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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Jeremy S. Littell

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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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

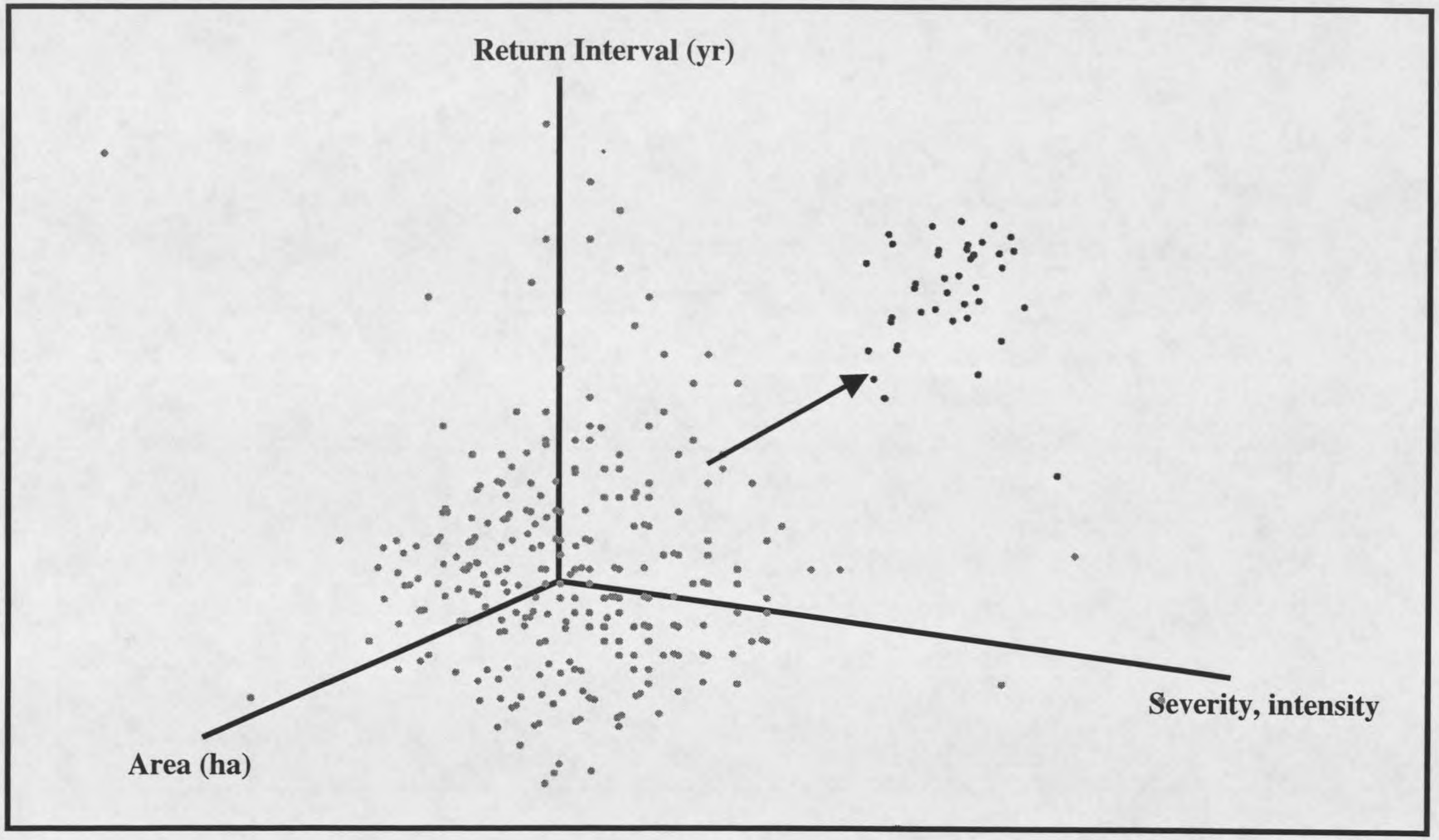

Figure 1. Three-axis Conceptual Diagram of Fire Regime. Fire regime is the scatter of points described by a statistical distribution of events through time (light points). A change in management practices, climate, or vegetation cover can produce a shift in fire regime towards a fundamentally different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