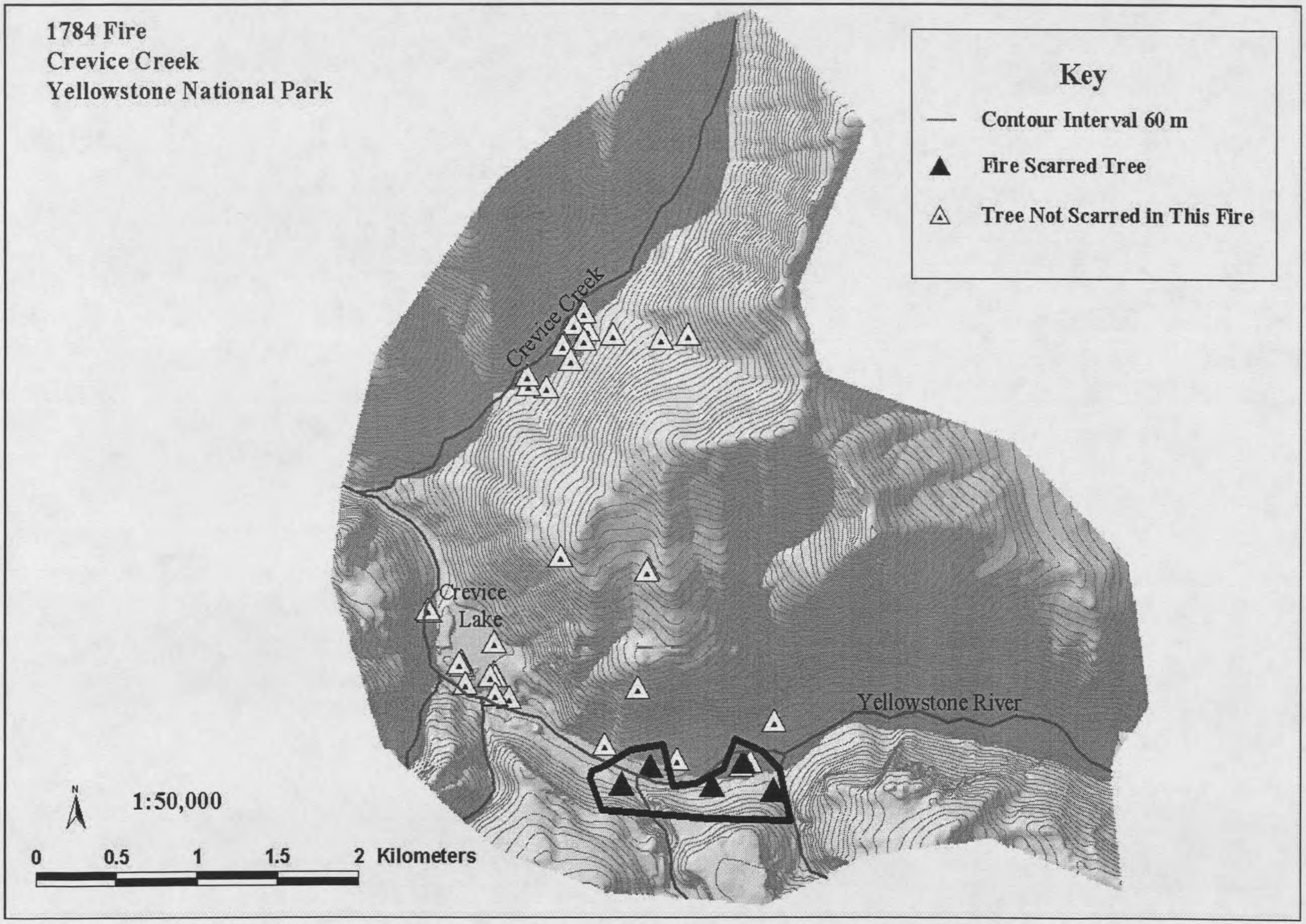

1729 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
N
1:50,000
0 0.5 1 1.5 2 Kilometers

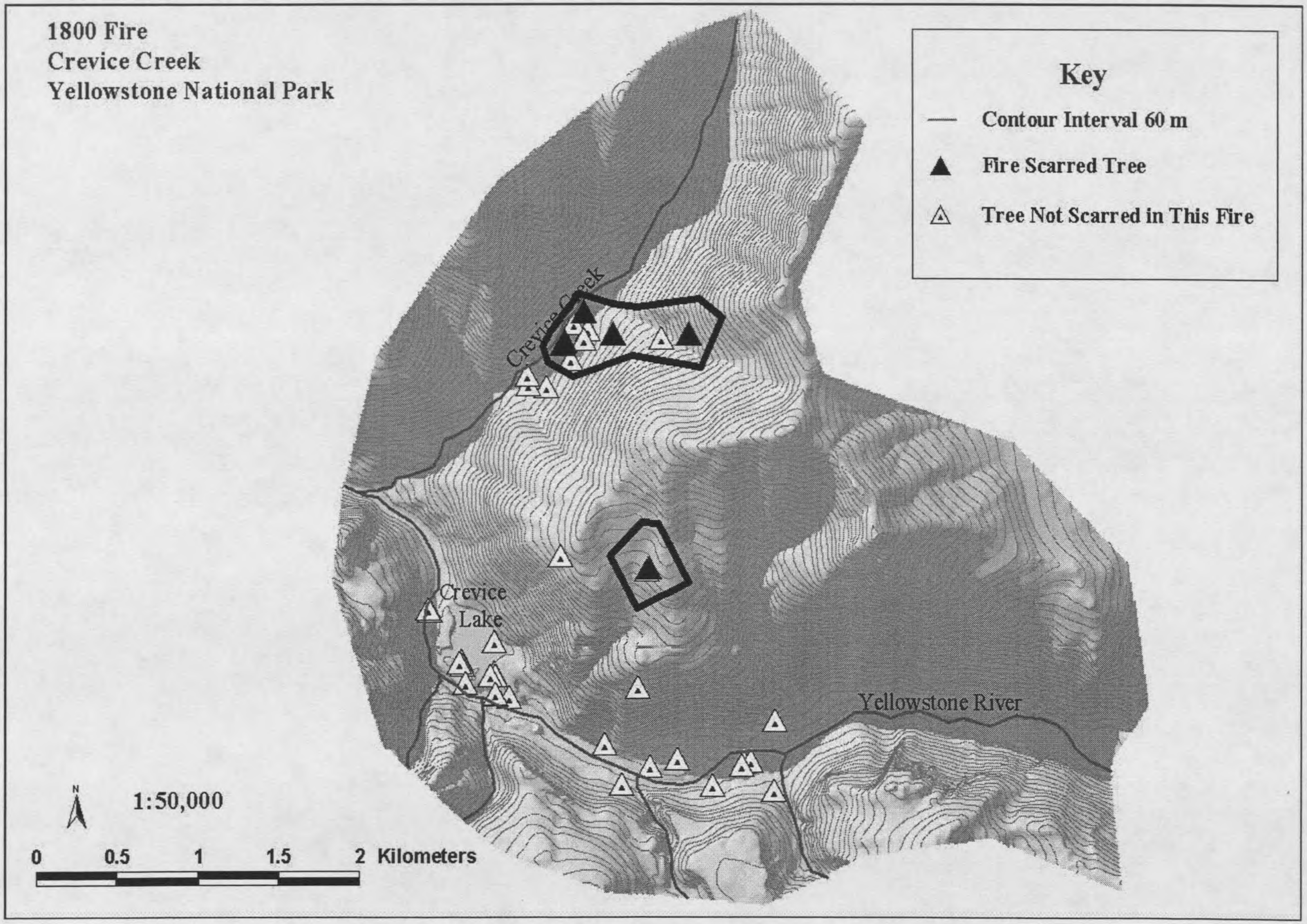

1732 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
1:50,000
N
0 0.5 1 1.5 2 Kilometers

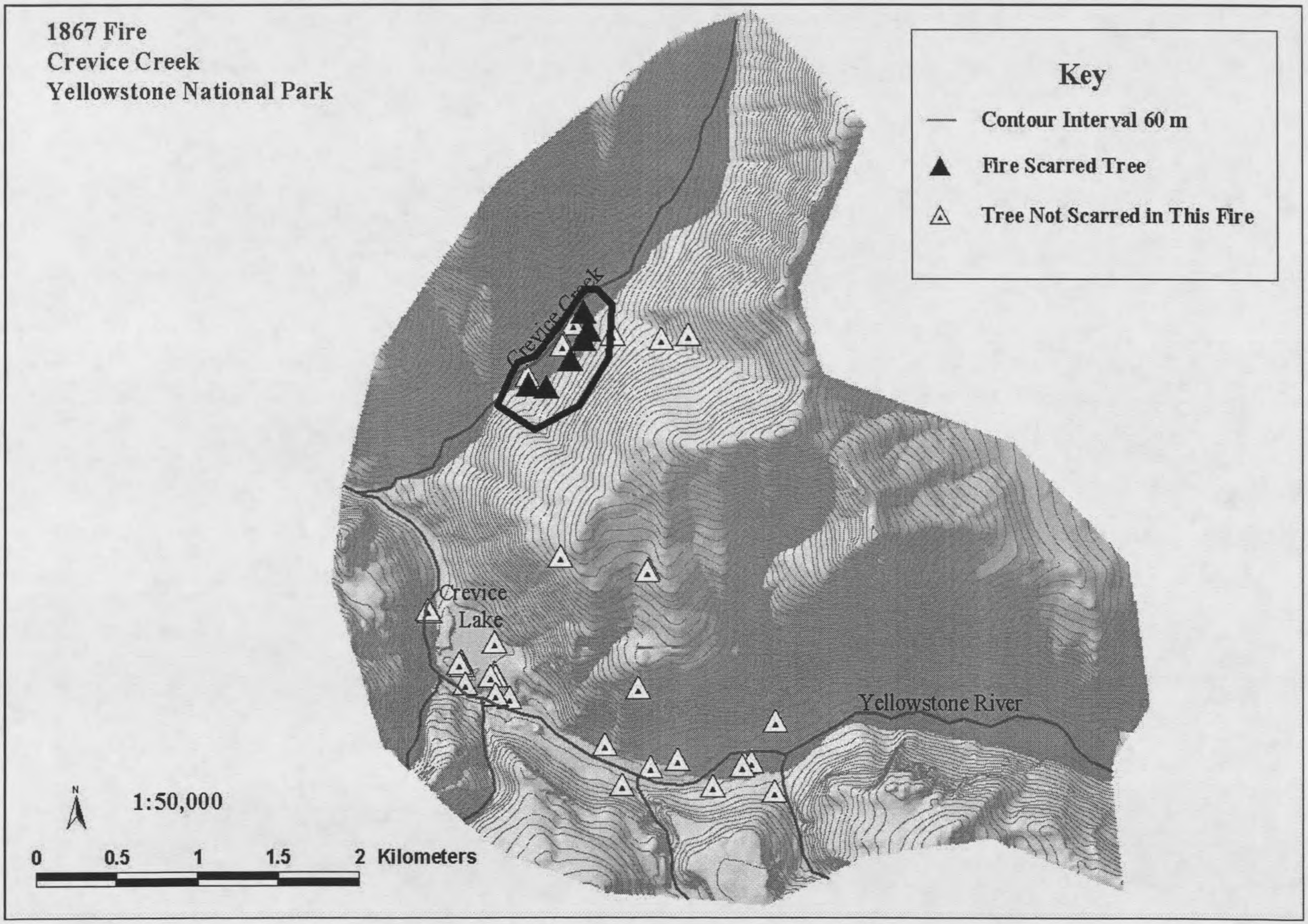

1740 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice
Lake
Yellowstone River
N
1:50,000
0 0.5 1 1.5 2 Kilometers

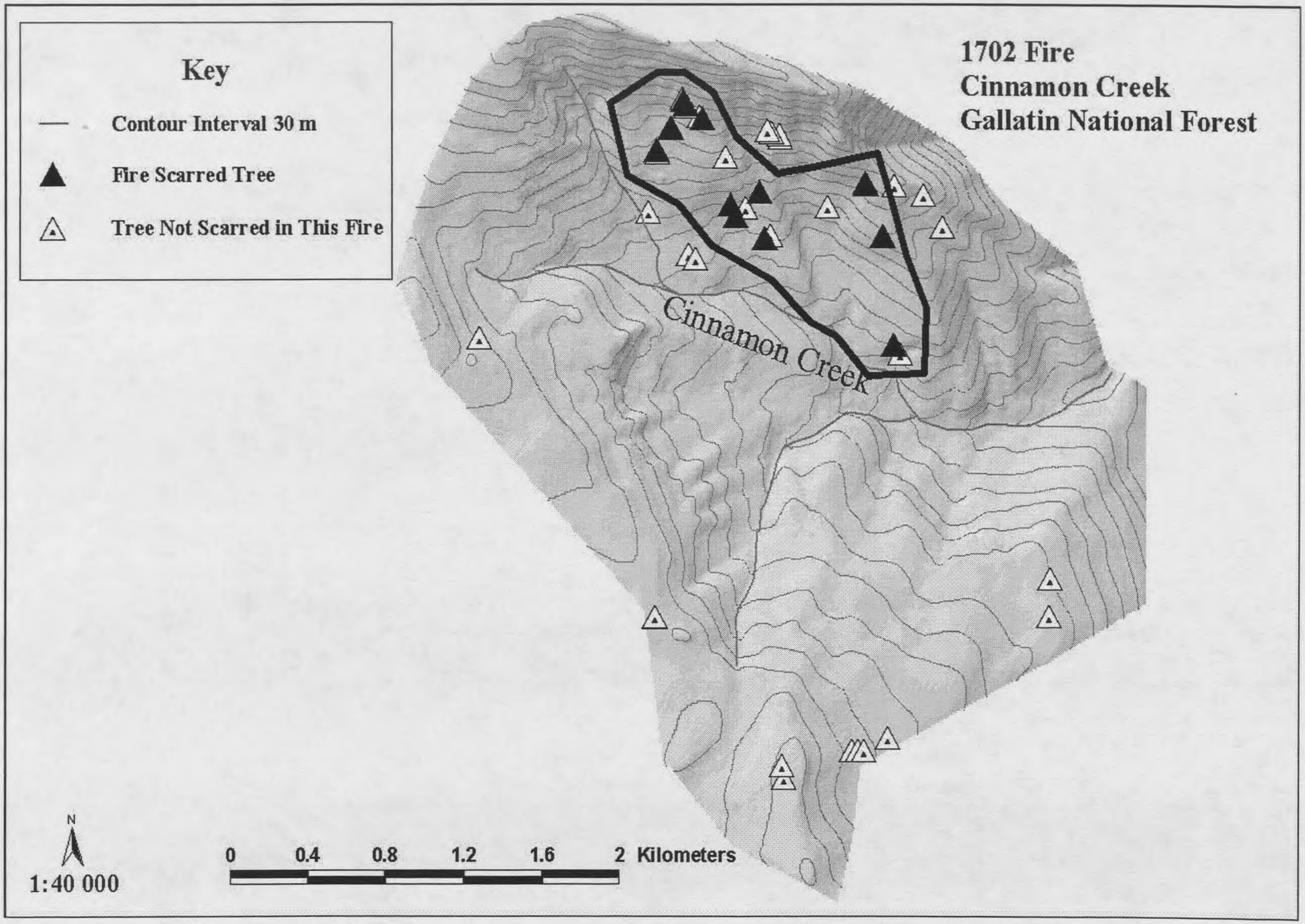

1771 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
N
1:50,000
0
0.5
1
1.5
2 Kilometers

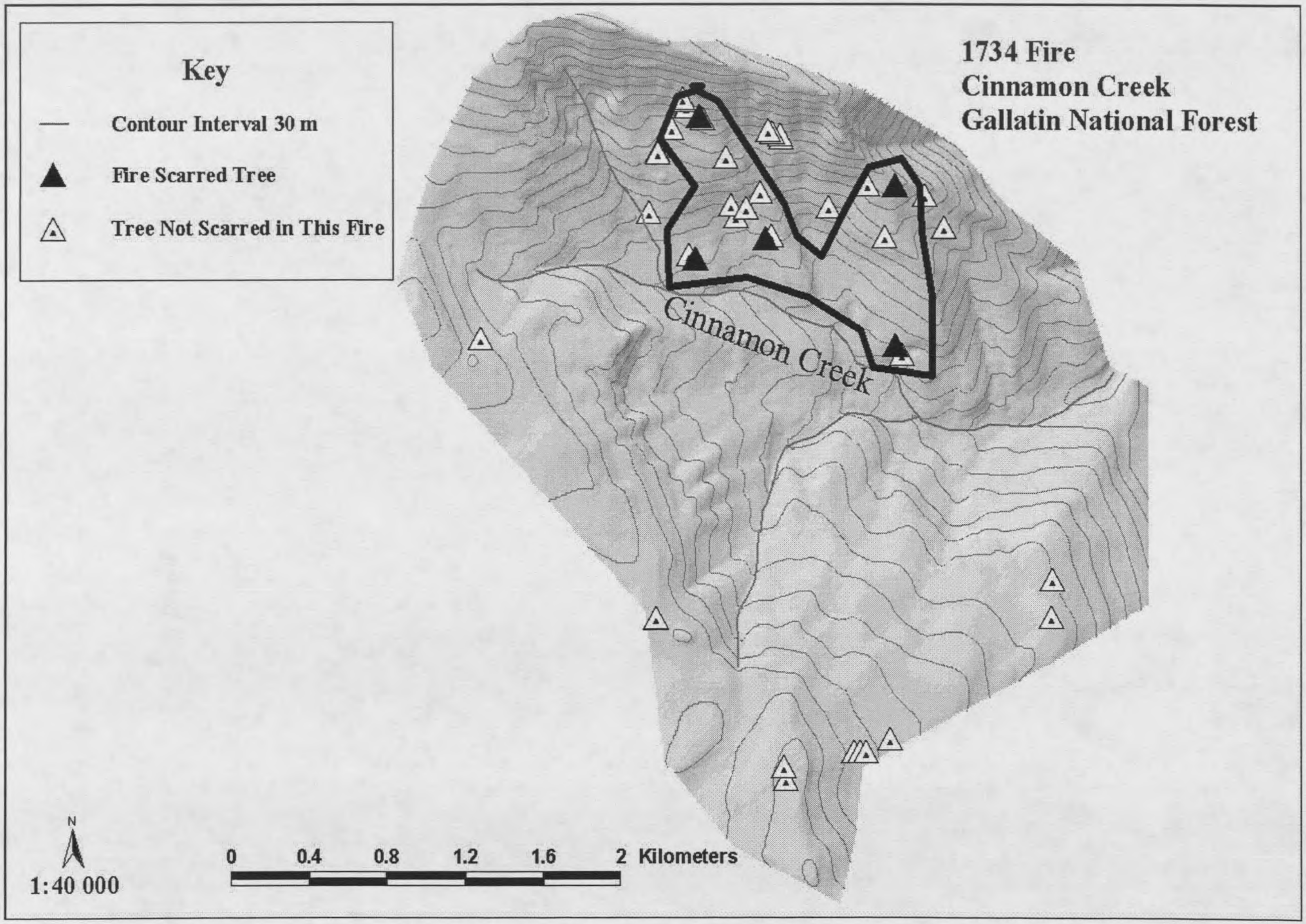

1775 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
N
1:50,000
0 0.5 1 1.5 2 Kilometers


1784 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
1:50,000
0 0.5 1 1.5 2 Kilometers

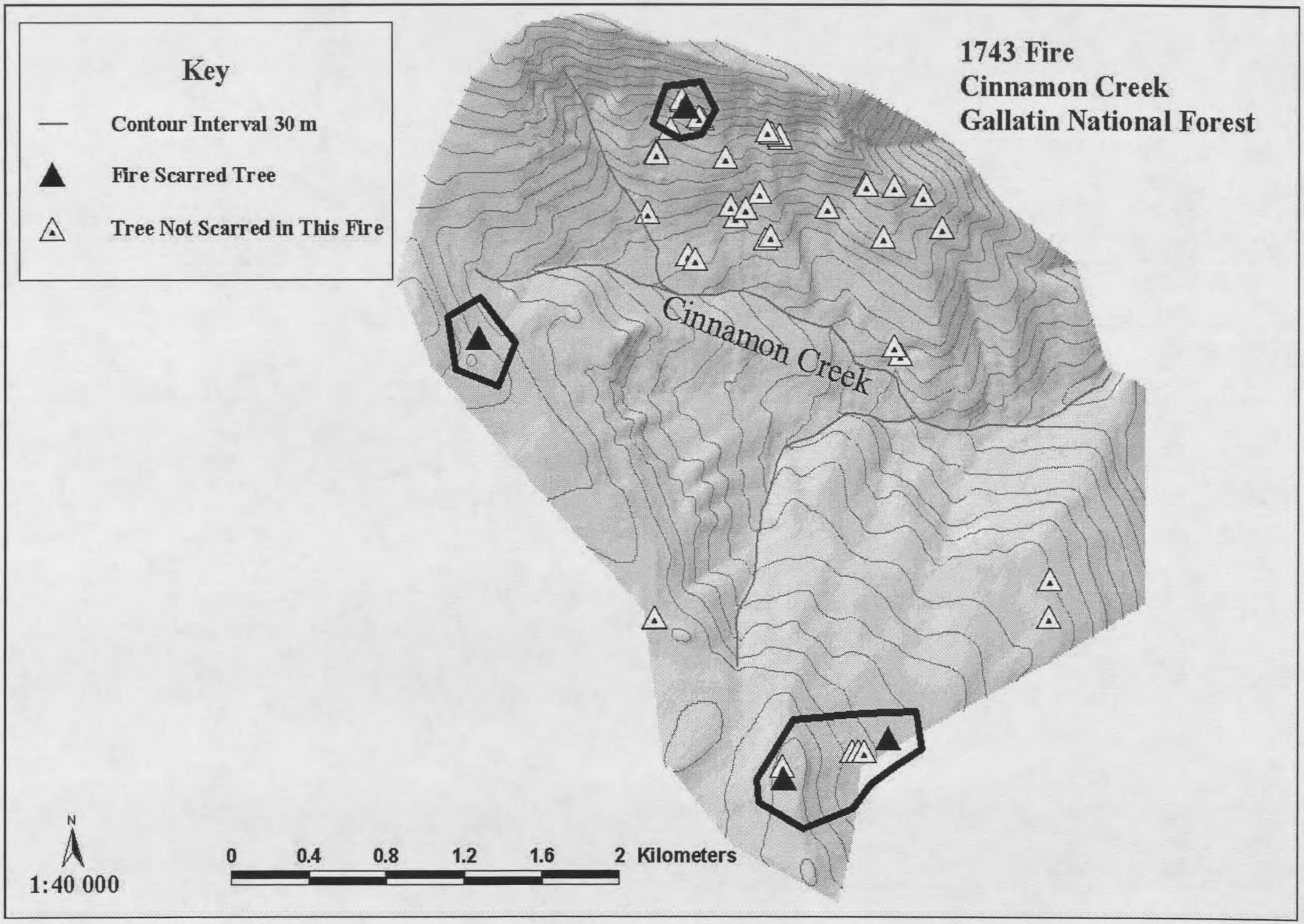

1800 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
N
1:50,000
0 0.5 1 1.5 2 Kilometers

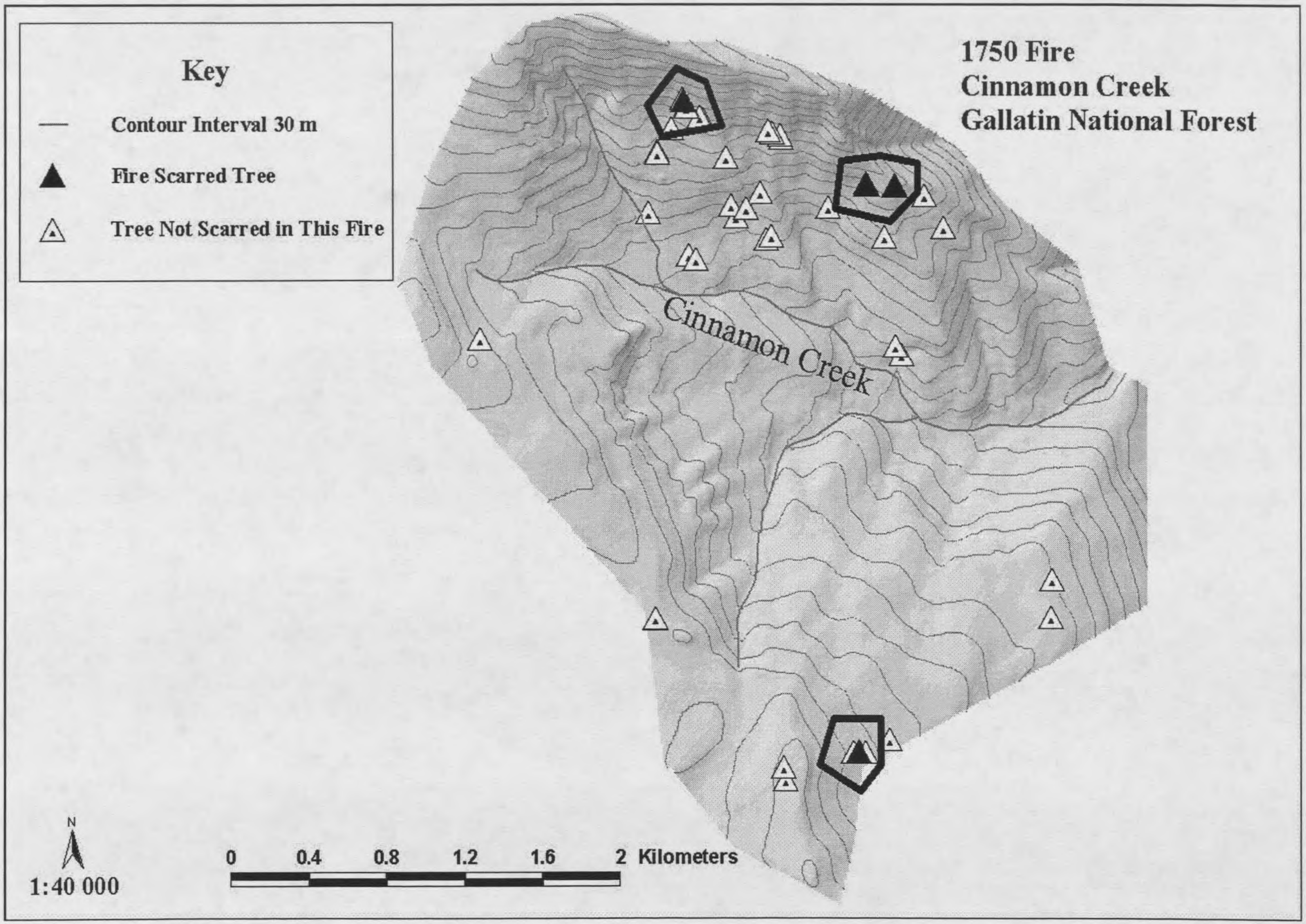

1867 Fire
Crevice Creek
Yellowstone National Park
Key
Contour Interval 60 m
Fire Scarred Tree
Tree Not Scarred in This Fire
Crevice Creek
Crevice Lake
Yellowstone River
N
1:50,000
0 0.5 1 1.5 2 Kilometers

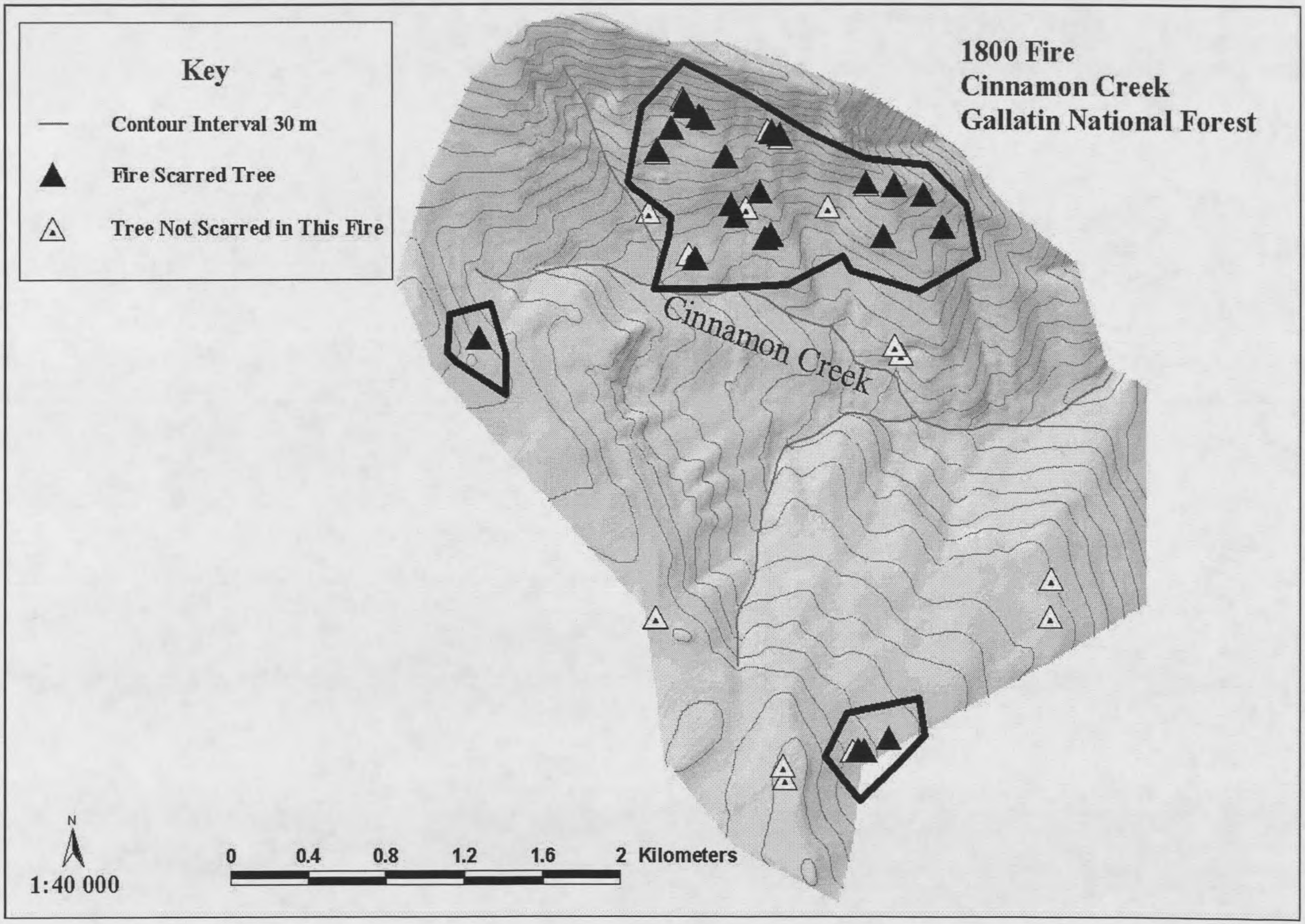

Key
Contour Interval 30 m
Fire Scarred Tree
Tree Not Scarred in This Fire
1702 Fire
Cinnamon Creek
Gallatin National Forest
Cinnamon Creek
N
1:40 000
0 0.4 0.8 1.2 1.6 2 Kilometers



Key
Contour Interval 30 m
Fire Scarred Tree
Tree Not Scarred in This Fire
1734 Fire
Cinnamon Creek
Gallatin National Forest
Cinnamon Creek
N
1:40 000
0
0.4
0.8
1.2
1.6
2 Kilometers


Key
Contour Interval 30 m
Fire Scarred Tree
Tree Not Scarred in This Fire
1743 Fire
Cinnamon Creek
Gallatin National Forest
Cinnamon Creek
N
1:40 000
0 0.4 0.8 1.2 1.6 2 Kilometers


Key
Contour Interval 30 m
Fire Scarred Tree
Tree Not Scarred in This Fire
1750 Fire
Cinnamon Creek
Gallatin National Forest
Cinnamon Creek
N
1:40 000
0 0.4 0.8 1.2 1.6 2 Kilometers


Key
Contour Interval 30 m
Fire Scarred Tree
Tree Not Scarred in This Fire
1800 Fire
Cinnamon Creek
Gallatin National Forest
Cinnamon Creek
N
1:40 000
0 0.4 0.8 1.2 1.6 2 Kilometers

APPENDIX B

Data for Chapter 4

Sample	Latitude Northing (m)	Longitude Easting (m)	Slope (%)	Topographic Convergence	Transformed Aspect	Elevation (m)	Estimated Fire Return Interval
SBC_002	566305.74	4967799.73	37.05975	47	-0.842696200	2075.383	70
SBC_003	566283.41	4967793.94	30.07349	40	-0.518978200	2075.688	63
SBC_004	566443.92	4967299.37	35.61506	26	-0.271460200	2168.042	67
SBC_005x	566553.34	4967543.07	28.57163	27	-0.811534300	2123.542	54
SBC_006x	566534.98	4967663.23	26.47888	82	-0.887216800	2097.329	15
SBC_007	566644.82	4967738.43	12.05719	101	-0.910366500	2095.5	27
SBC_008	566704.23	4967724.24	59.07614	31	0.095308670	2124.456	65
SBC_009x	566736.95	4967996.76	49.93813	16	0.668964700	2083.918	81
SBC_010	566739.06	4967920.87	57.77386	44	-0.245156800	2081.784	36
SBC_011	566960.41	4968162.03	39.46441	82	-0.257662800	2071.726	56
SBC_012	567360.65	4968419.89	35.44068	62	-0.248375600	2065.325	44
SBC_013x	567583.69	4968372.24	45.83452	50	-0.274721300	2112.264	28
SBC_014	567832.19	4968532.25	23.91028	41	0.398726100	2121.408	50
SBC_015x	567780.67	4968548.37	21.27147	44	0.771930100	2114.093	44
SBC_016x	567977.39	4968498.61	49.29902	66	-0.152057100	2129.638	28
SBC_018	568439.06	4968918.28	31.49278	70	0.721387200	2158.898	118
SBC_019	568466.72	4968916.72	40.02451	57	0.757768700	2164.08	59
SBC_022	568134.50	4969452.00	15.61613	90	0.316227600	2082.089	44
SBC_023	568006.58	4969098.84	36.62355	62	0.047565280	2098.243	118
SBC_024x	568941.22	4969729.11	36.71637	61	0.521450000	2190.902	38
SBC_025x	568872.85	4969843.17	38.28695	66	0.559857300	2164.385	43
SBC_026x	569023.81	4970005.89	44.82436	58	0.088932070	2183.587	38
SBC_028x	569000.76	4970068.59	41.52402	58	0.059892190	2168.042	57
SBC_029x	568908.63	4970065.75	28.40597	68	0.196116200	2153.717	70
SBC_030x	568853.65	4970037.39	30.97472	63	0.235599800	2147.621	70
SBC_031x	569175.71	4969959.38	51.00027	53	0.400818600	2236.622	44
SBC_032	569216.61	4969950.57	43.96554	53	0.439867500	2250.338	83
SBC_034	569328.30	4969970.29	62.18096	35	0.307820300	2307.641	70
SBC_036	567187.74	4967075.67	56.57306	44	0.198359400	2412.187	72
SBC_037	567111.93	4967147.09	52.39295	52	0.108936800	2370.43	87
SBC_038x	566984.79	4967340.18	53.64144	59	0.312320900	2284.781	72
SBC_039x	566880.93	4967322.43	70.43312	79	0.772836400	2239.975	51
SBC_040	568188.94	4967054.75	50.11161	46	0.221621000	2421.026	32
SBC_041	568217.87	4967182.82	47.1009	51	0.246399000	2404.872	86
SBC_043x	568113.56	4967207.63	41.86582	55	0.256434600	2378.964	63
P1	567593	4968452	43.21072	55	-0.338719700	2092.452	178
P2	567889	4968222	66.89948	33	-0.392098600	2257.958	145
P3	568744	4968629	32.72094	68	0.990492300	2218.03	115
P4	568756	4968964	53.99063	35	0.346896000	2232.66	130

P5	569008	4969287	23.84264	65	0.960000000	2223.821	155
P6	568288	4969511	45.50138	49	0.295306300	2103.73	75
P7	567153	4967902	13.51969	74	-0.294085700	2143.658	200
P8	567115	4967935	17.36707	75	-0.734803400	2140.001	130
P9	566741	4967610	49.9755	39	0.757156700	2138.477	65
P10	566173	4966999	68.79409	31	-0.438964200	2175.967	65
P11	565903	4967341	47.03909	42	0.543251300	2090.014	130
P12	569895	4968617	45.22208	41	-0.017541340	2546.299	145
P13	569911	4968278	39.25562	78	0.627329400	2496.007	200
P14	569547	4967905	41.13368	54	0.586967500	2474.062	200
P15	569210	4967617	48.36646	60	0.141421300	2464.613	200
P16	569425	4967434	40.9229	56	-0.040782460	2534.412	151
P17	568875	4967486	45.43207	36	-0.121891600	2482.901	100
P18	568528	4967763	34.46869	46	-0.206010700	2356.714	200
P19	568640	4967587	34.61868	52	0.051214670	2332.634	160
P20	568390	4967195	45.07589	51	0.158678300	2454.25	70
P21	567146	4967274	50.79768	51	0.475818500	2357.628	78
P22	570547	4969444	60.6621	34	0.904142000	2571.598	100
P23	570492	4969686	44.9327	63	0.124035000	2540.813	200
P24	570165	4969171	54.99641	32	0.965615800	2524.354	200
P25	569675	4969362	61.69086	43	-0.238052200	2392.07	250
P26	568257	4969189	41.81031	52	0.316227600	2129.942	150
P27	569616	4969878	50.28279	55	0.499298700	2396.033	130
P28	569363	4970071	62.44363	31	-0.498124700	2278.075	250
P29	569300	4969006	64.80956	48	-0.066519220	2369.21	70
P30	569434	4970278	62.33603	39	0.129735100	2268.626	130
P31	568964	4970562	45.71584	47	0.184000000	2108.302	70
P32	568738	4970324	45.23529	41	-0.035066110	2123.846	168
P33	568632	4970198	46.94195	49	0.379918700	2111.045	200
P34	568301	4969763	25.99665	71	0.688749300	2084.222	100
P35	569865	4968132	43.97996	52	0.146548700	2506.066	87
P36	568524	4967655	51.19401	43	0.255892500	2374.392	225