AN ABSTRACT OF THE DISSERTATION OF

Peter J. Weisberg for the degree of Doctor of Philosophy in Forest Science presented on August 24, 1998. Title: Fire History, Fire Regimes, and Development of Forest Structure in the Central Western Oregon Cascades.

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Abstract approved: ______________________________
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Fire history and fire regimes were reconstructed for a 450 km^2 area in the central western Oregon Cascades, using tree-ring analysis of fire scars and tree origin years at 137 sampled clearcuts. I described temporal patterns of fire frequency, severity, and size, and interpreted topographic influences on fire frequency and severity. I then evaluated the influences of fire history and topography on the development of forest structure.

Ninety-four fire episodes were reconstructed for the 521-year period from 1475 to 1996. The average mean fire interval, Weibull median probability interval, and maximum fire interval of 4-ha sites were 97 years, 73 years, and 179 years, respectively. Fire regime has changed over time as a result of climate change, changing anthropogenic influences, and patterns of fuel accumulation related to stand development. Fire frequency and severity patterns were weakly but significantly associated with spatial variation in hillslope position, slope aspect, slope steepness, and elevation. Fire frequency was lower for higher elevations, lower slope positions, and more mesic slope aspects. Fire severity was lower for higher elevations, lower slope positions, more north-facing slopes, and more gradual slopes. Three fire regime classes were defined and mapped.

Forest stand structures were strongly associated with stand age, fire history and topography. The number of years since the last high-severity fire was an important predictor for nearly all measured aspects of stand structure. Low-severity fires were important for creating variability in tree diameter sizes, reducing tree density and allowing more rapid diameter growth, and creating stand structures with many large snags and few overstory shade-tolerant trees. However, stands of the same age, and of the same general fire history, often had different structures. Much of this variation was explained by differences in topography. The strongly positive influence of wet aspects and high elevations on the relative dominance of shade-tolerant tree species has been important for shaping the structure of forest stands. Development of old-growth stand attributes (i.e., high stand basal area, maximum tree diameter, variability of tree diameters, and density of large Douglas-fir trees) appears to have been slowest on steeper slopes, wetter aspects, and higher elevations.

Fire History, Fire Regimes, and Development of Forest Structure in the Central Western Oregon Cascades

by

Peter J. Weisberg

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Peter J. Weisberg, Author

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FIRE HISTORY, FIRE REGIMES, AND DEVELOPMENT OF FOREST STRUCTURE IN THE CENTRAL WESTERN OREGON CASCADES

Chapter 1. Introduction

1.1. Background

In the western Cascade Range of the Pacific Northwest (PNW), wildfires have played a major role in determining the structure and function of forest ecosystems, patterns of habitat, and patterns of resource availability for human use. Fires in this region have burned with a complex mixture of severities, ranging from non-lethal underburns to stand-replacing crown fires that cause virtually complete tree mortality over extensive areas (Teensma 1987, Morrison and Swanson 1990, Agee 1993). As a result, forested landscapes in the PNW are heterogeneous over multiple scales, representing complex mosaics of stand seral stages and structural types. Whether at stand or landscape scales, current ecological patterns and processes are greatly influenced by fire history, and must be understood in that context.

Fire regimes are typically defined by fire frequency, severity, and size (Agee 1993), and are derived from studies of fire history that may make use of dendrochronological, paleoecological, and archival data sources to interpret past patterns of fire. Dendrochronological (i.e., tree-ring-based) studies reconstruct past fire occurrence by dating fire scars on the boles of trees, or by using establishment dates of early-successional tree species. Advantages of tree-ring-based studies include high temporal precision if tree-ring counts are accurate, and high spatial precision if sampled trees and sites are precisely geo-referenced. The temporal extent of fire history reconstruction using tree-ring methods is limited by the ages of the oldest trees at each site.

Paleoecological fire history studies that utilize charcoal found in lake sediments are temporally imprecise due to the limited resolution of ^{14}C and ^{210}Pb dating, and lags in charcoal accumulation from secondary sources following fire (Whitlock and Millspaugh 1996). They are spatially imprecise because lake sediments receive a great deal of airborne charcoal when fires burn nearby, and the area of the "airshed" is unknown, and likely varies for different weather conditions. Also, paleoecological studies have very limited ability to describe the size and severity of past fires (Whitlock and Millspaugh 1996). However, paleoecological studies can reconstruct aspects of fire history over long (e.g., to >10,000 years) temporal extents, and thus allow researchers to frame results of more precise but temporally limited fire history studies within a long-term perspective. Such studies may be used for long-term analysis of the combined, interactive response of fire and vegetation to climatic change (Swain 1973, Cwynar 1987).

Archival sources of fire history information may be very spatially and temporally precise, but for ecosystems where written records have not been maintained by humans for long periods of time, are limited in temporal extent. The fire history of a 2378 km^2 area in the central western Oregon Cascades was generally described for the 1850 to 1909 period, and reconstructed in great detail for the 1910 to 1977 period, using written records (Burke 1979).

Multiple studies have employed dendrochronological methods to describe fire history over the past 400 to 800 years in Douglas-fir forests of the western Cascades

(Hemstrom and Franklin 1982, Means 1982, Klopsch 1985, Stewart 1986, Teensma 1987, Agee et al. 1990, Morrison and Swanson 1990, Garza 1995, Krusemark et al. 1996, VanNorman 1998). From these studies, we can draw important conclusions about broad temporal patterns of fire frequency and extent (Chapter 4), and about influences of vegetation type and topography on fire regimes. Despite these many efforts to characterize fire regimes of the region, there have been few landscape-level attempts to explicitly link climatic and topographic variation to fire regime pattern, and to link fire regime pattern to vegetation pattern, at either stand or landscape scales. Little is known about historical fire influences on species composition, stand structure, the development of stands with old-growth characteristics, the distribution of stand structures or vegetation types over landscapes, coarse woody debris, species habitat, and species population dynamics. Previous studies of the relationships between fire history and stand structure in the western Cascades have focused on a small number of stands (Means 1982, Klopsch 1985, Stewart 1986, Huff 1995); none has described these relationships over large landscapes, with different forest types and physical environments represented.

Even after so many studies have been conducted, it remains unclear as to how dendrochronological methods should be used to reconstruct and interpret fire history in this region. Various ecosystem and fire regime attributes of the western Cascades may not be conducive for fire history methods successfully employed elsewhere (Chapter 2). In many cases, the error associated with alternative methods used in the western Cascades has not been quantified.

1.2. Overview

Most of this dissertation is based on a tree-ring-based, fire history reconstruction for the Blue River study area, a 450 km^2 landscape in the central western Oregon Cascades, described in Section 4.2. I use the fire history data to characterize fire regime, and to quantify some of the influences of fire history and the physical environment on stand structure. However, I begin with two chapters addressing methodological issues for dendrochronological fire history studies. Chapter Two provides a theoretical framework for the analytic processes of fire history reconstruction and fire regime characterization. The question is broached: how might different methodological considerations and sources of error vary for different fire regime types? Chapter Three describes an empirical study quantifying the error associated with fire dating when cross-dating, a method of using correlations among tree-ring widths and tree-ring characteristics to precisely date tree-ring chronologies, is not employed. I discuss research questions and interpretations that may be appropriate or inappropriate for non-cross-dated fire history studies in the central western Oregon Cascades.

The fourth chapter describes and analyzes a non-cross-dated, tree-ring-based fire history reconstruction for the Blue River study area. I reconstruct fire history and characterize fire frequency, severity, and extent for the 1475 - 1996 period, and analyze temporal changes in fire regime over that period. Using fire frequency and severity estimates described for 90 4-ha sample sites, I analyze the spatial variability of fire regime, and identify key topographic influences on fire pattern. Finally, I map the spatial variability of fire regime continuously over the Blue River study area.

Chapter Five applies these fire history results in an analysis of how fire history, stand age, and environmental factors are associated with forest structure at the level of 4-ha sites. I examine the influences of fire history and stage of successional development on stand structure, particularly as stand structure relates to the development of old-growth characteristics (Spies and Franklin 1991). I also describe how interactions of environmental factors with fire history influence stand structure, and the rate and trajectory of stand development.

Important questions addressed by this study include: (1) What are the error and uncertainty inherent in different procedural steps of the fire history reconstruction and description process, and how should fire history methodology be adapted to both study objectives and fire regime characteristics? (2) What have been the temporal and spatial patterns of fire in the Blue River study area, and how are they associated with climatic and topographic variability? and (3) What have been the influences of fire history and environmental variability on forest stand structures, particularly as stand structure relates to the development of old-growth characteristics in the western Cascades?

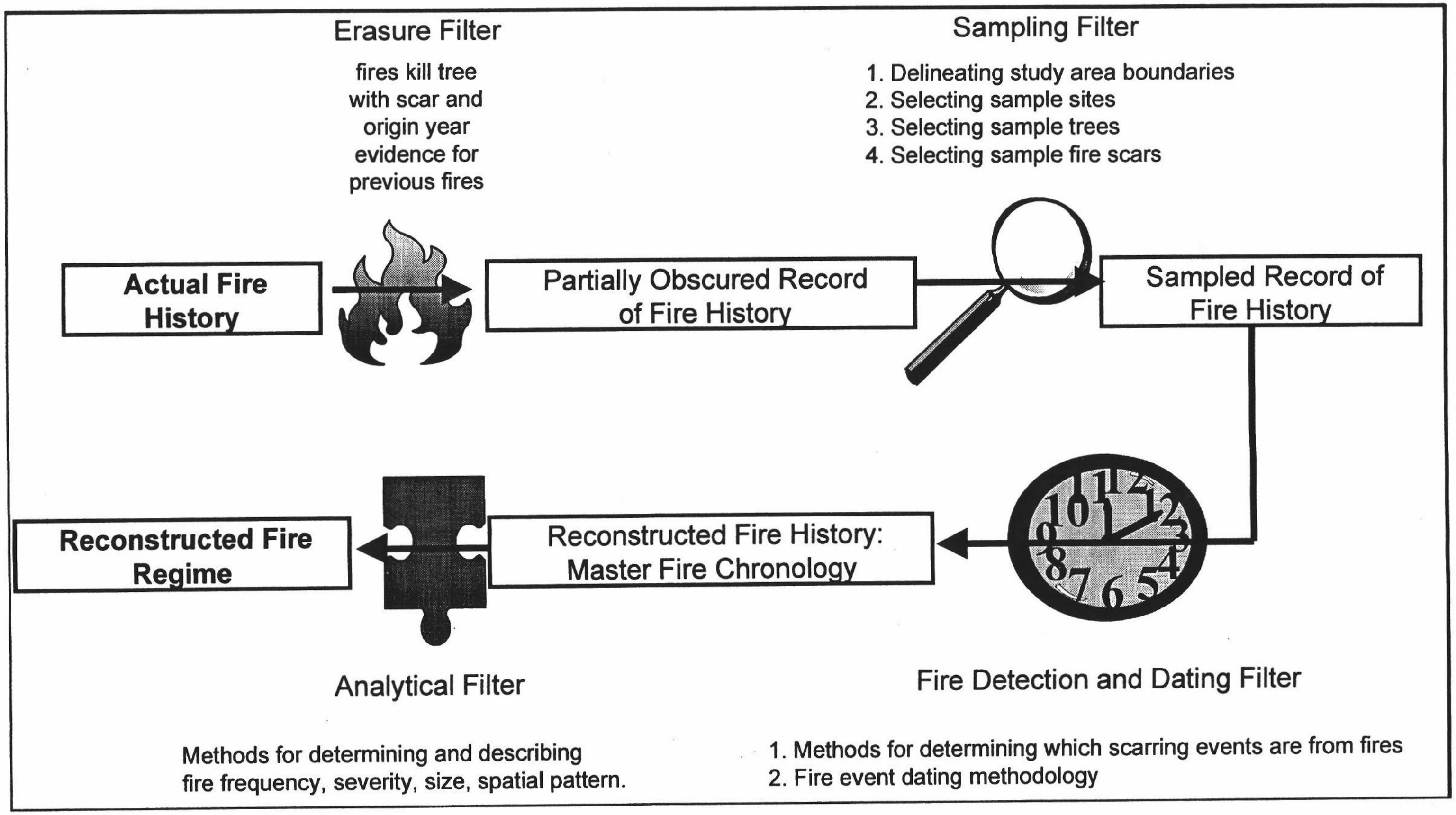
Chapter 2. Seeing Through the Smoke: Error and Uncertainty in Fire History Analysis

2.1. Introduction

Every tree-ring-based fire history study assays patterns of past events given an incomplete sample of fragmentary evidence. Despite the widespread use of ecological and statistical techniques designed to increase precision, quantify uncertainty, and foster objectivity, fire history studies typically involve elements of detective work, where information gaps are filled with reasonable inferences. Before any fire history data have even been collected, much valuable information in the form of fire scar or tree origin years, used to date past fires, has been lost to a variety of factors including subsequent fires, wind disturbance, insects, and wood decomposition. Each procedural step in fire history reconstruction adds to the cumulative load of uncertainty, a quantity that is best understood by the researcher, but is seldom adequately described in the literature.

In addressing these issues, I present a conceptual model where the actual fire pattern is shown to go through a series of filters that distort the record of evidence (Fig. 2.1). The first of these filters is intrinsic to any tree-ring-based fire history reconstruction: fire scar and tree origin year evidence of past fires is removed as trees are killed in subsequent fires, or by other causes of mortality. This effect has been termed the "erasure problem" of fire history reconstruction (Agee 1993), where the record of a fire becomes more obscured over time. A fire history study must also impose a sampling filter on the data, where a subset of all available stands, trees within stands, and even scars within trees, is used to reconstruct the fire record. A subsequent filter involves the methods employed in detecting, distinguishing, and dating fires from tree-ring data. This

Figure 2.1. A conceptual model illustrating the sequence of information filters that create error and uncertainty in reconstructing historical fires and fire regimes using tree-ring methods.



may include the selection of a rule-set, which may be arbitrary or based solely on expert opinion, for deciding what quantity and type of scar evidence are interpreted as a fire. If crossdating were not employed to obtain fire year estimates of annual precision, the fire detection and dating filter might also involve deciding how approximate estimates of fire scar years are used to estimate when past fires occurred, and the temporal resolution used to determine whether fire scar year estimates close in time represent the same or different fires. Finally, an analytical filter is imposed when reconstructed fire patterns are summarized as fire regime descriptors, typically measures of frequency, severity, and size (Agee 1993).

2.2. The Erasure Filter

Tree-ring-based fire history studies rely on the presence of detectable fire scars and tree origin years of early seral species to date past fires. Both of these features disappear over time as trees die and decompose. Thus, the fire history record becomes progressively more obscured for earlier fires. Erasure can limit the length of record by reducing the age of the oldest tree available for sampling, or can reduce the quality and quantity of fire evidence within the period of record. The latter contingency is more difficult to control, since it is difficult to detect and perhaps impossible to measure. The rate at which this degradation of the record occurs is a function of fire regime, type and intensity of non-fire mortality factors, and biological limitations on tree longevity in the absence of disturbance.

In high-severity fire regimes, where fires are typically stand-replacing except at their margins, nearly all evidence of previous fires within an area is removed by mortality and decomposition following each subsequent fire. Examples of such fire regimes are the boreal forests of North America, or chaparral shrublands in Mediterranean climates. Although in some cases the previous fire may be dated from fire-killed snags using dendrochronological techniques, little can be said about fire history at the stand level beyond the age of the stand itself. In this situation, erasure is complete. The only tree-ring-based fire history reconstruction possible is to consider the landscape or regional mosaic of stand ages as a chronosequence of past fires, and use analytical models to obtain estimates of fire frequency and hazard from maps of time-since-fire, based on the distribution of stand age-classes (Van Wagner 1978, Johnson and Van Wagner 1985, Johnson and Gutsell 1994).

Where low-severity, surface fires compose the fire regime, as in many semi-arid, pine-dominated ecosystems, overstory trees survive fire and may record fire scar evidence of many events. For these areas, fire evidence is erased not by tree mortality due to subsequent fires, but by non-fire mortality agents (e.g., windthrow, insect epidemics) and the death of senescent trees. The length of fire record is controlled primarily by physiological limitations on tree longevity and not by patterns of fire occurrence, as in areas with high-severity fires. However, even in these low-severity fire environments, fire scars may be obliterated or disfigured as a result of subsequent fires and weathering (Brown and Swetnam 1994).

The erasure filter (Fig. 2.1) is unavoidable, but fire history researchers should be sensitive to the effects of evidence erasure on their ability to accurately reconstruct fire history. In particular, fire record degradation over time can generate spurious differences in fire frequency, severity, and/or size for different time periods that may erroneously be attributed to changes in climatic or human factors. In variable- or- moderate-severity fire regimes, one might observe the frequency of smaller, lower severity fires to decline with increasing time into the past when the actual frequency of these fires has remained constant. Such small fires that leave little evidence are more quickly eliminated from the record than are large, widespread fires. Also, time-dependent distortion of the fire record may frustrate efforts to accurately estimate the spatial extents of past fires.

2.3. The Sampling Filter

Fire history sampling occurs over at least three nested spatial scales: delineating a study area boundary, sampling sites within a study area, and sampling trees within sites (Fig. 2.1). For each scale, there is a trade-off between the intensiveness and extensiveness of sampling that relates to the fire regime being studied, the research objectives, the relative degrees of resolution and extent required, and logistical constraints.

Study area boundaries may encompass a region, landscape, watershed, or stand, depending on the study objectives (Table 2.1). The relevant aspects of the fire environment differ for each scale, as do the physical features of the environment that are important for influencing fire pattern. The selection of a particular scale of investigation comes from the research questions of interest, and carries with it a set of appropriate fire history methods. Regional-scale variation in fire history may be described by observing patterns of synchronicity between disjunct clusters of sampled sites, as was done to relate years of widespread fire to fluctuations in temperature and precipitation in giant sequoia groves (Swetnam 1993), to correlate frequency of widespread fire with phases of the El

Table 2.1. Three spatial scales over which fire history studies have been conducted, with associated spatial considerations and fire history methods.

Scale	Fire Environment and Spatial Influences on Fire Pattern	Fire Frequency Methods	Fire Extent Methods	Examples
Region $(10^4 - 10^6 \text{ km}^2)$	1. Macroclimate (precipitation, temperature) 2. Weather patterns 3. Vegetation type 4. Orographic effects	1. Fire chronologies at multiple sites (fire interval analysis) 2. Fire cycle (stand age analysis)	1. Synchronicity of fire occurrence between sites	Swetnam and Betancourt 1990; Swetnam 1993
Landscape or **Watershed** $(10^1 - 10^3 \text{ km}^2)$	1. Forest stand mosaic 2. Mesoclimate (cold air drainage, wind patterns, insolation) 3. Topographic variation in climate and fire spread potential	1. Master fire chronology over multiple sites (fire interval analysis) 2. Fire cycle (stand age analysis: if large landscape relative to fire size)	1. Synchronicity of fire occurrence between sites 2. Fire boundary reconstruction	Hemstrom and Franklin 1982; Romme 1982; Agee et al. 1990; Morrison and Swanson 1990; Johnson and Larsen 1991; Arno et al. 1993
Stand or **Site** $(10^{-2} - 10^0 \text{ km}^2)$	1. Microclimate 2. Microtopography 3. Fine-scale variation in fuel loading, structure and moisture	1. Master fire chronology over multiple trees	1. Percent of site area burned	Pitcher 1987; Brown and Swetnam 1994; Cutter and Guyette 1994

Nino-Southern Oscillation cycle in the southwestern United States (Swetnam and Betancourt 1990) and in northern Patagonia (Kitzberger and Veblen 1997), and to compare major fire years between southeastern Labrador and nearby areas (Foster 1983). In contrast, landscape-level studies evaluate fire patterns or regimes continuously over the spatial heterogeneity of a large (10^3 to 10^5 ha) study area, by interpolating between site-level fire history reconstructions (Heinselman 1973, Hemstrom and Franklin 1982, Teensma 1987, Heyerdahl and Agee 1996, Impara 1997). At both stand and regional scales, case studies of fire history are described in a discontinuous manner, since stands are too small and regions too large for interpolation of past fire patterns between sampled sites (Table 2.1).

Larger study areas and more extensive fire history sampling are associated with research objectives oriented toward an understanding of spatial variation in fire patterns, while smaller study areas and the more intensive fire history sampling that this allows are appropriate for research objectives involving precise, detailed descriptions of temporal patterns. An exception to this occurs when fire frequency is described using stand age-class distributions, sampled at landscape scales, to analytically model fire cycle (Johnson and Gutsell 1994). In this case, study area size should be quite large (e.g., at least three times as great) relative to the size of the largest fire (Johnson and Gutsell 1994). Fire cycle methods which rely on a mapped chronosequence of stand ages may not be appropriate for studies at the scale of stands, small landscapes, or very large regions (Table 2.1). Study area extent is also important to the accuracy of fire frequency analysis in that study areas that are small relative to the size of a representative, high-severity fire contain little evidence of fire before the last such event.

Larger study areas include greater variation in vegetation and features of the physical environment that influence fire behavior and pattern. For studies that seek to characterize the temporal variation of fire history at annual or seasonal precision, it may be desirable to sample trees from smaller study areas that are relatively homogeneous with regard to environmental factors (e.g., topography) influencing fire pattern. Also in such studies, the logistical problems of collecting fire-scarred slabs for crossdating and other dendrochronological analyses may preclude the sampling of large, heterogeneous areas. Such studies may bypass the step of sampling trees at multiple sites within a larger study area, since the entire study area is essentially a single site. However, spatially-oriented fire history studies require study areas that include a range and diversity of fire environments. Studies that attempt to characterize fire extent should have study area sizes that are large relative to the sizes of larger fires. With larger study area sizes, the boundary effects of fires overlapping the study area perimeter, making fire size estimations less accurate, are reduced.

The placement of samples within fire history study areas may be random, systematic (i.e., regularly spaced), or opportunistic. Random sampling may involve stratification of sampling effort (e.g., by topography or vegetation type, or by fire patches observed on aerial photographs) to reduce the number of samples required to obtain fire frequency estimates with low variance (Johnson and Gutsell 1994). Systematic sampling may involve the clustering of sites to sample over multiple, nested, spatial resolutions, or the placement of random samples within a regular grid (Impara 1997, Chapter Four). Opportunistic sampling implies that sites with optimal fire history information are identified and sampled (Hemstrom and Franklin 1982, Brown and Swetnam 1994).

No clear consensus defines which fire history sampling method is preferable at the site level; in fact, strong differences of opinion exist (Johnson and Gutsell 1994, Swetnam and Baisan 1996). Systematic sampling has the advantage of most representatively capturing spatial patterns of past fires, and of minimizing the possibility that parts of the study area are under sampled. Opportunistic placement of sites within a study area increases the likelihood that sites with especially long fire records are sampled. However, Johnson and Gutsell (1994) suggest that fire frequency estimates (e.g., mean fire return interval) based on samples not taken from a completely randomized design are statistically invalid, and have unknown bias associated with them. Where the expectation of accurate and relatively complete fire history information at every sample point is high, as for high severity fire regimes where the time since the last fire may be the only information available for a given location, a randomized sampling design is appropriate. However, fire history researchers attempting to characterize areas with low or variable severity fire regimes may seek to obtain the longest and most inclusive fire chronologies possible at optimal locations, where trees have survived to contain evidence for multiple fire events (Swetnam and Baisan 1996). Where fire chronologies are desirable for time series analyses, such as the comparison of long-term fire records with climatic fluctuations (e.g., Swetnam 1993), it is appropriate to concentrate the sampling effort in places that would yield the longest fire history records. However, fire history studies with research questions involving the spatial variability of fire pattern, or that describe the fire history of the study area as the aggregation of site-level fire history parameters, should sample the study area in a more spatially representative manner, such as is provided by either randomized or systematic sampling.

In addition to the arrangement of samples, sampling intensity (i.e., number of samples per site) and density (i.e., number of sites per study area) are also important considerations for satisfying fire history study objectives. Where fire regime (e.g., frequency, severity, size) is described for the study area at the site level (e.g., as average site-level mean fire return interval), enough sites should be sampled so that the variability around the fire regime descriptor is low. Further, studies that compare fire regime attributes over sites characterized by different strata of some factor (e.g., elevation) should include sufficient sites for each level, and should sample each level proportionately. Sampling density is also important for accurate mapping of fire boundaries. Accuracy in fire boundary reconstruction, as well as the ability to detect small fires, declines with increasing spacing between sites. The ability to detect extensive fires early in the record may also be reduced by a large spacing between samples, since the evidence for these fires may have become limited to discrete, small clusters of trees or sites as a result of record erasure by subsequent fires.

Regardless of how sample sites are selected, it is important that they be of comparable size. Brown and Sieg (1996) argue that having variable sizes of data collection units does not invalidate statistical data analysis, since what is deemed to be a complete record of fire has been obtained for each unit. This statement is true in its strictest sense, but flawed in its application since the meaning of a given fire frequency descriptor differs for differently sized units of analysis. In particular, fire frequency has been shown to increase with increasing size of the sampling unit for giant sequoia-mixed conifer forests in California (Kilgore and Taylor 1979), several forest types in the northern Rocky Mountains (Arno and Peterson 1983), and ponderosa pine forests in central Oregon (Bork 1985). Larger areas are likely to have experienced more past fires. Also, more intensive searching in an area will increase interpreted fire frequency (Morrison and Swanson 1990), to the point where all fires having burned in that area are recorded. The relationship between sampling unit size and fire frequency likely differs for different fire regimes. One would expect the effect of sampling unit size on frequency estimates to be greater for fire regimes of more frequent and/or smaller fires.

One way to determine appropriate sizes for fire history sample sites, or sampling intensity of trees within sites of a given size, would be to adopt an approach analogous to species-area curves used by plant ecologists to estimate minimal area for plant community classification purposes, or to establish an appropriate quadrat size for sampling of species distribution and abundance (Moore and Chapman 1986). Following a pre-sample of fire history in the study area, the fire history researcher might adopt a large enough plot size that fire frequency was relatively stable, if such a size existed. In any case, it would be valuable to know the range of plot areas over which fire frequency was relatively sensitive to the sample extent. Once plot size was established, different sampling intensities (e.g., number of trees sampled or searched for scars) might be tested. An optimal intensity would record virtually all of the fires with a minimum of sampling effort. To my knowledge, neither of these methods has been employed to guide the sampling design of a fire history study.

An important issue in sampling fire history over large areas managed with dispersed clearcut timber harvesting is the potential contrast in samples provided by clearcut vs. primary forest sites. Fire history may best be sampled in either clearcuts or intact stands, depending on the fire regime, study objectives, and logistic or legal constraints. If clearcuts are sampled, the sampling design may be biased toward patterns of record exposure by timber harvesting. If intact forest is used, these same clearcuts represent a potential bias by selective record erasure. Regardless, fire history records are erased where timber harvesting occurred early enough for stumps containing fire history evidence to have decomposed; clearcuts provide a narrow temporal window of opportunity for sampling. In either case, there may be bias associated with patterns of timber harvesting, which are usually neither random nor systematic relative to fire history. For example, harvest units may be absent from steep, unstable slopes, or may be absent from higher elevations where a road network has not yet been constructed. Also, young and early mature (i.e., less than 140 years old) stands may be under-represented in clearcut samples on Federal land. Where such sampling bias is great, reconstructed fire history and fire regimes may not be representative, and simple extrapolations from sample sites to the whole study area may be misleading. One solution might be to sample in both clearcuts and intact forests. However, it is difficult to aggregate information from these two forest conditions because the quality of fire history reconstruction differs greatly.

A variety of sampling designs is also possible for sampling trees within sites. The same considerations with regard to the efficacy of random sampling and statistically valid designs discussed above apply in the context of site selection. If fire regime descriptors are summarized at the site level, it is imperative that the fire history of the entire site be sampled as completely as possible in space and time. Thus, the sample should cover the full extent of the site, since not every fire that burns within the site covers the entire site, and should also include those trees with the longest fire records - -

trees that typically are sparsely distributed. This usually necessitates some degree of opportunistic searching for trees with fire evidence. The non-random sampling of trees does not invalidate statistical analysis of fire intervals at sites, as implied by Johnson and Gutsell (1994). The sampling unit in this case is not the tree, but rather the intervals between fire events that are more accurately and efficiently detected by systematic searching than by random sampling (Brown and Sieg 1996, Swetnam and Baisan 1996). Random samples of trees without fire evidence would be superfluous, since data from these would not be useful for analyzing fire regime in any case.

Regardless of how trees are sampled, it is important that the intensity of sampling effort is consistent between sites. Until a critical threshold of number of trees is reached, where all fires having occurred at the site over the period of record are sampled, more fires will be detected with increasing sampling intensity. This implies that it is necessary to sample fewer trees per site in forests of even-aged stands where only one or two fires are represented, and more trees per site in forests of complex stands where more fires are recorded (Agee 1993).

After sampling, the researcher has obtained a record of fire pattern distorted by sampling limitations and evidence erasure (Fig. 2.1). This may be quite different from the true fire pattern. To reduce error and uncertainty as much as possible, the researcher should ensure compatibility between sites in terms of both area and number of trees sampled, and should adjust the intensiveness and extensiveness of sampling to the fire regime and study objectives. This may require a preliminary sample to gauge the type of sampling most suitable for the system.

2.4. The Fire Detection and Dating Filter

The methods employed in distinguishing and dating past fires are critical to the accuracy and precision of any fire history study. Researchers may be overly conservative in deciding what quality and quantity of apparent fire evidence is needed to define a reconstructed fire event, and so would underestimate the occurrence of past fires, particularly low severity or small ones. Less conservative criteria might lead to overestimation of past fire occurrence. Once decisions have been made as to which of the detected disturbance events are to be interpreted as fires, dating methods strongly affect the resulting descriptions of the reconstructed fire regime (Fig. 2.1).

Where scars are used to date fires, it is necessary to decide which scars represent fire scars. Many scars result not from fire, but from other agents, such as mechanical injury from falling trees, native American bark-stripping (Swetnam 1984), bears (Molnar and McMinn 1960), *Armillaria* infections (Molnar and McMinn 1960), and attacks by insects, such as the bark beetle (Stuart et al. 1983). A comprehensive review of differences between fire scars and other scars is provided in Agee (1993). Many of these differences, while apparent in standing trees, are not obvious for healed-over scars on cut stumps. It is possible to clearly differentiate fire scars from other scars where fire recurrence intervals are typically less than the time it takes for fire-resistant tree species to heal over areas of killed cambium, as in ponderosa pine forests of the western U.S. Here, "recorder trees" have open catfaces that record most fires as charred surfaces on sapwood along the edges of an open catface. The first scar is not counted as a fire scar, since an open catface was not present when it originated, but successive scars are.

Certain ecosystem, species and fire regime characteristics may cloud the distinction between fire scars and other sources of tree injury. Scars sampled on cut stumps in clearcuts may have completely healed over years or centuries ago, and such diagnostic fire scar features as charred bark, deltoid shape, and scar extending to the base of the tree (Johnson and Gutsell 1994) may no longer be discernible. This is particularly the case for fire history studies in the Douglas-fir forests in the Cascade Mountains of the western United States, where long fire-return intervals (e.g., mean fire intervals from 80 to 400 years), rapid (e.g., 5 to 15 years) healing of the small scars on thick-barked Douglas-fir, and rapid decomposition rates (so that trees that receive scars large enough to cause big open "catfaces" do not often survive to record evidence) combine to make classic, easily recognizable fire scars rare (Morrison and Swanson 1990). In these forests, most fire scars are "buried" and may not be noticeable from inspection of standing trees, necessitating sampling on cut stumps where they may be confounded with scars resulting from non-fire causes.

When deciding which sampled scars represent fire scars, it is important to use temporal, spatial, and scar-level criteria. Scarring of trees from the same fire occurs over a time period of hours to weeks (or rarely, months), and so should date to the same year (Agee 1993). However, many areas in low-severity fire regimes may regularly experience fire in successive years, while in some areas catastrophic windstorms and other non-fire disturbances may also cause scars that date to the same year, so temporal criteria alone are clearly insufficient. Further, studies that do not utilize dendrochronological procedures (i.e., cross-dating) to date fires with annual precision are not able to use such temporal criteria.

Spatial criteria operate over within-site and between-site scales. A specified number of contemporaneous scars at a site, or sites within a study area, may be required before the event is considered to have been extensive (and spatially contiguous) enough to have been a significant fire. There is typically a trade-off between the two scales of criteria that is associated with the fire history sampling methodology. Where sites are sparse, but many trees are sampled at a site, within-site criteria are emphasized (e.g., Chapter Four); where site densities are high, but few trees are sampled at each site, between-site criteria are emphasized (e.g., Morrison and Swanson 1990). Rule sets for deciding which scar year estimates represent fires may incorporate tree origin year evidence (e.g., of early-seral species likely to have established following fire) or a variety of fire scar characteristics (e.g., size, morphology, hillslope orientation, distance from the pith, relationship to positions of other scars, presence of char), and may be simple or quite complex. In any case, the decision as to whether sampled scars represent fires may have subjective elements, and further confounds the record of actual fire patterns (Fig. 2.1).

Fires may be dated using fire scars, origin years of early-seral species, years of growth release or canopy accession, or combinations of the above. Dating of fire scars and growth releases is subject to error from the following sources: counting error, missing rings, locally absent rings, and double rings (Stokes and Smiley 1968). Temporal clusters of fire scar year estimates may be combined into a single estimate by averaging (Morrison and Swanson 1990), or by assigning dates from years of low fire incidence to adjacent years of greater incidence, focusing on trees with consistent deviations from the majority (Arno and Sneck 1977). The dating of tree origin years is subject to further error in that the number of years required for the tree to reach the height of the core or stump surface is unknown. This problem may be circumvented by coring (or removing a cross-section) as close to the root collar as possible.

Fire scars can be dated to annual (or seasonal) precision using dendrochronological cross-dating, where correlations between radial growth increments (and various other tree-ring features) of trees in a common area are used to correct ring counts (Stokes and Smiley 1968). This process is time-consuming compared to tree-ring counts in the field, especially because it requires that intact cores or slabs be collected and prepared in the laboratory. Perhaps for this reason, only 22 of 116 fire history studies conducted in the western United States prior to 1995 used cross-dating (Heyerdahl et al. 1995). Few studies have quantified the error associated with not cross-dating ring counts in a fire history study. A study comparing cross-dated and non-cross-dated scar year estimates from 123 partial cross-sections of ponderosa pine found that, while non-cross-dated estimates, which were otherwise adjusted using correlations with nearby trees, agreed with crossdated estimates only 26% of the time, the average error was only one year (Madany et al. 1982). Non-adjusted scar year estimates matched the cross-dated year estimates only 13% of the time, and had an average error of 2.4 years. Interestingly, results from this study have been cited to show both that cross-dating is essential for accurately dating fires (Johnson and Gutsell 1994), and that cross-dating is not critical for dating fires in ecosystems with long fire return intervals (Agee et al. 1990). In another study in dry Douglas-fir forests of the westside Oregon Cascades, Means (1989) found errors from zero to three years, with a single exception of 18 years, in a cross-dating comparison study of 21 tree scars. Apparently, errors associated with not cross-dating are small relative to the fire return intervals of all but the most high frequency fire regimes, provided counts are made on well-prepared samples, as was the case for the cited studies.

However, many fire history studies that use non-cross-dated ring counts have conducted these counts on minimally prepared slabs or cores under field conditions (e.g., Teensma 1987, Masters 1990, Morrison and Swanson 1990, Impara 1997, Chapter Four). For the Blue River study area in the central western Oregon Cascades, field-counted scar years on Douglas-fir were within 10 years of their true values for about 75%, and within 20 years for about 87%, of the observed cases (Chapter Three). Fires were estimated as having occurred from 1 to 16 years later than they actually did, and, for one of four sites, a "fire" that never occurred was erroneously reconstructed.

It should be standard practice for fire history studies to either use cross-dating, or to quantify the error associated with not cross-dating in a pilot study prior to constructing a fire chronology and analyzing fire history data. Where fire intervals are short relative to ring counting error, cross-dating is essential. Where fire intervals are long relative to ring counting error, there may be a trade-off between increased temporal precision and the necessary level of sampling effort required to carry out a cross-dated fire history study, which allows far fewer trees and sites to be sampled overall.

Certain research objectives may be satisfied with a coarse level of resolution in fire dating. Comparisons of area burned over 30-year or longer time intervals may be little affected by whether or not fire year estimates were crossdated. Where fire intervals are large relative to dating errors, results of fire interval analyses may be valid. Alternatively, results of fire interval analyses may be greatly altered by even slight errors in fire year estimation, since incorrect fire year estimates may result in an incorrect number of fire events as well as incorrect fire years (Madany et al. 1982, Chapter Three). To adjust for this, non-cross-dated fire history studies may define coarse-resolution "fire episodes," ranging over multiple years and possibly representing multiple fires closely occurring in time and space (Teensma 1987, Morrison and Swanson 1990, Impara 1997, Chapter Four). The issue of cross-dating in fire history studies is discussed in detail in Chapter Three.

Once the actual fire pattern has passed through the erasure filter, the sampling filter, and the fire detection and dating filter, the researcher has obtained a reconstructed fire history that may then be analyzed in a variety of ways (Fig. 2.1). This reconstruction often takes the form of a tabular master fire chronology, where the presence or absence of particular fires (columns) is recorded over all available sites (rows). As we have seen, the fire history reconstructed in such a chronology may represent the actual fire pattern only approximately, and with a variety of potential biases.

2.5. The Analytical Filter

It is not enough to present a master fire chronology, or a set of maps, showing when and where fires have occurred. Most research objectives require that the reconstructed pattern of fire history be summarized using descriptions of frequency, severity, size, and/or other aspects of spatial pattern (Fig. 2.1). These components together describe a fire regime (Agee 1993). It is outside the context of this chapter to attempt to describe the various methods of fire regime description. I instead refer the reader to Agee (1993) for a comprehensive overview, and to Johnson and Gutsell (1994) for a review of analytical models for quantifying fire frequency. Whatever the method employed, there is ample room for error and uncertainty in expressing a reconstructed fire history as a fire regime. I briefly review a few of the more common examples.

Fire severity, defined here as the effects of fire on dominant vegetation, is seldom estimated in tree-ring-based fire history studies because it is so difficult to reconstruct for all but the most recent fire. Current size and age distributions are of limited use in reconstructing the effects of past disturbances. Most fire history studies that address fire severity do so only very generally by calculating separate fire frequencies for fires associated with subsequent regeneration of early-seral tree species, and for fires that lack any such regeneration (Teensma 1987, Morrison and Swanson 1990, Impara 1997). However, the absence of post-fire regeneration at the time of sampling does not necessarily indicate that there never was a post-fire regeneration cohort. Subsequent fires and other mortality agents confound interpretations of fire severity. Also, fire severity may be estimated using the proportion of basal area establishing shortly following a fire relative to the proportion of basal area that originated prior to the fire. It is assumed that there is a positive correlation between the amount of "growing space" for regeneration liberated by a fire, and the amount of overstory canopy cover killed by it. Such estimates are confounded by age and species dependent relationships between fire timing, intensity, and severity. Where two fires have occurred closely in time, it may be impossible to accurately estimate the severity of the earlier fire. Even intricate “decision trees” designed to estimate fire severity on the basis of apparent tree regeneration response, species-specific differences in fire susceptibility and recovery, and timing between fires (Chapter Four) are prone to a great deal of error.

Fire size may be reconstructed by interpolating between sites with and without fire history evidence, after accounting for sites lacking trees old enough to have burned in that particular fire. Such interpolation may be subjective, incorporating knowledge of the study area and topographic effects on fire spread (e.g., fire breaks), or may be accomplished through more objective means such as Thiessen polygons (Heyerdahl and Agee 1996, Impara 1997) or convex hulls (Heyerdahl and Agee 1996). Fire extent may also be estimated without drawing fire boundaries using the ratio of the number of sites recording fire to the ratio of the number of sites that did not record the fire, but were capable of doing so (Teensma 1987, Morrison and Swanson 1990, Impara 1997, Chapter Four). Accurate reconstructions of historical fire size distributions require study areas large enough to completely contain the largest fires, and a high enough density of sampled sites to detect small fires and allow for valid spatial interpolation. Both of these conditions are seldom met in the same fire history study.

Most fire history studies attempt to characterize fire frequency. For high severity regimes, fire frequency can seldom be measured for a given point on the landscape, because each fire removes virtually all evidence of previous fires. Estimates of fire hazard and fire frequency for large areas may still be obtained using the fire cycle method, where a time-since-fire distribution is fitted with a negative exponential or Weibull model (Van Wagner 1978, Johnson and Van Wagner 1985). This method assumes complete erasure from each fire, temporal and spatial homogeneity in fire regime, and, implicitly, that individual landscape units burn independently (i.e., that spatial autocorrelation of fire probability due to fire spread is not important) (Boychuk et al. 1997). Where these assumptions are not approximately met, the fire cycle model may inadequately characterize fire frequency and the landscape age class distribution (Baker 1989, Boychuk and Perera 1997, Boychuk et al. 1997).

Fire frequency is readily quantified for low severity, high frequency, surface fire regimes, where fire intervals are short relative to the length of the fire record. Fire chronologies containing evidence for numerous fires can be constructed for study areas as small as individual trees (Dieterich and Swetnam 1984). Numerous intervals between fires can be summarized using statistics such as the mean, median, variance, skewness, or Weibull median probability interval.

The greatest problems in fire frequency analysis occur in fire regimes of variable severity and frequency, such as occur in the western Oregon Cascades (Morrison and Swanson 1990, Chapter Four). In such environments, low and moderate severity fires preclude the use of time-since-fire maps to calculate fire cycles with analytical models, since stands typically contain multiple post-fire age cohorts. However, the occurrence of high severity fires, and generally long fire intervals between fires, result in site-level fire chronologies where relatively few fire intervals are recorded. Where few intervals are present, site-level estimates of frequency (e.g., mean fire interval, median fire interval, parameters of Weibull distributions for fire intervals) have high variance and do not adequately summarize fire regime beyond the chance effects of a few fires. Therefore, both fire cycle (chronosequence) and fire chronology (longitudinal) approaches may result in poor estimates of fire frequency for areas with variable fire regimes.

2.6. Fitting the Methods to the Ecosystem

The tree-ring-based reconstruction of past fire patterns and accurate characterization of those patterns involve passing the fire record through multiple filters where fire evidence is obliterated, distorted, erroneously introduced, or deleted in ways that may be known or unknown to the researcher, and may even be unknowable (Fig. 2.1). While precise methodologies exist for overcoming some of these error sources (e.g., dendrochronological techniques for precisely dating fire scar years), it is important that researchers are explicit about biases and uncertainties that remain. As with any form of disturbance reconstruction, tree-ring-based fire history reconstruction involves an element of detective work and subjectivity. This becomes a problem when researchers are not explicit about uncertainty in their studies, and present their results as though they were precise and complete descriptions of fire history.

To assert that study protocols for one regime type pertain to all others is misguided. Various sources for information and error are manifested differently in different fire regimes, and so fire history researchers should adjust their methods to fit the fire regime they seek to describe (Table 2.2). That they already are doing so is evidenced by the widespread use of the fire cycle approach to analyze areal fire frequency in high severity, boreal fire regimes (e.g., Johnson and Van Wagner 1985, Masters 1990, Johnson and Larsen 1991), and the widespread use of the fire chronology approach in low severity, high frequency fire regimes (e.g., Swetnam 1993, Brown and Swetnam 1994, Swetnam and Baisan 1996). Where variable fire regimes consist of both low severity and high severity fires, so that stands are of multiple age cohorts but few fire intervals are represented at any one site, special problems are presented for fire history analysis. The

Table 2.2. Methodological considerations for tree-ring based fire history reconstruction. Columns refer to three levels along a fire regime gradient, described at the bottom of the table using fire behavior, severity, and frequency.

Stand Characteristics	Uneven Aged	Discrete Cohorts	Even Aged
Scar Characteristics	Many "catface" scars on recorder trees 5 -15 fires / scarred tree 1 in 5 old trees scarred	Scars uncommon, often small and oriented along a common radial axis associated with a bark furrow 1 - 5 fires / scarred tree 1 in 20 old trees scarred	Scars very rare, limited to edges of burns 1 fire/scarred tree few old trees predating the fire
Fire History Data Source	scars	scars + tree origin years	stand origin years
Length of Record relative to Fire Interval Length	long (e.g., 30 yrs.)	moderate to short (e.g., 5 years)	very short (e.g., 1 year)
Fire History Reconstruction Method	fire chronology	fire chronology or chronosequence	fire chronosequence
Fire Behavior	low-intensity surface	mixed surface and crown	crown
Severity Gradient	LOW	VARIABLE/MODERATE	HIGH
Frequency Gradient	HIGH	MODERATE	LOW
Examples	*ponderosa pine forests, w. U.S.*	*Douglas-fir forests, western Oregon Cascades, U.S.*	*boreal forests, Canada*

type and quality of fire history data, including stand characteristics, scar characteristics, potential data sources, and relative length of the fire history record, vary over gradients of fire type, severity, and frequency (Table 2.2). Methods for fire history reconstruction and fire regime analysis, and associated error and uncertainty, vary predictably along these same gradients (Table 2.3).

Table 2.3. Sources and relative degree of error and uncertainty in tree-ring-based fire regime characterization. Columns refer to three levels along a fire regime gradient, described at the bottom of the table using fire behavior, severity, and frequency.

Evidence Erasure		low	moderate	high
Confusion of Fire Scars with other Types of Scars (on cut stumps)		low	high	high
Uncertainty in Characterizing Fire Frequency	**fire interval analysis**	low	high	high
	fire cycle analysis	high	high	low
Uncertainty in Characterizing Fire Extent and Spatial Pattern	**reconstructed fires**	high	high	high
	recent fires	high	low	low

Fire Behavior	low-intensity surface	mixed surface and crown	crown
Severity Gradient	LOW	VARIABLE/MODERATE	HIGH
Frequency Gradient	HIGH	MODERATE	LOW
Examples	*ponderosa pine forests, s.w. U.S.A*	*Douglas-fir forests, western Oregon Cascades, U.S.A.*	*boreal forests, Canada*

Chapter 3. To Cross-Date or Not to Cross-Date: Precision and Accuracy in Fire History Reconstruction

3.1 Introduction

Dendrochronological studies are used to reconstruct fire history over centuries, or for as long as the oldest trees survive. Cross-dating, or the matching of tree-ring patterns to correct tree-ring chronologies, is a valuable technique for precisely determining years of fire injury or tree origin which can then be used to date wildfires (Stokes and Smiley 1968, Fritts 1976). Cross-dating may also be used to extend the length of record using tree-ring data from snags and other dead materials (Baisan and Swetnam 1990, Kitzberger and Veblen 1997). Since it is a laborious and time-consuming technique, many fire history studies have relied on non-cross-dated ring counts. Only 22 of 116 fire history studies conducted in the western United States prior to 1995 used cross-dating (Heyerdahl et al. 1995). Few studies have quantified the error associated with not cross-dating tree-ring counts in a fire history study (but see Madany et al. 1982, Means 1989). To my knowledge, none has quantified the error of a fire history study where tree-ring counts were made on minimally prepared stump surfaces in the field, even though many fire history studies that used non-cross-dated ring counts had conducted these counts on minimally prepared slabs or cores under field conditions (e.g., Hemstrom and Franklin 1982, Teensma 1987, Masters 1990, Morrison and Swanson 1990, Impara 1997, Chapter Four).

Fire history studies designed to describe patterns in much detail over space, but with little concern for fine-scale (e.g., inter-annual) temporal patterns, may be the most likely to eschew cross-dating. Such studies require numerous observations to derive multiple site-level chronologies across large areas. Cross-dating requires collecting and processing wood samples, which greatly constrains the number of observations possible.

In the Douglas-fir forests of the Pacific Northwest (PNW), the application of dendrochronological techniques (e.g., cross-dating) may be especially difficult due to: large tree sizes; steep topography and limited access; rapid decomposition of stumps; scarcity of trees with multiple scars; and low sensitivity of tree-ring widths to climatic variation (i.e., complacency). Although there have been many fire history studies in these forests, most have not employed cross-dating techniques (Hemstrom et al. 1982, Means 1982, Teensma 1987, Agee et al. 1990, Agee 1991, Morrison and Swanson 1990, Garza 1995, Impara 1997, Krusemark et al. 1996, VanNorman 1998, Chapter Four). Researchers have justified the decision not to cross-date by asserting that the limited temporal resolution obtained is accurate enough to satisfy their ecological research objectives (Teensma 1987, Morrison and Swanson 1990, Agee et al. 1990, Impara 1997, Chapter Four). However, there has been little discussion as to how accurate is "accurate enough", and there has been little published research quantifying actual dating error, and resulting implications for fire history description and fire regime characterization. To aproach this problem for one study area in the central western Oregon Cascades, I initiated this comparison study by counting tree-rings on scarred stumps in the field, and then collecting these same stump surfaces for dendrochronological analysis in the laboratory.

The goal of this study was to determine the accuracy and precision of non-cross-dated, field-counted fire history data (i.e., fire scar and tree origin years). I also quantified how much of the dating error was associated with counting errors, and how much was due to tree-ring anomalies, such as double, partial, or missing rings. Specifically, I compared the accuracy of:

(1) field and cross-dated counts;

(2) counts on non-cross-dated, well-prepared slabs under a microscope and cross-dated counts;

(3) fire chronologies derived from field counts and from cross-dated counts; and,

(4) fire frequency estimates derived from field counts and from cross-dated counts.

I then posed two general questions:

(1) Given the observed error, should future fire history studies in the Pacific Northwest employ cross-dating?

(2) Given the observed error, how should results from existing, non-cross-dated fire history studies in the region be interpreted?

3.2 Methods

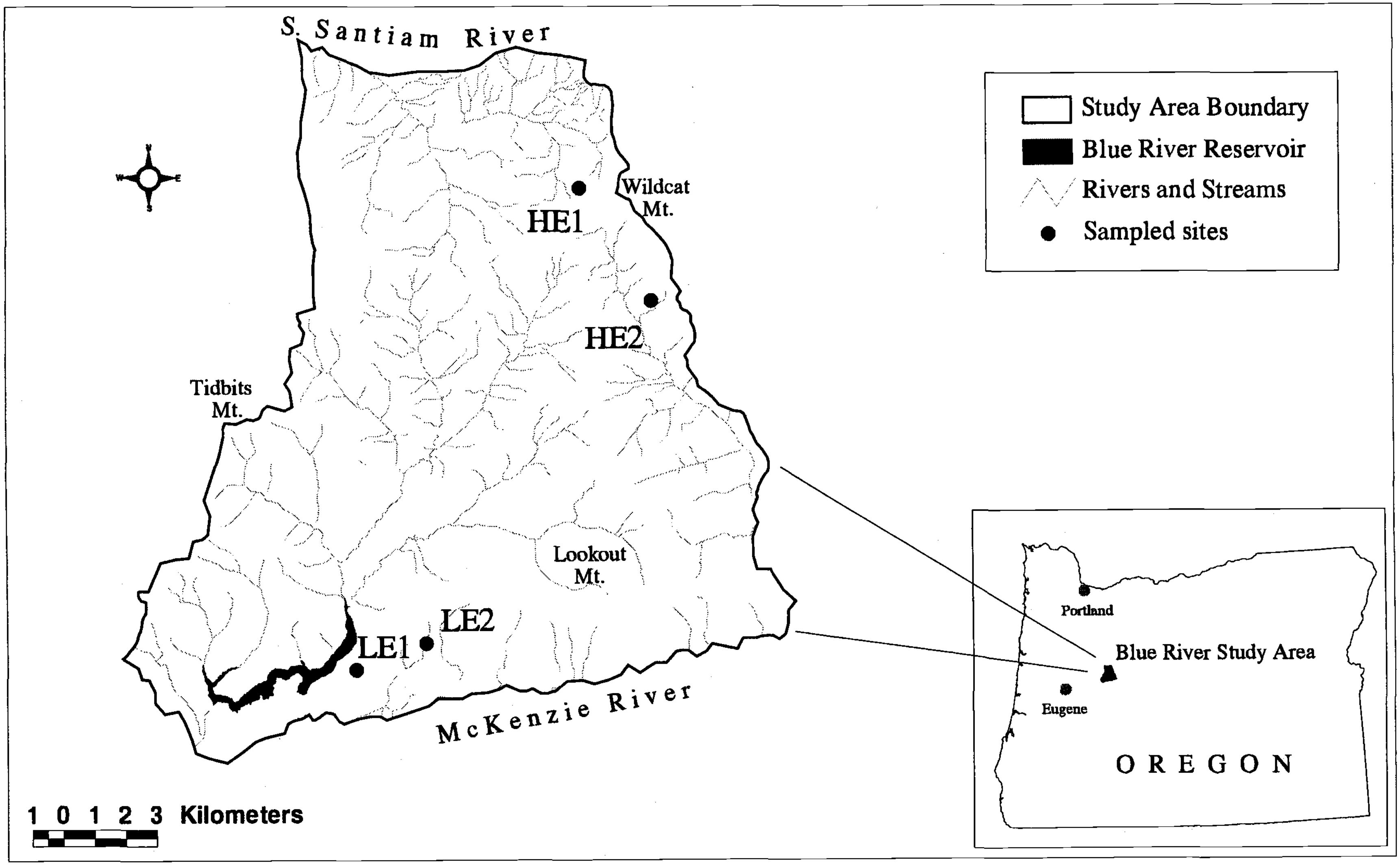
3.2.1. Field Methods

The four clearcut sites are located within the Blue River study area (Table 3.1, Fig. 3.1), described in Chapter Four. These sites were chosen from the set of 137 sampled fire history sites described in Chapter Four (Fig. 4.1), on the basis of having experienced a relatively high fire frequency, a high proportion of scarred Douglas-fir stumps, and a relatively recent harvest year, so that stumps were not too rotten for accurate sampling. Sites were located in clearcuts to facilitate collection of fire history data (Chapter Four). Sites were also chosen to represent both high and low elevations

Table 3.1. Environmental characteristics of the four fire history sites, sampled in 1997. Elevation, slope position, and approximate UTM coordinates were derived from GIS data layers; the other variables were measured in the field. Plant association was determined for standing forest adjacent to the clearcut sites (Franklin and Dyrness 1973).

Site	UTM Coordinates	Harvest Year	Elevation (m)	Slope Aspect	Slope Steepness	Plant Association
LE1	559465, 4892245	1989	740	Flat	Low	TSHE/ GASH-WILL
LE2	562225, 4893265	1991	575	203	Moderate	TSHE/ BENE
HE1	568405, 4911085	1992	1269	271	Low	ABAM/ TITR
HE2	571225, 4906645	1986	1187	222	Moderate	ABAM/ TITR

Fig. 3.1. Map of the Blue River study area, showing the four crossdated fire history sites.



and Pacific Silver Fir and Western Hemlock forest series, since fire dating error may differ for sites with different growing conditions (Table 3.1). I expected that trees at higher elevation sites would have both narrower rings and a greater incidence of tree-ring anomalies, such as missing, partial, or double rings, because of site conditions (e.g., delayed snowpack, cold temperatures, thin soils) leading to greater stress and lower productivity. These four sites were not intended to provide a representative fire history for the Blue River study area.

At each clearcut site, I searched an area up to approximately two hectares for fire-scarred stumps with adequately sound wood. I sampled 15 Douglas-fir stumps at each site. Sampling was limited to Douglas-fir because other species likely have different radial growth characteristics that would influence counting error and the occurrence of tree-ring anomalies, and Douglas-fir is the species that has been most frequently used for fire history interpretation. For each stump, I estimated fire scar and tree origin years in the field by counting tree-rings under 3X, 10X, or 16X magnification, after stump surface preparation with a wire brush, surform, and scrapers. I then collected the stump surface as a complete cross-section or as a wedge encompassing the area immediately adjacent to the fire-scarred portion of the bole, depending on the diameter of the tree. In some cases, multiple slabs were collected from a stump in order to sample all scars and origin years present. Sampled slabs were as long as two meters, and most were at least one meter long. Slabs often had to be cut as thick as 15 centimeters or more, so that sections of rotten wood would hold together.

3.2.2. Laboratory Methods

Slabs were air-dried, mounted on wooden boards, planed, and sanded until cellular structure was clearly visible (i.e., to grits 320 - 600). Dates of tree-rings containing scars or tree origin years were estimated by counting backwards from the outermost ring, which corresponded to a known harvest year. All counts were checked independently by a second researcher prior to further analysis. Fire year estimates were then determined precisely by cross-dating all tree-ring series using standard dendrochronological procedures (Stokes and Smiley 1968). An existing master tree-ring chronology from the study area was used to provide dating control[1].

I used skeleton plotting to match ring-width patterns, that had been represented as vertical lines on strips of paper, by matching ring-width patterns against the master tree-ring chronology, and also against skeleton plots of already cross-dated tree-ring series (Stokes and Smiley 1968). Important narrow marker rings included: 1982, 1959, 1945, 1930, 1918, 1890, 1889, 1883, 1880 (site HE1 only), 1849, 1812, 1804, 1769, 1740, 1691 (site HE1 only), 1677-1679, 1663 (site HE1 only), 1576, 1571, and 1546. The 1918, 1883, and 1849 marker rings were especially distinctive and ubiquitous. Certain years were also consistently associated with wide rings, including: 1990, 1983, 1960-1961, 1904, 1805, 1801-1803, 1773-1775, and 1621. Variation in latewood widths was marked on the skeleton plots and also used for cross-dating.

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[1] The master tree-ring chronology was obtained from Peter Brown, Director, Rocky Mountain Tree-Ring Research, Inc., 2901 Moore Lane, Ft. Collins, CO. 80526, U.S.A., and is a compilation of Douglas-fir master chronologies from the 1991 and 1997 Dendroecological Fieldweeks at the H.J. Andrews Experimental Forest. The chronology uses a 60-year spline to filter low-frequency variation.

Tree-rings with light-colored latewood (i.e., low latewood density) have proved valuable for cross-dating in higher elevation, more northerly parts of the Pacific Northwest, such as the Mount St. Helens area (Yamaguchi 1983, Yamaguchi and Hoblitt 1995). However, light rings were rare and not consistently associated with "signature years" in the Blue River study area, and were not used for cross-dating. The study area may not experience cool enough growing-season temperatures to induce formation of light rings from incomplete latewood cell wall development (Yamaguchi et al. 1993).

Since the master tree-ring chronology was not useful prior to ca. 1600 due to insufficient sampling depth, I matched skeleton plots for those trees with ring series extending before 1600 with each other, and so was able to cross-date some fire scar and tree origin years from as early as 1513. Earlier scar and origin years, including origin years at ca. 1318, ca. 1386, and ca. 1428, and scar years at ca. 1332, ca. 1368, and ca. 1428, could not be cross-dated.

3.2.3. Data Analysis

I compared scar and origin year estimates from both field counts and non-cross-dated, prepared slabs with cross-dated scar and origin years. Origin years were not corrected to stump height, and so refer to the year of accession to stump height (generally, 60 - 90 cm). Field-counted and prepared-slab estimates were compared with cross-dated ones graphically using histograms showing the distributions of differences between non-cross-dated and cross-dated estimates. I considered the cross-dated estimate to be the true year of scarring or of stump height accession, and so these differences are also referred to as "errors." I also calculated the mean, median, minimum, maximum, and standard deviation of dating errors. For calculating the mean, median, and standard deviation, the absolute value of the error was used, since errors could be positive or negative. Errors were not independent, since multiple scars often occurred on the same tree. An error in the outer rings would then propagate inwards towards the pith, with the effect that one counting error could affect several scar and origin year estimates. Therefore, no statistical analyses were conducted to compare error distributions. Sources of error, including harvest year errors, missing rings, double rings, and counting errors, were analyzed graphically for each site and for all sites pooled.

I also compared reconstructed fire history between field-counting and cross-dating methods. Two sets of criteria were used to reconstruct fire history for the cross-dating method. The 10% and 25% rules required that at least 10% or 25%, respectively, of all trees old enough to have recorded a given scar year recorded that scar year for a fire to be detected. Further, at least two scars had to be present for each detected fire year. The purpose of these rules was to exclude scars from non-fire sources (e.g., mechanical injury, animal damage) from the fire chronology, under the assumption that scars from non-fire sources were less likely to occur in the same year (Agee 1993). The same criteria were used to reconstruct fire history for the field-counting method, but were applied to scar year estimates clustered in time. Maximum duration of scar year clusters was 8 years for the 1800-1996 period, 10 years for the 1700-1799 period, and 12 years for the 1500-1699 period, as used in Chapter Four. Also, I split the scar "cluster" accordingly when two scars close in time were counted on the same radius of a single tree, indicating that two fires had occurred. The average scar year within a scar cluster was used to estimate the fire year, under the assumption that tree-ring counting errors were normally distributed around the correct value. For both field-counted and cross-dated methods, at least two origin years within a 40-year period prior to 1600, or three origin years within a 40-year period following 1600, indicated a fire even in the absence of scar evidence. Douglas-fir establishment may occur for at least 40 years following high-severity fire (Hemstrom and Franklin 1982). The earliest such origin year was used to estimate the fire year. Origin year data were essential for fire history reconstruction because many fires in the study area have initiated regeneration cohorts of Douglas-fir, but left very few surviving, scarred trees. Fire year estimates based solely on origin year data likely underestimated the actual age of the fire because: (1) origin years were not corrected to stump height, a correction of at least several years; and, (2) an unknown number of years had elapsed between the fire and establishment of the earliest recorded regeneration tree.

Some of the fire scars counted in the field were not found on the prepared-slab sections. They were not collected, were lost due to rotten wood or accidental removal during the slab preparation process, or were not found because they were not present on the lower slab surface, which was used instead of the upper surface for two or three samples. These scars were not used in the fire history reconstruction comparison, since they were unavailable for the cross-dated reconstruction. However, scars that were missed in the field but were observed and counted on prepared slabs were used in the fire history reconstruction comparison, since one advantage of using prepared slabs may be an enhanced ability to detect fire scars.

I reconstructed fire frequency for each site using both cross-dated and field-counted data sets, and 10% and 25% rules. Fire frequency was calculated, as defined in Chapter Four, as mean fire interval, median fire interval, maximum fire interval, and the number of fires. The interval between the estimated year of the last fire and the year of sampling was included in these calculations only when it exceeded 99 years.

3.3 Results

3.3.1. Time Expenditures

Much additional time was required to obtain cross-dated fire scar and tree origin year data. Field-counted data for the four sites were obtained in only 24 person-hours, including driving time. The cross-dated data required nearly 530 person-hours to obtain, distributed as follows:

(1) 12 hours (one person) to locate and mark scarred stumps of maximum suitability;

(2) 57 hours (three people at 19 hours each) to remove and transport slab sections;

(3) 340 hours (one person) to trim, mount and sand the slabs; and,

(4) 120 hours (two people) to count, cross-date, and check for accuracy.

3.3.2. Cross-dating Success

Only eight of sixty trees (13 %) could not be cross-dated for at least a portion of their tree-ring series. Over all four sites, 73 of 89 (82 %) prepared-slab fire scars were cross-dated. The other 16 scars were located along complacent tree-ring series (i.e., series with low interannual variation), located along tree-ring series with variability that was not consistent with overall patterns of variability for the study area, or (in one case) occurred too early in the record. I had expected Douglas-fir trees at the two high-elevation (HE) sites to have been more sensitive to climatic variation, and so more suitable for cross-dating. The HE sites did have narrower tree-rings than the low-elevation (LE) sites, suggesting that these are more marginal environments where growth factors may be more limiting. However, I was able to cross-date 30 of 38 scars (79 %) at the two HE sites and 43 of 51 scars (84%) at the two LE sites.

Patterns of cross-dating success for tree origin years were similar, as expected, since fire scar years and tree origin years were taken from the same set of tree-ring series. It makes sense that cross-dating success should be slightly less for origin years, since they involve longer records than fire scars, and so may be more prone to counting errors and tree-ring anomalies. I was able to cross-date 26 of 35 (74 %) prepared-slab, tree origin years over all four sites, including 14 of 20 (70 %) at the HE sites, and 12 of 15 (80 %) at the LE sites.

3.3.3. Error from Tree-ring Dating in the Field

Errors associated with tree-ring dating in the field were of two types: incorrect estimates of the fire scar or tree origin year, and failure to detect fire scars on minimally prepared stump surfaces. I detected 11 scars (i.e., 12% more) on prepared slab surfaces that were not detected in the field. These were distributed among sites LE1, LE2, HE1, and HE2 as 2, 3, 3, and 3 scars, respectively. Many of these scars were difficult to detect because they were very small and/or located on sections of very narrow growth-rings. Others were super-imposed upon scars from earlier fires, where the cambial layer had been repeatedly injured along the same radius, corresponding with a point of weakness in the bark. Such scars may be difficult to distinguish from patterns of healing over previous scars, even with appropriate magnification.

Far more common were errors in fire scar or tree origin year estimation. Over all four sites, the mean error for estimating scar years was 9.25 years, with a standard deviation of 13.53 years. The median error was 4.5 years, while minimum and maximum errors were -13 and +78 years, respectively. The distribution of errors was greatly skewed towards larger values, and most errors were positive values, indicating that scar ages were typically underestimated in field counts from failure to detect narrow tree-rings (Fig. 3.2). Field estimates of scar years fell within 10 years of their true values for about 75 %, and within 20 years for about 87 %, of the observed cases. Errors in scar year estimation were not closely associated with the age of the scarring event (i.e., fire), although ages of the four pre-1650 scars were estimated relatively poorly (Fig. 3.3).

The accuracy of fire scar year estimation differed among the four sites. The range of fire scar year errors was greater for the two high-elevation sites (Table 3.2, Fig. 3.4). These sites, with longer fire intervals (Chapter Four) and more marginal growing conditions for Douglas-fir, contain stumps from especially old trees with long sections of extremely narrow tree-rings, and so may be most prone to error. However, the median scar-year error did not differ consistently between LE and HE sites (Table 3.2).

Tree ages were also consistently underestimated, and were estimated less accurately than scar years (Fig. 3.5). Over all four sites, the mean and median origin year errors were 25 and 14 years, respectively, and the standard deviation was 26 years. The greatest overestimate and underestimate of tree age were 89 years for both, although most large errors were underestimates (Fig. 3.5). Errors in tree origin years were not strongly associated with tree age, although tree ages prior to ca. 1550 were estimated less accurately (Fig. 3.6). The three oldest tree origin years could not be cross-dated, but

Fig. 3.2. Distribution of errors for field-counted scar year estimates, with all four sites pooled. The number of scar counts with errors within ten-year classes is shown as the difference between the field-counted estimate and the cross-dated value.

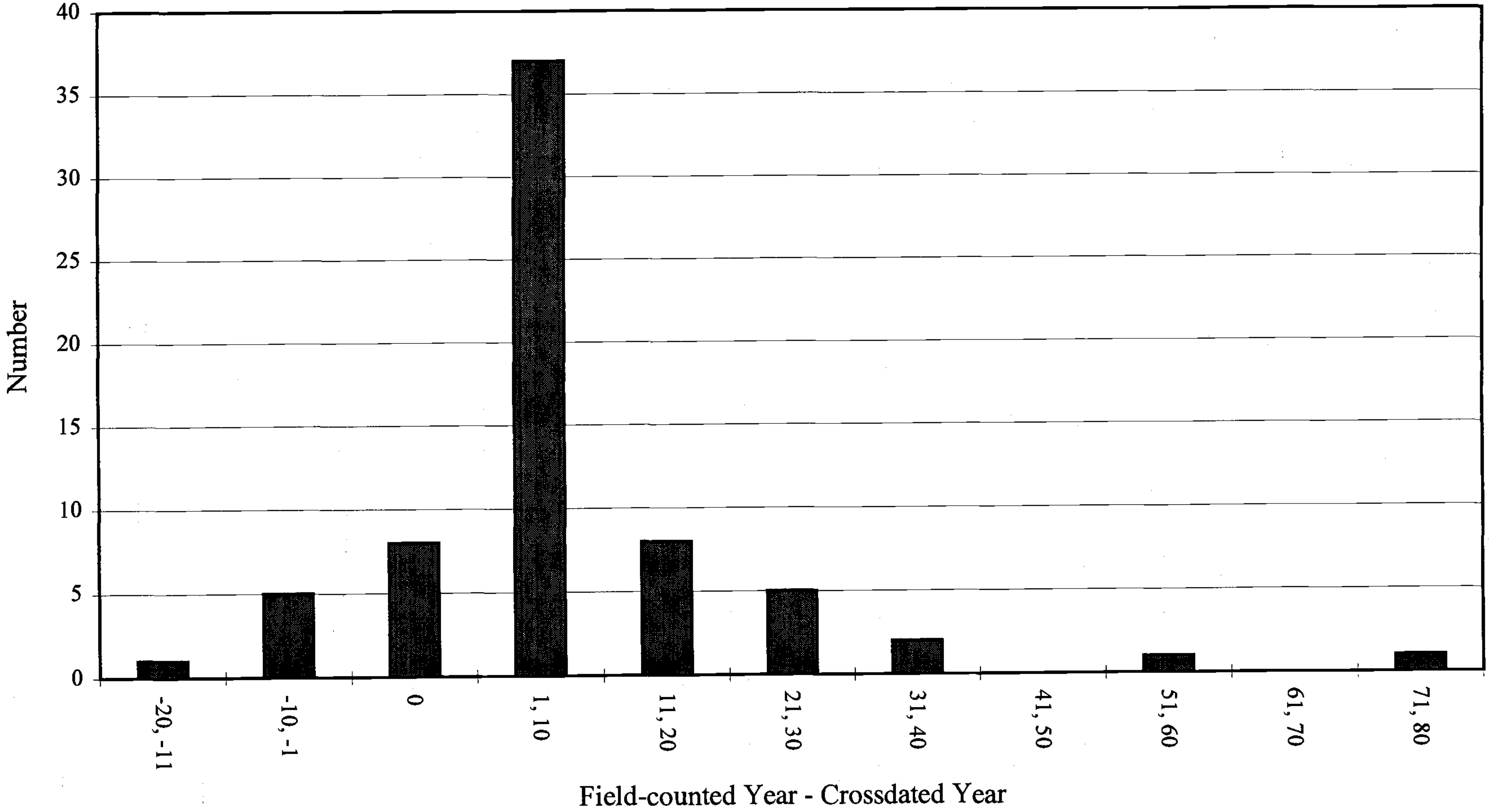


Fig. 3.3. Errors in field estimates of scar years over time. Positive values on the y-axis indicate the field-counted estimate is more recent than the cross-dated scar year.

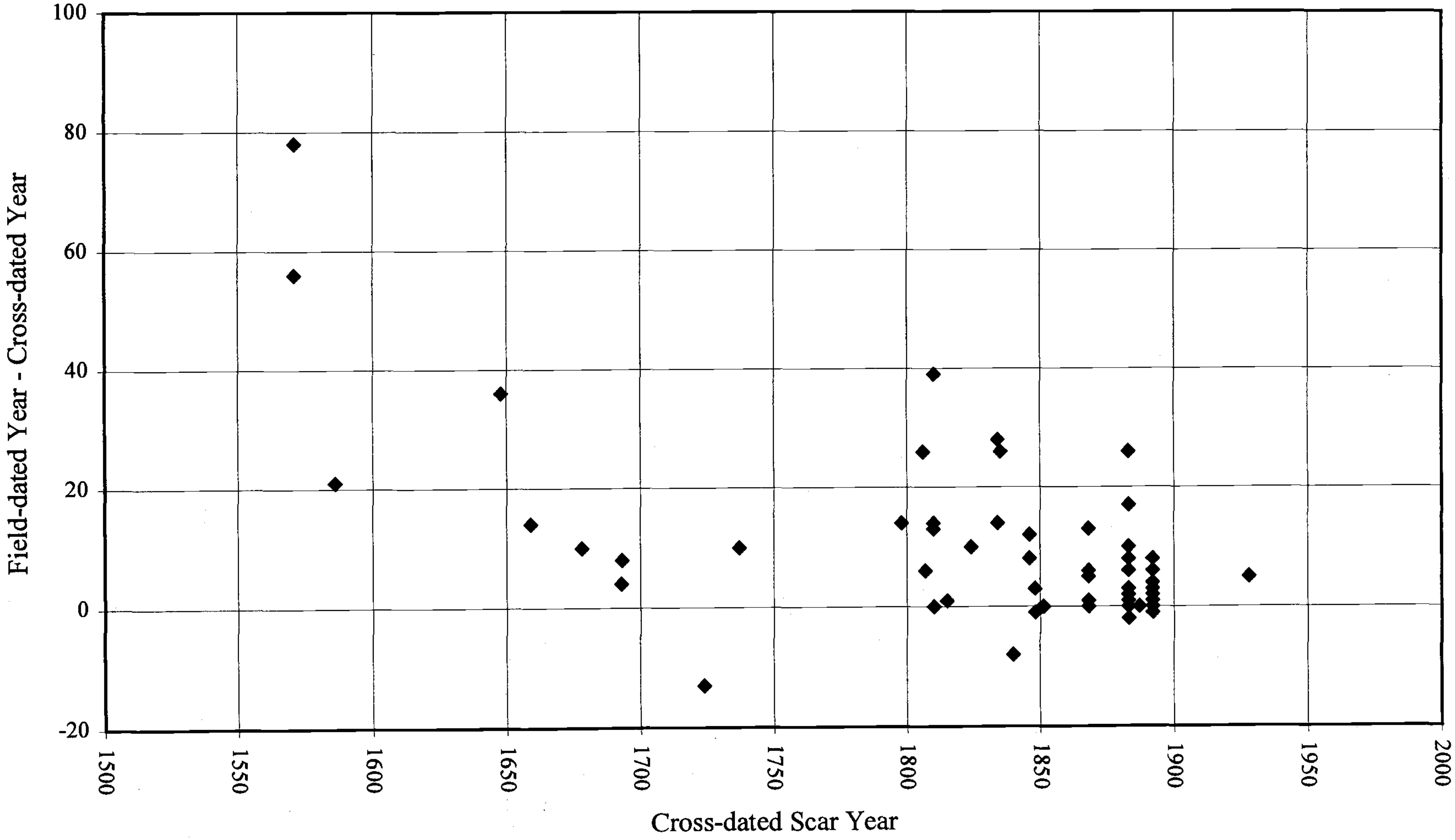
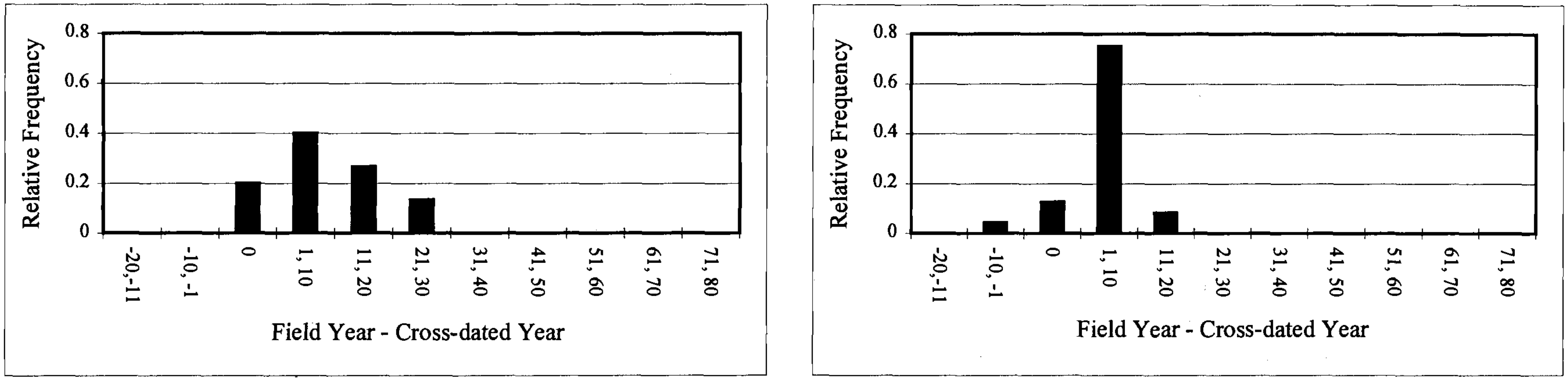


Table 3.2. Parameters of error distributions for field-counted fire scar and tree origin years. The mean, median, and standard deviation are calculated for absolute values of the errors.

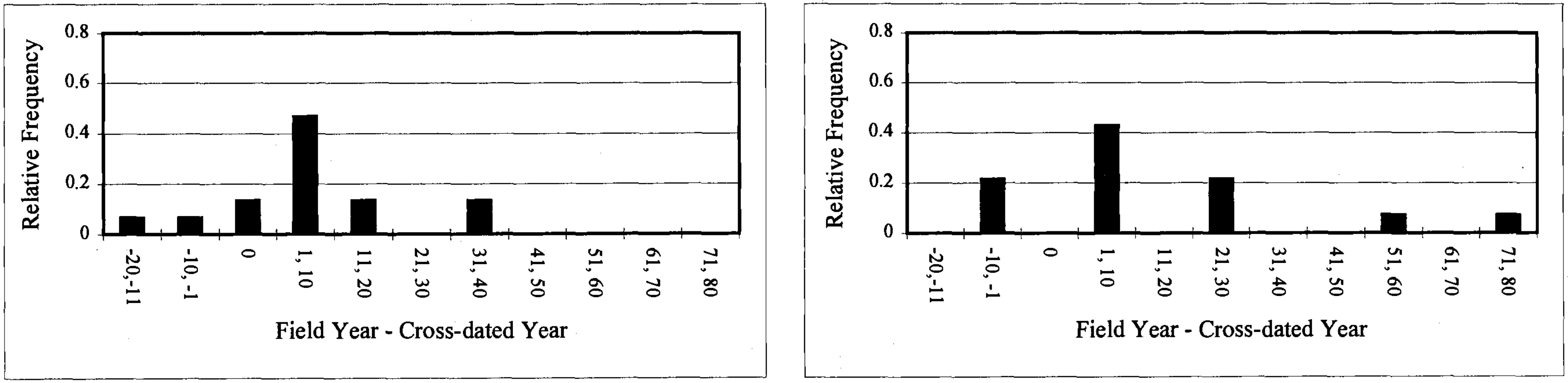
Scar Year Errors				
Site	**LE1**	**LE2**	**HE1**	**HE2**
Mean	9.47	3.75	10.60	17.00
Median	8	2	8	4.5
Std. Deviation	9.11	4.26	11.79	23.43
Min, Max	0, 28	-1, 14	-13, 39	-2, 78
Sample Size	15	24	15	14
Origin Year Errors				
	LE1	**LE2**	**HE1**	**HE2**
Mean	11.00	10.71	49.67	13.40
Median	11.5	9	53	12
Std. Deviation	6.48	10.18	30.15	7.80
Min, Max	-3, 18	1, 31	-89, 88	6, 22
Sample Size	4	7	9	5

Fig. 3.4. Distributions of errors for field-counted scar year estimates over the four sites. The cross-dated scar years are used as the basis for comparison.



a. LE1

b. LE2



c. HE1

d. HE2

Fig. 3.5. Distribution of errors for field-counted origin year estimates, with all four sites pooled. The number of scar counts with errors within ten-year classes is shown as the difference between the field-counted estimate and the cross-dated value.

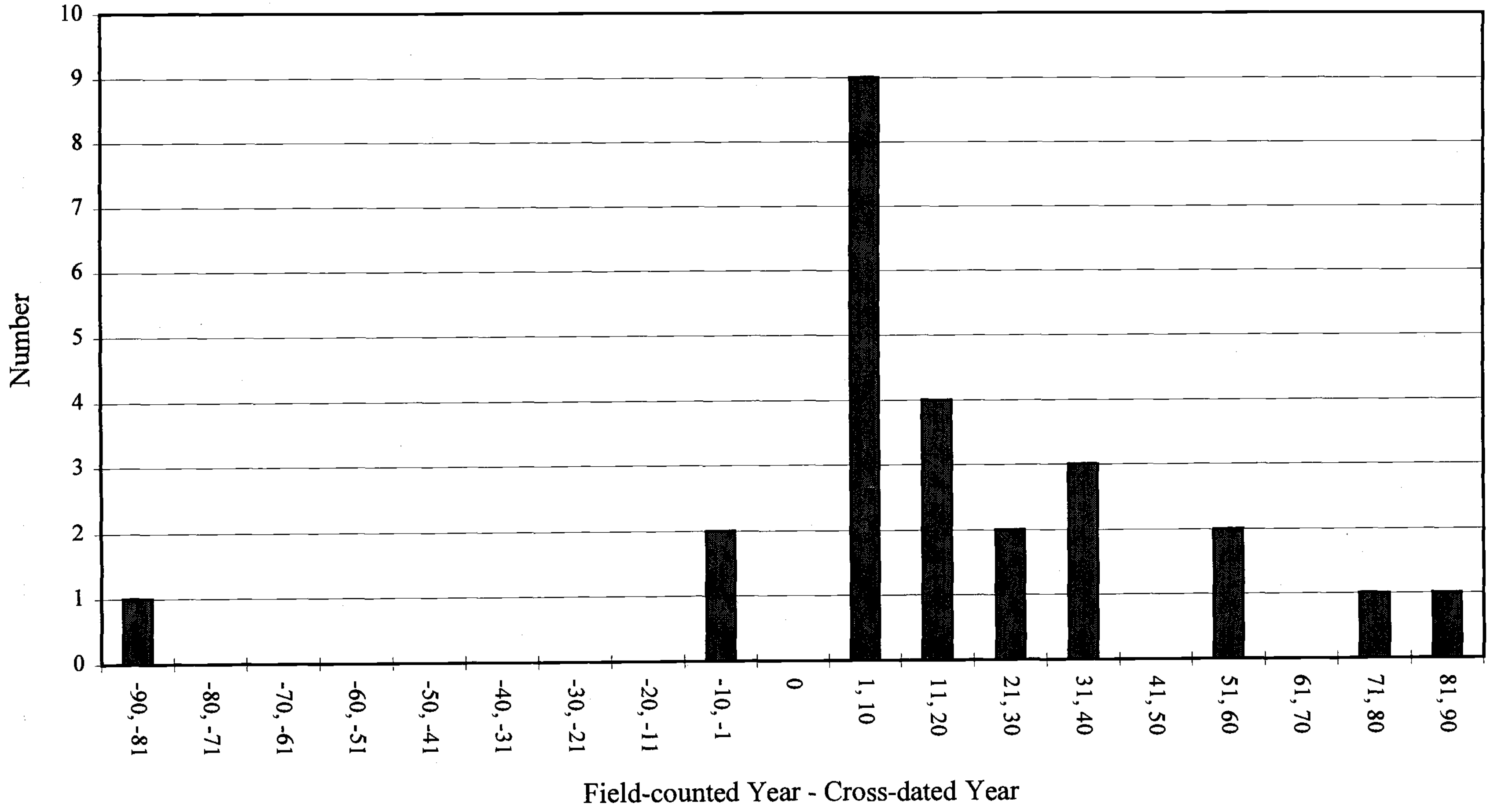
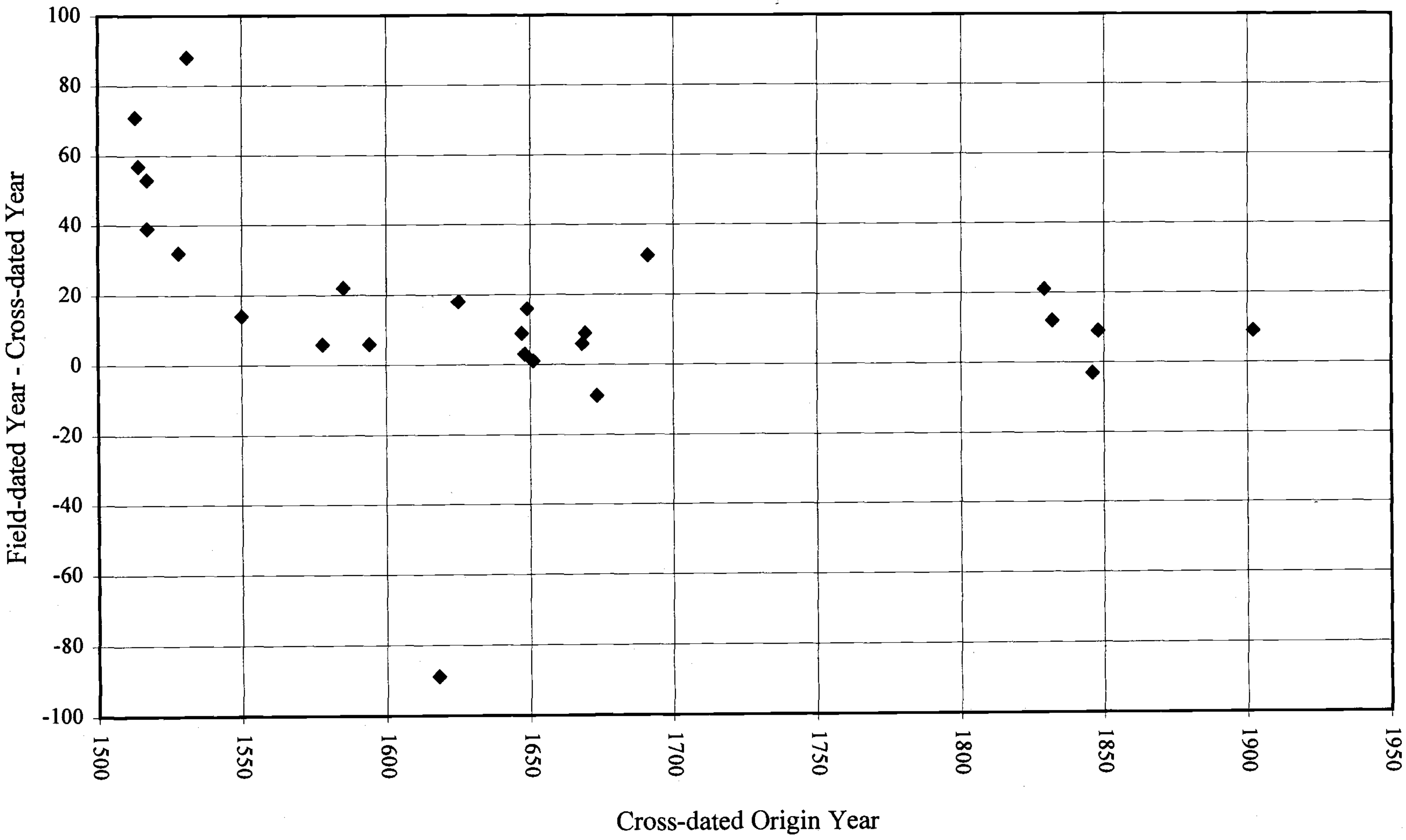


Fig. 3.6. Errors in field estimates of origin years over time. Positive values on the y-azis indicate the field-counted estimate is more recent than the cross-dated origin year.



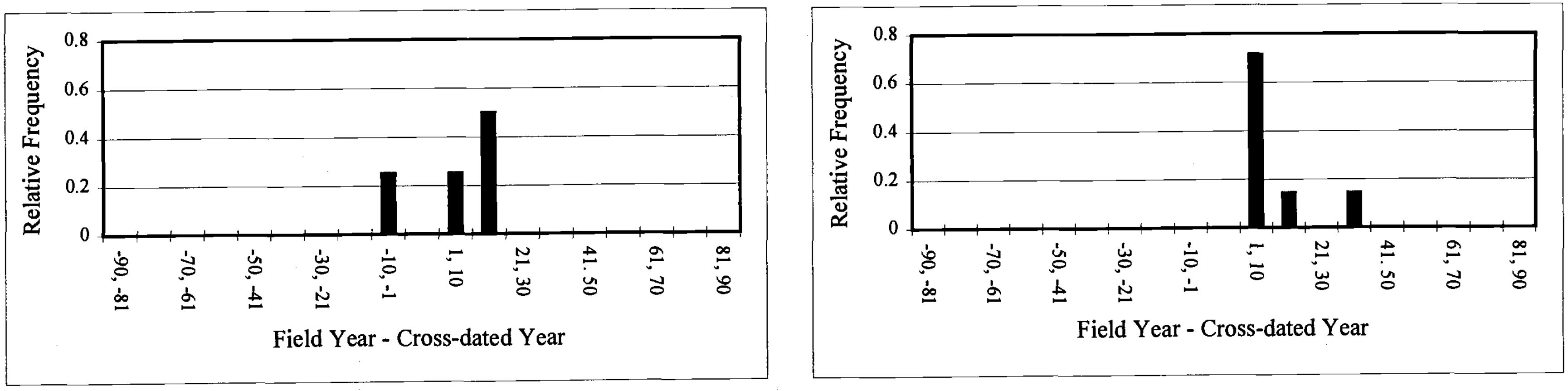
prepared-slab counts suggested even greater errors for earlier tree ages, with errors (i.e., field-counted vs. prepared but non-cross-dated slabs) of 11 years, 121 years, and 70 years for estimated ages of 1307, 1307, and 1316, respectively.

Origin years at site HE1 were estimated far less accurately than at the other three sites (Table 3.2, Fig. 3.7). If site HE1 were removed from the analysis, pooled origin year errors would have a mean, median, standard deviation, minimum, and maximum of 12, 9, 8, -3, and +31 years, respectively. Site HE1 occupies the highest elevation of the four sites, and may represent especially marginal growing conditions for Douglas-fir. However, all three origin years from the 1300s were from site HE2. Had these three tree ages been cross-dateable, it is likely that both HE sites would have been observed to have greater error in origin year estimation than the LE sites. Since the HE sites had both longer stretches of narrow rings and a greater proportion of older trees, this was not a surprising result.

3.3.4. Error from Not Cross-dating Prepared Cross-sectional Surfaces

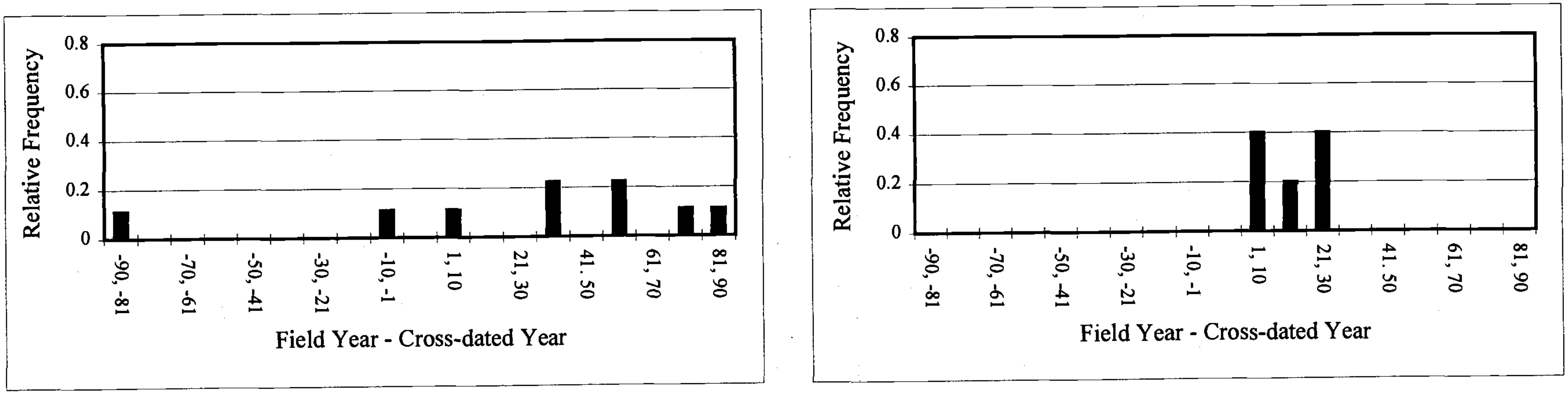
The error from using non-cross-dated but well-prepared slab surfaces was not nearly as great as the error from using field counts to estimate scar and tree origin years. Except for two 20-year errors resulting from 20 missing outer rings on one slab, there was minimal error associated with not cross-dating scar years (Fig. 3.8). Including the 20-year errors, the mean error was 1.47 years, with a median error of 1 year and a standard deviation of 3.25 years. Excluding the 20-year errors, since errors of this type could be avoided by using only slab sections with evidence of the outer bark present, the mean

Fig. 3.7. Distributions of errors for field-counted origin year estimates over the four sites. The cross-dated origin years are used as the basis for comparison.



a. LE1

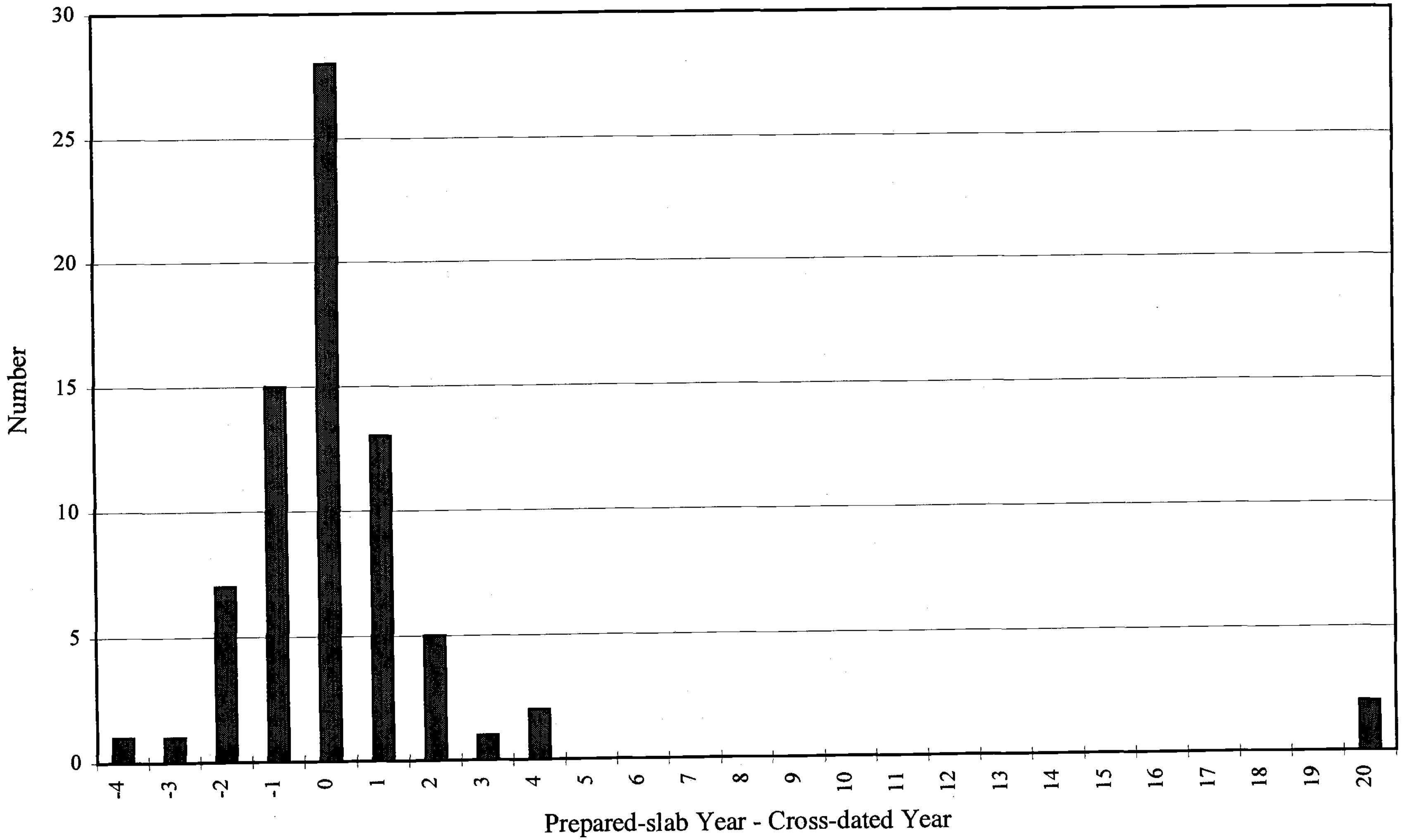
b. LE2



c. HE1

d. HE2

Fig. 3.8. Distribution of scar year errors for non-cross-dated, prepared slabs for all four sites pooled.



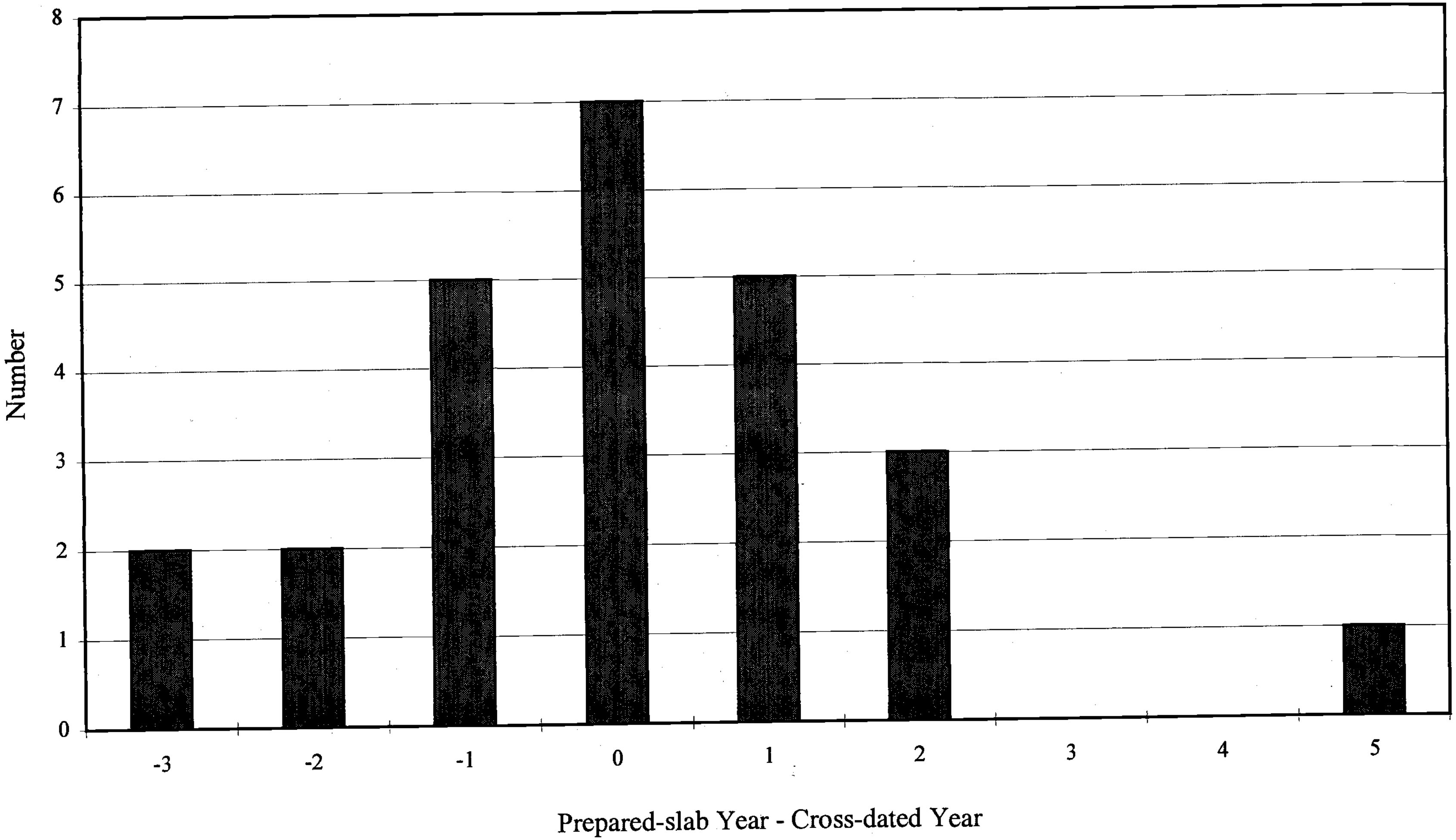
error was 0.96 years, with a median error of 1 year and a standard deviation of 1.02 years. Scars were dated without error on 28 of 75 (37 %) sampled scars.

Origin year errors were also low for non-cross-dated counts on well-prepared slabs (Fig. 3.9). The mean error was 1.24 years, with a median error of 1 year and a standard deviation of 1.2 years. Origin years were dated without error for 7 of 25 (28 %) trees. For well-prepared slabs, overestimations and underestimations of both scar and origin years were about equally likely (Figs. 3.8, 3.9).

3.3.5. Sources of Error

Errors in estimates of scar and origin years from well-prepared, but not cross-dated, slabs were of four general types: outer ring errors, missing rings, double rings, and counting errors. Outer ring errors included both errors in assigning the season of harvest and errors due to missing outer rings. While the year of harvest was available from U.S. Forest Service records for each site, such records often confound the year of harvest with the year of planting, and the season of harvest was unknown for sites where harvest occurred during the "dormant" season. Also, harvest at a given site may have been protracted over a longer period including multiple seasons. Thus, there was a potential error of one year where only the year, and not the date, of harvest was known. Outer ring errors due to missing outer rings can have more serious consequences. The bark was sometimes lost when the slab was cut, or during sanding. Without having bark present, it could be difficult to tell whether the outer rings of the slab included the last years prior to harvest.

Fig. 3.9. Distribution of origin year errors for non-cross-dated, well-prepared slabs, for all four sites pooled.



Missing rings occurred when the tree did not produce an annual radial growth increment during an especially stressful year, or where a partial ring was produced that did not include the radius being counted. These were inferred from shifts in tree-ring series suggested by cross-dating against a master chronology, where additional tree-rings needed to be added for the previous marker years to correlate well, and counting errors were not found. Double rings occurred when the tree produced a narrow band of latewood between two periods of earlywood production, during the same growing season. This may have resulted from periods of extreme drought followed by rainfall adequate to relieve growth stress. Double rings were usually detectable due to their extreme narrowness and gradual transition into the earlywood on both sides (Stokes and Smiley 1968), but were sometimes difficult to differentiate when part of a long series of very narrow rings. Counting errors were sometimes found, despite careful checking of tree-ring counts.

Most errors were outer ring errors and counting errors, pooled over all four sites (Fig. 3.10). Relatively few missing and double rings were observed. Only 7 of 60 (12 %) trees had missing ring errors, and only 6 of 60 (10 %) trees had double ring errors. No errors were found on 17 trees (28 %). Most trees did not have multiple decades with errors of a given type (Fig. 3.10). One tree had four missing rings in a single decade.

The distributions of error types differed among HE and LE sites. All but one of the detected missing and double ring errors were found at the HE sites (Fig. 3.11). Eleven of 24 LE trees (46 %) were counted without error, compared to 6 of 28 HE trees (21%). Dating error at the LE sites was due mainly to counting and outer ring errors.

Fig. 3.10. Types of errors on prepared slabs that were corrected by cross-dating, pooled over all four sites.

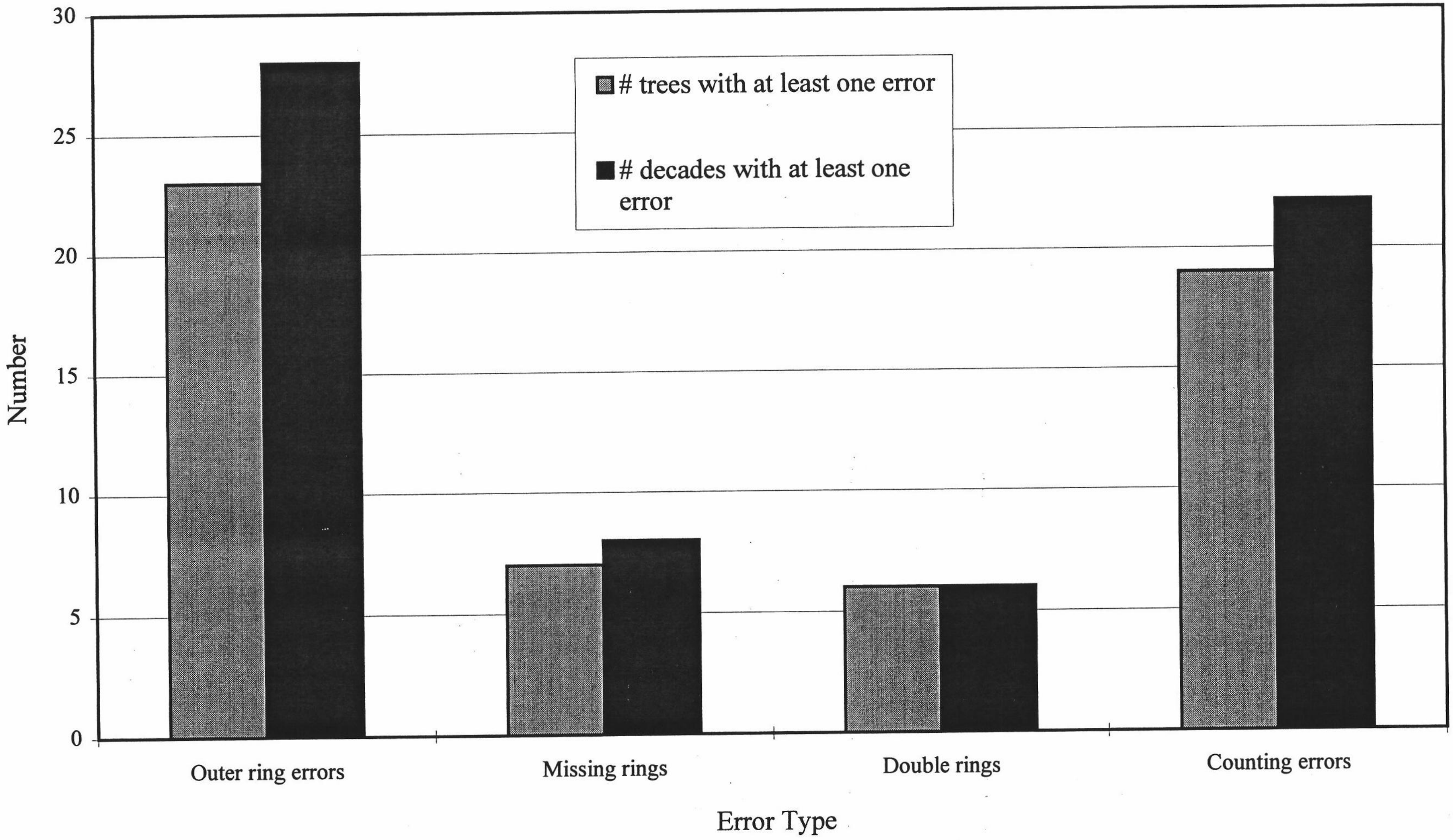
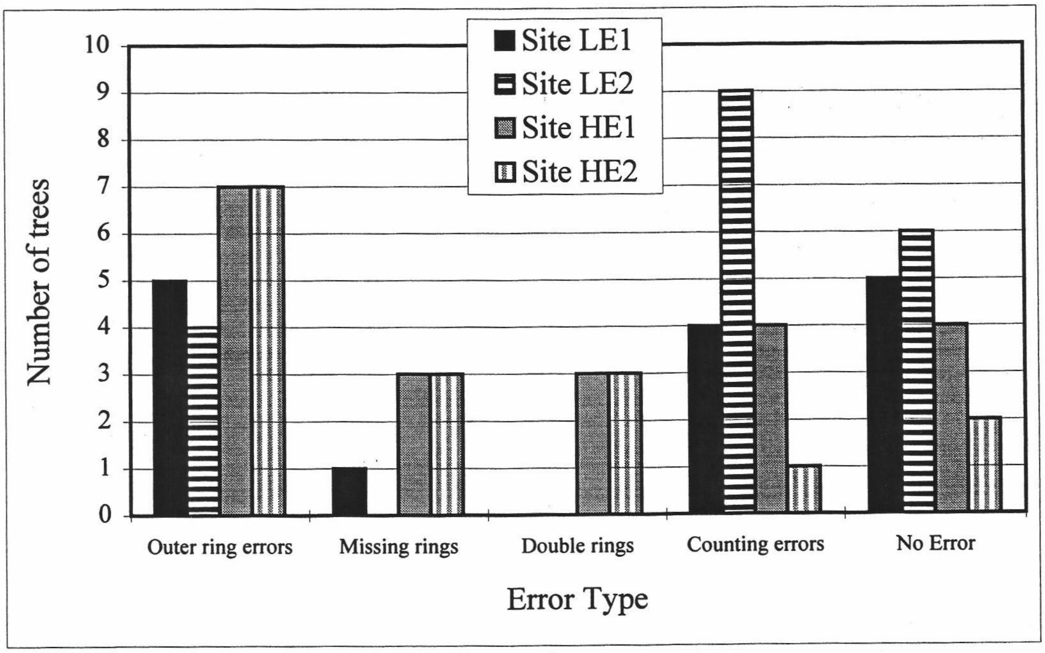
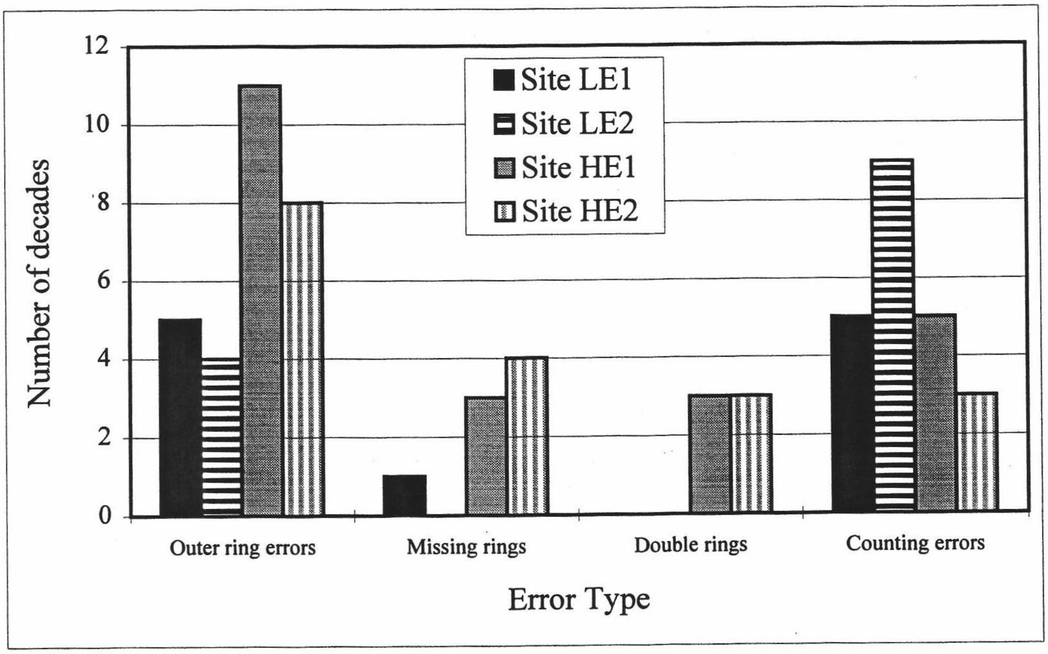


Fig. 3.11. The number of trees and decades with errors of various types that were corrected by cross-dating, shown separately for each site.



a. Number of trees with errors



b. Number of decades with errors

3.3.6. Errors in Fire Detection and Dating

Detected fires are shown for the four sites, for cross-dated and field counts over the two fire detection rule-sets (Tables 3.3 - 3.6). For site LE1, analysis of the field-counted data resulted in one additional fire for the 10% scarred rule-set, and the same number of fires for the 25% scarred rule-set (Table 3.3). The 1550 fire was included in the cross-dated analysis, despite being represented by only one cross-dated origin year, because a well-prepared (but not cross-dated) slab was counted with a similar origin year, and errors were small between cross-dated origin years and counts from well-prepared slabs (Fig. 3.9). Using the field-counted data, the 1550 fire was estimated to have occurred in 1564, the 1834 fire to have occurred in 1850, the 1846 fire to have occurred in 1860, and the 1883 fire to have occurred over two fires in 1886 and 1897. The 1897 fire results from two 1883 scar years having been under-counted by 10 and 17 years. The 25% fire detection criterion eliminates the 1846/1860 fire from both reconstructions, and eliminates the erroneous 1897 fire from the field-counted reconstruction. Thirteen of fifteen cross-dated scars (87%), and 15 of 20 (75%) field-counted scars, were used in the fire history reconstruction (i.e., considered fire scars).

The same number of fires was detected for site LE2, regardless of fire detection criteria used and whether or not cross-dating was employed (Table 3.4). Fire ages were underestimated slightly in the field-counted reconstruction. The 1647 fire was estimated to have occurred in 1651, the 1868 fire to have occurred in 1872, and the 1892 fire to have occurred in 1893. I used 21 of 23 (91%) cross-dated scars, and 17 of 20 (85%) field-counted scars, in the fire history reconstruction.

Table 3.3. Reconstructed fires for cross-dated and field-counted fire history data (1500 - 1996) collected at site LE1. See text for explanation of fire delineation criteria. Fire year estimates based solely on origin year data underestimate fire ages, and are italicized.

Site LE1

Cross-dated Scar Years (number)	Cross-dated Origin Years	Cross-dated Fires: 10% Scarred	Cross-dated Fires: 25% Scarred	Field-counted Scar Year Clusters (number)	Field-counted Origin Years (number)	Field-counted Fires: 10% Scarred	Field-counted Fires: 25% Scarred
1693 (1)	1550 (1)	*1550*	*1550*	1697 (1)	1564 (1)	*1564*	*1564*
1834 (3)	1625 (1)	1834	1834	1757 (1)	1572 (1)	1850	1850
1846 (2)	1840 (1)	1846		1805 (1)	1619 (1)	1860	
1883 (8)	1846 (1)	1883	1883	1848-54 (3)	1643 (1)	1886	1886
1887 (1)	1848 (1)			1858-62 (3)	1666 (1)	1897	
				1868 (1)	1843 (1)		
				1883-89 (7)	1847 (1)		
				1893 - 00 (2)	1857 (1)		
				1909 (1)	1860 (1)		

Table 3.4. Reconstructed fires for cross-dated and field-counted fire history data (1500 - 1996) collected at site LE2. See text for explanation of fire delineation criteria. Fire year estimates based solely on origin year data underestimate fire ages, and are italicized.

Site LE2

Cross-dated Scar Years (number)	Cross-dated Origin Years	Cross-dated Fires: 10% Scarred	Cross-dated Fires: 25% Scarred	Field-counted Scar Year Clusters (number)	Field-counted Origin Years (number)	Field-counted Fires: 10% Scarred	Field-counted Fires: 25% Scarred
1659 (1)	1647 (1)	*1647*	*1647*	1673 (1)	1651 (1)	*1651*	*1651*
1824 (1)	1648 (1)	1868	1868	1834 (1)	1652 (1)	1872	1872
1868 (8)	1649 (1)	1892	1892	1868-74 (5)	1656 (1)	1893	1893
1892 (13)	1651 (1)			1881 (1)	1665 (1)		
	1668 (1)			1891-94 (12)	1674 (1)		
	1669 (1)				1678 (1)		
	1691 (1)				1722 (1)		

Table 3.5. Reconstructed fires for cross-dated and field-counted fire history data (1500 - 1996) collected at site HE1. See text for explanation of fire delineation criteria. Fire year estimates based solely on origin year data underestimate fire ages, and are italicized.

Site HE1

Cross-dated Scar Years (number)	Cross-dated Origin Years	Cross-dated Fires: 10% Scarred	Cross-dated Fires: 25% Scarred	Field-counted Scar Year Clusters (number)	Field-counted Origin Years (number)	Field-counted Fires: 10% Scarred	Field-counted Fires: 25% Scarred
1648 (1)	1513 (1)	*1513*	*1513*	1684 (1)	1529 (1)	*1551*	*1551*
1724 (1)	1514 (1)	1810	1810	1711 (1)	1551 (1)	1826	
1810 (4)	1517 (2)	1892	1892	1810 (1)	1556 (1)	1894	1894
1837 (1)	1528 (1)			1823-32 (3)	1560 (1)		
1840 (1)	1531 (1)			1849 (1)	1570 (1)		
1883 (1)	1618 (1)			1891-96 (6)	1571 (1)		
1892 (5)	1673 (1)			1900 (1)	1584 (1)		
1912 (1)	1902 (1)			1933 (1)	1619 (1)		
1928 (1)					1664 (1)		
1932 (1)					1911 (1)		

Table 3.6. Reconstructed fires for cross-dated and field-counted fire history data (1500 - 1996) collected at site HE2. See text for explanation of fire delineation criteria. Fire year estimates based solely on origin year data underestimate actual fire ages, and are italicized.

Site HE2

Cross-dated Scar Years (number)	Cross-dated Origin Years	Cross-dated Fires: 10% Scarred	Cross-dated Fires: 25% Scarred	Field-counted Scar Year Clusters (number)	Field-counted Origin Years (number)	Field-counted Fires: 10% Scarred	Field-counted Fires: 25% Scarred
1571 (2)	1578 (1)	*1571*	*1571*	1607 (1)	1550 (1)	*1584*	*1584*
1586 (1)	1585 (1)	1848		1627 (1)	1584 (1)	1815	
1678 (1)	1594 (1)	1883	1883	1649 (1)	1600 (1)	1849	
1807 (1)	1829 (1)			1688 (1)	1607 (1)	1884	1884
1835 (1)	1832 (1)			1725 (1)	1630 (1)		
1848 (2)				1813-17 (2)	1844 (1)		
1883 (5)				1847-51 (3)	1850 (1)		
1892 (1)				1861 (1)			
				1881-86 (5)			

At site HE1 the same number of fires was detected using the 10% criterion, while one cross-dated fire was lost using the 25% criterion (Table 3.5). Using the 10% criterion, the 1513 fire was estimated to have occurred in 1551, the 1810 fire estimated to have occurred in 1826, and the 1892 fire to have occurred in 1894. The 1810/1826 fire was lost for the field-counted reconstruction using the 25% criterion because one of the four 1810 scars was correctly counted, and so was not temporally offset with the other three scars of that year, and could not be counted in the same scar year cluster. I used 9 of 17 (53%) cross-dated scars, and 9 of 15 (60%) field-counted scars, in the fire history reconstruction.

At site HE2, the field-counted reconstruction included an additional, erroneous fire for the 10% criterion (Table 3.6). However, the 1815 fire in the field-counted reconstruction likely should have been present as an 1807 fire in the cross-dated reconstruction. Scars counted to 1813 and 1817 in the field were both counted to 1807 on well-prepared slabs, but the 1817 field-counted scar could not be cross-dated, and so was omitted from the cross-dated fire history reconstruction. Excluding the 1807/1815 fire, discrepancies in fire history reconstruction were not great (Table 3.6). The 1571 fire was estimated to have occurred in 1584, the 1848 fire to have occurred in 1849, and the 1883 fire to have occurred in 1884. I used 9 of 14 (64%) cross-dated scars, and 10 of 16 (63%) field-counted scars, in the fire history reconstruction.

Fire years were better correlated between LE and HE site pairs than within them. The 1883 fire year was recorded at sites HE2 and LE1, and a single crossdated scar at HE1 indicates that it may have burned there also. The 1892 fire year was recorded at sites HE1 and LE2, with a single scar at HE2. None of the other fire years was recorded at more than one site.

3.3.7. Errors in Fire Frequency Analysis

Calculated measures of fire frequency were similar between cross-dated and field-counted sites where the number of fires detected was the same, but differed considerably where a different number of fires was detected (Table 3.7). For example, where the number of fires detected was different, the error in calculated mean fire interval, median fire interval, and maximum fire interval varied from 23 to 62 years, 40 to 119 years, and 2 to 47 years, respectively. Although it is tenuous to generalize from only four sites, these results suggest that the maximum fire interval may be relatively insensitive to errors in fire dating, while the median fire interval may be especially sensitive.

Although the range of fire scar year errors was greater for HE than for LE sites (Table 3.2, Fig. 3.4), fire detection and fire frequency errors were comparable between the two elevation zones (Table 3.7). The most extreme field-counted errors, found in the HE sites, were not included in scar year clusters for the fire history reconstruction.

3.4 Discussion

3.4.1. The Context of Fire-Dating Error in Fire Regime Analysis

Error in dating fire events is but one of many sources of error and uncertainty for fire history analysis in the western Cascades (Chapter Two; Figure 2.1). In Chapter Two, I discuss how four factors distort the actual fire history for tree-ring-based, fire regime

Table 3.7. Estimates of fire frequency (years) for the four fire history sites, for both cross-dated and field-counted methods of fire history reconstruction, using two different rules for the percentage of scars required to define a fire year.

Site LE1

	Cross-dated		Field-Counted	
	10% Rule	25% Rule	10% Rule	25% Rule
Mean Fire Interval	109	149	83	144
Median Fire Interval	75	113	19	110
Maximum Fire Interval	284	284	286	286
Number of Fires	4	3	5	3

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Site LE2

	Cross-dated		Field-Counted	
	10% Rule	25% Rule	10% Rule	25% Rule
Mean Fire Interval	116	116	115	115
Median Fire Interval	104	104	103	103
Maximum Fire Interval	221	221	221	221
Number of Fires	3	3	3	3

Table 3.7. *Continued.*

Site HE1

	Cross-dated		Field-Counted	
	10% Rule	25% Rule	10% Rule	25% Rule
Mean Fire Interval	161	161	149	223
Median Fire Interval	104	104	102	223
Maximum Fire Interval	297	297	276	344
Number of Fires	3	3	3	2

****

Site HE2

	Cross-dated		Field-Counted	
	10% Rule	25% Rule	10% Rule	25% Rule
Mean Fire Interval	142	213	103	206
Median Fire Interval	113	213	74	206
Maximum Fire Interval	277	312	231	300
Number of Fires	3	2	4	2

characterizations: (1) the erasure problem, where trees carrying fire evidence are killed over time, and through successive fire events; (2) sampling methodology, where an incomplete sample of the population of trees and sites with fire evidence is sampled; (3) the fire detection and dating filter, where certain scarring events are determined to have been fires, and fires are dated through approximation from imprecise estimates, or precisely by cross-dating; and, (4) the analytical filter, where reconstructed fire history is described in terms of fire frequency, severity, size, and spatial pattern.

While field-counted scar and origin year estimates may include large errors (Figs. 3.2, 3.5), sometimes resulting in incorrect estimates for fire frequency descriptors (Table 3.7), these errors may be small compared to other error sources. The Blue River study area for the past several centuries was characterized by a variable fire regime, where stand-replacing crown fires, partial-stand-replacing fires, and non-lethal underburns were all important (Chapter Four), depending on fuel and weather conditions. Such fire regimes present the greatest problems for fire history reconstruction with regard to the erasure problem and analytical methods for fire regime characterization (Chapter Two). Especially important is the inability to consistently and objectively determine which scars represent fire scars, due to the scarcity of "recorder trees" with open catfaces (Chapter Two). For studies in many low-severity fire regimes, all scars but the earliest on an open, multiple-scarred catface can safely be considered fire scars. When cross-dating is employed, such studies neatly circumvent the "fire detection and dating filter" (Fig. 2.1).

Studies in the central western Oregon Cascades do not allow confident determination of which scars are fire scars, and so must rely upon arbitrary criteria to objectively define fire events from the population of sampled scars (e.g., Table 4.1).

Differences in fire history reconstruction and fire regime characterization associated with such criteria may exceed error associated with field-counting and not cross-dating. For example, 17 of 69 (approximately 25%) of cross-dated scar years shown in Tables 3.3 - 3.6 were not used to date fire episodes using either the 10% or 25% criteria. If it were known that all sampled scars were of fire origin, then the criterion for detecting a fire would be a single scar, and many more fires would have been detected. Resulting estimates for fire frequency descriptors (Table 3.7) would differ greatly from those obtained using either the 10% or 25% criterion. In fact, differences in fire frequency resulting from use of either the 10% or 25% criterion often exceeded differences associated with field-counted vs. cross-dated methods (Table 3.7).

3.4.2. Are Field Counts Accurate Enough for Fire History Reconstruction in the Westside Cascades?

The suitability of non-cross-dated, field-counted fire history studies is determined by the study objectives and the fire regime being studied. In the westside Cascades, fires are generally infrequent with mean fire intervals ranging from 80 to 300 years (Hemstrom and Franklin 1982, Teensma 1987, Garza 1995, Morrison and Swanson 1990, Chapter Four). However, fires of the past 400 to 500 years have not been evenly distributed over time. They have been clustered from the 1400s to the early 1600s, and from the 1800s to the early 1900s (Chapter Four). Within these periods, fire intervals have often been short. If research objectives require differentiation of fires that occur within 20 years of each other, field-counted studies may not provide sufficient accuracy, since errors in fire scar estimation average nine years. Although most fire scar years were estimated to within ten years of their correct value, the 25% that were not may cause actual fires to be undetected, or cause nonexistent fires to be falsely detected. Estimates that are far off the mark will generally be recognized as such, and excluded from the process of fire history reconstruction. Estimates within ten or twenty years of the true value are more problematic because they are more likely to result in erroneous fires being introduced into the chronology, particularly when fires occur closely in time.

For example, let us suppose a site burned in 1880 and 1890. Some of the 1880 fire scars are likely to be counted accurately (e.g., from 1878 to 1882), and others estimated to have occurred over a broad range from 1883 to 1892 or so. Meanwhile, some of the 1890 fire scars are likely to be counted accurately, and others to have occurred over a broad range from 1893 to 1902 or so. As a result, the field-counted fire scar data set will include a range of estimates from 1878 to 1902, a 24-year period. With such a wide spread of scar estimates, it is unlikely that the correct number of fires will be reconstructed. Most estimates will occur between 1883 and 1892, when overestimates from the 1880 fire overlap accurate estimates from the 1890 fire. Many estimates will also fall shortly before and after that period. It is likely that either one or three fires will be reconstructed, depending upon the criteria used, even though two fires actually occurred.

This scenario did not happen for any of the four sites sampled. Only one of the sites (LE1) had a false fire for the 10%-criterion, field-counted reconstruction, if we assume that the 1807/1815 event at site HE2 was a real fire (Table 3.6) and that this did not result from two fires occurring closely in time (Table 3.3). Large errors in counts of individual scar and origin years (Figs. 3.2, 3.5) were attenuated at the level of individual, reconstructed fires. But, while it may be inappropriate to generalize from the results of only four sites, recording an erroneous fire in one of four sites would not be suitable for most fire history research objectives in a fire regime where sites experience just two to eight fires over the period of record (Chapter Four). Reconstruction of an incorrect number of fires leads to greater errors for fire frequency descriptors when fire intervals are longer.

A more consistent effect of field-counted error is the temporal offset of reconstructed fire years. All fire years at all four sites were estimated to have occurred more recently than they likely did (Tables 3.3 - 3.6). In most cases (e.g., site HE2 fires 1848/1849, 1883/1884), the offset is minor. For a few cases (e.g., site LE1 fires 1834/1850, 1846/1860), it is not. This source of error is sufficient to make field-counted studies unreliable for studies of interannual climate or weather effects on fire occurrence, or for any other studies where precise estimates of fire years are important.

More problems arise when non-cross-dated, field-counted studies are used for evaluating fire extent and pattern. With imprecise fire dates, it is hard to tell which sites burned in the same fire or even in the same decade. For example, cross-dated fire reconstructions show that fire years were better correlated between LE and HE site pairs than within them, even though sites within these pairs are located within four kilometers (km), while site pairs are located approximately 10 km apart (Fig. 3.1). There are at least three explanations for these unexpected results:

(1) The fire regime of the study area was characterized by small fires igniting at multiple locations during episodes of suitable weather (e.g., drought, dry lightning storms);

(2) Fires during 1883 and 1892 were extensive but of very patchy severity, such that many sites within the burned area would not have recorded evidence of these fires; or,

(3) An insufficient number of trees were sampled and crossdated at each of the four sites, so that some fires which burned these sites were not detected.

A non-cross-dated field study that aggregated fire chronologies from individual sites to a single, study area master fire chronology (e.g., Teensma 1987, Morrison and Swanson 1990, Impara 1997, Chapter Four) might have combined the 1883 and 1892 fires into a single "fire episode" (*sensu* Teensma 1987). Results from such a study may have led to the erroneous interpretation that a single widespread fire burned the whole study area, sometime between 1883 and 1892. Alternatively, failure to aggregate non-cross-dated fire year estimates between sites may lead to erroneous interpretations of small fire extents when fires were actually large, since estimates for the same fire could differ between sites. Cross-dating is thus important for valid interpretation of fire extent. Even with cross-dating, it may be impossible to consistently distinguish separate fires that burned in the same season and year. It should be valid for field-counted fire history studies to report area burned over intervals of multiple decades (e.g., Chapter Four), since it is not essential to distinguish separate fire years at that scale of resolution.

Fire history reconstructions based on field-counted fire year estimates may be suitable for ecological objectives over coarse spatial and temporal scales. Such studies may be useful for: (1) providing a first look at patterns of fire regime over large areas, that might then be fine-tuned with detailed dendrochronological studies over smaller areas, and even used to guide dendrochronological sampling; (2) interpreting spatial variation in fire regime pattern as influenced by topographic and other environmental factors, provided the magnitude of fire detection and dating error is not greatly influenced by these same factors; and (3) interpreting temporal variation in area burned over periods of 30 years or longer.

3.4.3. Are Non-cross-dated, Prepared Slab Counts Accurate Enough?

Non-cross-dated fire history data obtained from careful ring counts on well-prepared slabs under a microscope should be suitable for most ecological objectives in western Cascades forest ecosystems. Average errors on the order of one to two years do not preclude fire interval analysis. Confounding of fires that are close in time should also not be a problem, particularly if reburns occurring within one or two years are not common or considered "ecologically important". However, most of the labor required for cross-dated fire history studies is used to prepare slab samples; once samples are prepared, it is not much additional work to cross-date. The added precision of cross-dating allows for more powerful, higher resolution fire history analyses. Even when research objectives do not require annual precision of fire history estimates, it is possible that a future study (e.g., of weather conditions and climatic events leading to widespread fire) might.

The results of this error analysis should be limited to study areas in the central western Oregon Cascades, to data obtained from Douglas-fir tree-ring series, and to fire history studies that use slab cross-sections to date fire scars and tree origin years. Douglas-fir trees elsewhere in the PNW might be prone to different magnitudes of error from tree-ring anomalies such as missing rings. In the Gifford Pinchot forest of Washington, 11 of 60 Douglas-fir trees (18%) had at least one missing ring, compared to 7 of 60 Douglas-fir trees (12%) in this study (unpublished data; Linda Wilkinson, College of Forest Resources, University of Washington). Western hemlock trees in the Gifford Pinchot study were observed to have a far greater incidence of missing and partial rings than Douglas-fir trees from the same stand.

Studies that use increment cores to date fire scars (Sheppard et al. 1988, Means 1989) would likely experience greater errors in the absence of cross-dating. When counting tree-rings on increment cores, it is impossible to choose an optimal radius for counting, and judgements about tree-ring anomalies, such as partial rings, are limited to what can be observed in a very narrow section of wood. It is also extremely difficult and time-consuming to sample and interpret fire scars using increment cores.

3.4.4. Implications for Past and Future Fire History Research in the Westside Cascades

Cross-dated fire history studies require great time, effort, and expense, and are difficult to conduct over landscape scales. It required more than 22 times the number of person-hours to carry out the cross-dating study than it did to obtain fire scar and tree origin year estimates by field-counting. Despite this, I recommend that most future fire history studies in the western Cascades employ cross-dating, or at least careful counts on finely sanded slab surfaces. While many sources of error in fire history studies cannot be resolved (Chapter Two), it seems prudent to resolve those that can be. Dating errors from field-counted slabs can be significant, but can be resolved by cross-dating. Landscape-scale questions might be approached through careful selection of sampled sites, and trees within sites, employing stratified sampling schemes. Multiple studies might be necessary to obtain a complete and accurate picture of spatial fire patterns, and the environmental factors that influence them, over large landscapes. Non-cross-dated studies that rely on field-counted data might be useful for generally describing past fire patterns, and for mapping spatial heterogeneity of fire regimes (Chapter Four). The results from such studies might be used to guide further, more accurate and precise, dendrochronological sampling.

Field-counted fire history studies provide data at too coarse a resolution for testing most hypotheses involving fire frequency or extent. They are imprecise in the sense that fire events may be undetected, or falsely detected. They are inaccurate in that detected fires, often dated using a narrow range of fire-year estimates, are likely to be consistently shifted forward in time (Tables 3.3 - 3.6). Cross-dating reduces fire detection errors, and eliminates dating errors. Where logistical limitations preclude extensive slab collection and cross-dating, I recommend that field-counted fire history studies begin with a pilot study where a subset of the study area is sampled using cross-dating, and error between field-counted and cross-dated fire history reconstructions quantified. Without such quantification of error, it is difficult to interpret results of field-counted studies at an appropriate resolution. Also, a knowledge of tree-ring patterns prevalent among trees within a study area, such as would be derived from a cross-dated pilot study, could be used to calibrate a study using field-counting. A researcher with a good "mental" master tree-ring chronology should be able to identify some key marker years on sensitive slabs, and so reduce some of the error associated with field-counting.

Existing, field-counted fire history studies need not be left to gather dust on the shelves. Interpretations from such studies may be appropriate over coarse spatial scales, and should be limited to coarse temporal scales of multiple decades or centuries. Descriptions of spatial pattern rest on safer ground where point patterns of fire occurrence or frequency are analyzed, rather then where interpolated fire boundaries are used, since interpretations that the same or different fires occurred between nearby sites cannot be validated without precise fire year estimates.

All fire history studies involve a great amount of subjectivity and uncertainty (Chapter Two), despite efforts of some researchers to present them as objective, repeatable exercises (Johnson and Gutsell 1994). It is important that fire history methods be adjusted to fit particular fire regimes and study objectives (Table 2.2). It is possible that the most appropriate fire history methods for forests of the western Cascades have yet to be adopted, or developed. While cross-dating does not solve many of the problems of fire history reconstruction in this region, it is prudent to limit sources of error where possible, particularly where errors are of the magnitude of field-counted errors reported here. The practice of cross-dating increases both the precision and accuracy of fire history reconstruction, allowing more accurate estimation of fire frequency, extent and spatial pattern.

Chapter 4. Fire History and Fire Regimes of the Blue River Watershed and Surroundings, Central Cestern Oregon Cascades, U.S.A.

4.1. Introduction

It has become apparent over recent decades that plant community composition, and patterns of forest and vegetation structure that relate to species habitat needs, cannot be well understood without a knowledge of how forest ecosystems change in response to disturbance processes (White 1979, Sousa 1984, Sprugel 1991). As ecological focus has shifted away from the climax community, and toward the many processes preventing most communities from ever achieving a true climax state, much effort has been devoted to reconstructing disturbance regimes (e.g., Hemstrom and Franklin 1982, Foster 1983, Heinselman 1983, Canham and Loucks 1984, Deal et al. 1991, Foster and Zebryk 1993, Veblen et al. 1995). An understanding of disturbance regime properties, including frequency, severity, size, and spatial pattern, may be used to interpret patterns of forest structure and species composition (Oliver 1981, Romme and Knight 1981, Bergeron and Dansereau 1993), patterns of landscape patch diversity (Romme 1982, Suffling et al. 1988), and patterns of vertebrate species distribution (Bunnell 1995).

For the Douglas-fir forests of the westside Cascades, wildfires have played a major role in determining the structure and function of forest ecosystems, patterns of habitat, and patterns of resource availability for humans. An understanding of forest dynamics in this region requires a knowledge of fire history and fire regimes, how vegetation responds to different fire regimes, and the range of post-fire successional trajectories. This understanding must occur over both stand and landscape scales. This chapter offers a landscape-level interpretation of fire history and fire regimes for a 440 km^2 area in the central western Oregon Cascades.

Fire is a highly variable disturbance process, capable of responding to weather fluctuations within seconds, and variations in fuel conditions within centimeters. Tree-ring records of fire are temporally limited, especially in high- and variable-severity regimes, where such records may reflect the idiosyncratic fire spread and weather patterns of a few dominant fires. It is necessary to generalize a highly variable fire record into its deterministic components, as weak in explanatory power as they may be, to extrapolate broad trends of fire regime to heterogeneous landscapes encompassing a range of physical environments.

My basic approach in this study was to use simple topographic variables in proxy for complex climatic gradients and conditions that might influence fire through effects on fuels, ignition and fire behavior. Patterns of any one fire were expected to be highly variable, but consistent topographic influences should be evident from examining patterns of multiple fires, as described in terms of fire regime components (i.e., frequency, severity, size). Of the three components of the fuels-weather-topography triangle (Chandler et al. 1983), topography is the only one that varies little over time. From relationships between fire and topography, fire regime patterns may be extrapolated across the spatial heterogeneity of a diverse landscape. Since many fire history studies have used vegetation to stratify fire regimes (e.g., Agee et al. 1990, Renkin and Despain 1992), I also compared the relative abilities of forest series boundaries and topographic variation to explain fire regime patterns.

This was a descriptive, exploratory, observational study. Fire history data of coarse resolution were collected to detect and quantify broad patterns and relationships. My general objectives were:

(1) To reconstruct fire history and characterize fire regime, for a central western Oregon Cascades study area, over the past several centuries;

(2) To analyze temporal changes in fire frequency, severity, and size over the time period of record (1475 - 1996);

(3) To describe spatial variability in fire frequency and severity, and identify key environmental influences on fire pattern; and

(4) To delineate portions of the study area with qualitatively different fire regimes.

4.2. Study Area

The Blue River study area occupies approximately 450 km^2 in the central western Oregon Cascades, and includes the north-facing slope of the McKenzie Valley from Simmonds Creek to the confluence with Deer Ck., as well as the Deer Ck., Lookout Creek, Blue River, Squaw Ck., and Sevenmile Ck. watersheds (Figs. 4.1, 4.2). Most of the area is managed by the Willamette National Forest, although small parcels of state and privately owned land are included. The H.J. Andrews Experimental Forest occupies 64 km^2 of the area. Elevations range from 316 m to 1645 m, and topography is steep and dissected, with narrow, incised stream valleys, and long, steep ridges. Slope lengths are longer and topography less dissected in the Lookout Creek drainage, while the northern part of the study area contains much earthflow-dominated terrain, associated with little topographic dissection and more gradual slopes (Fig. 4.3).

Fig. 4.1. Map of the study area, showing sampled fire history sites.

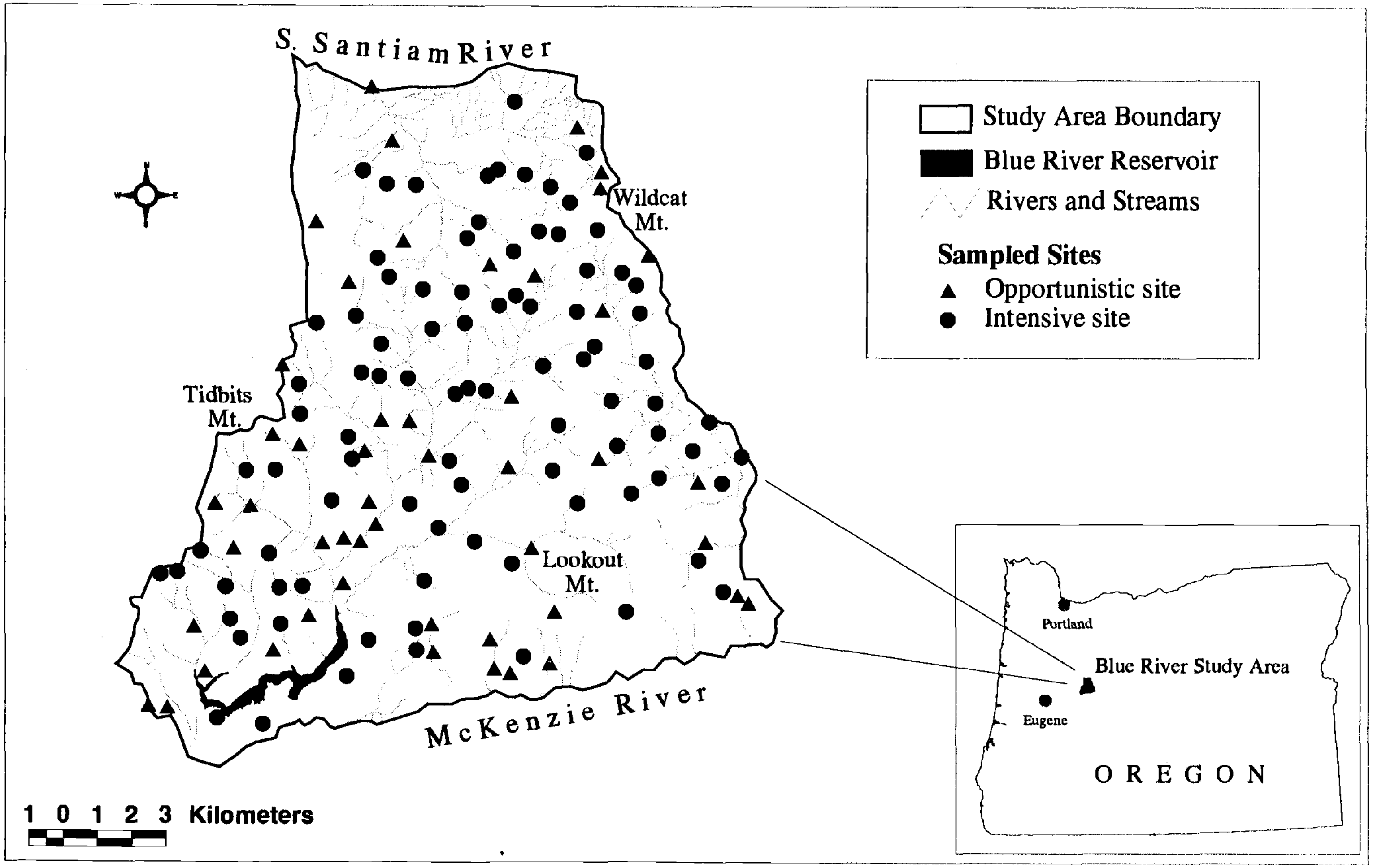


Fig. 4.2. Names of selected geographic locations in the Blue River Study Area.

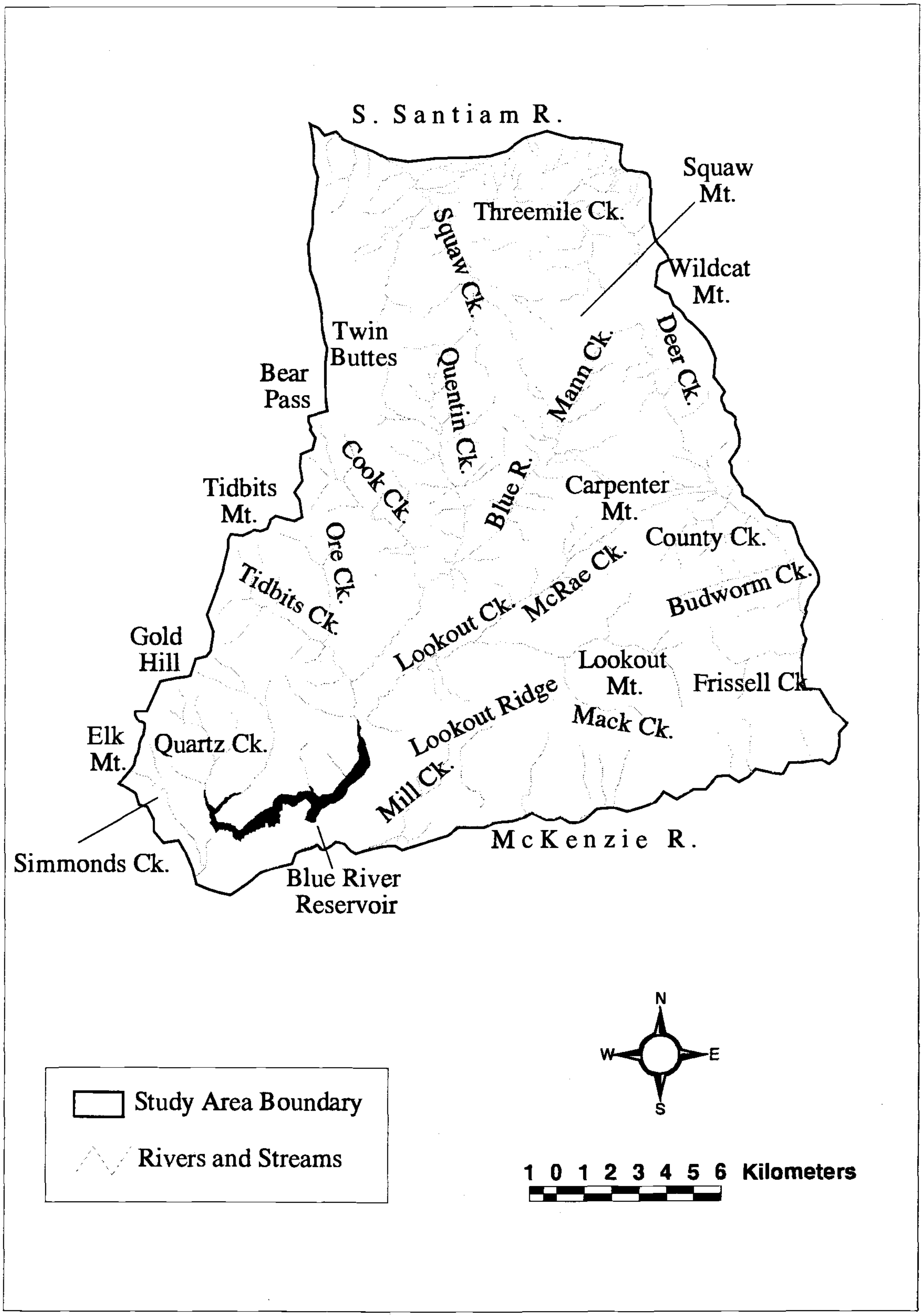
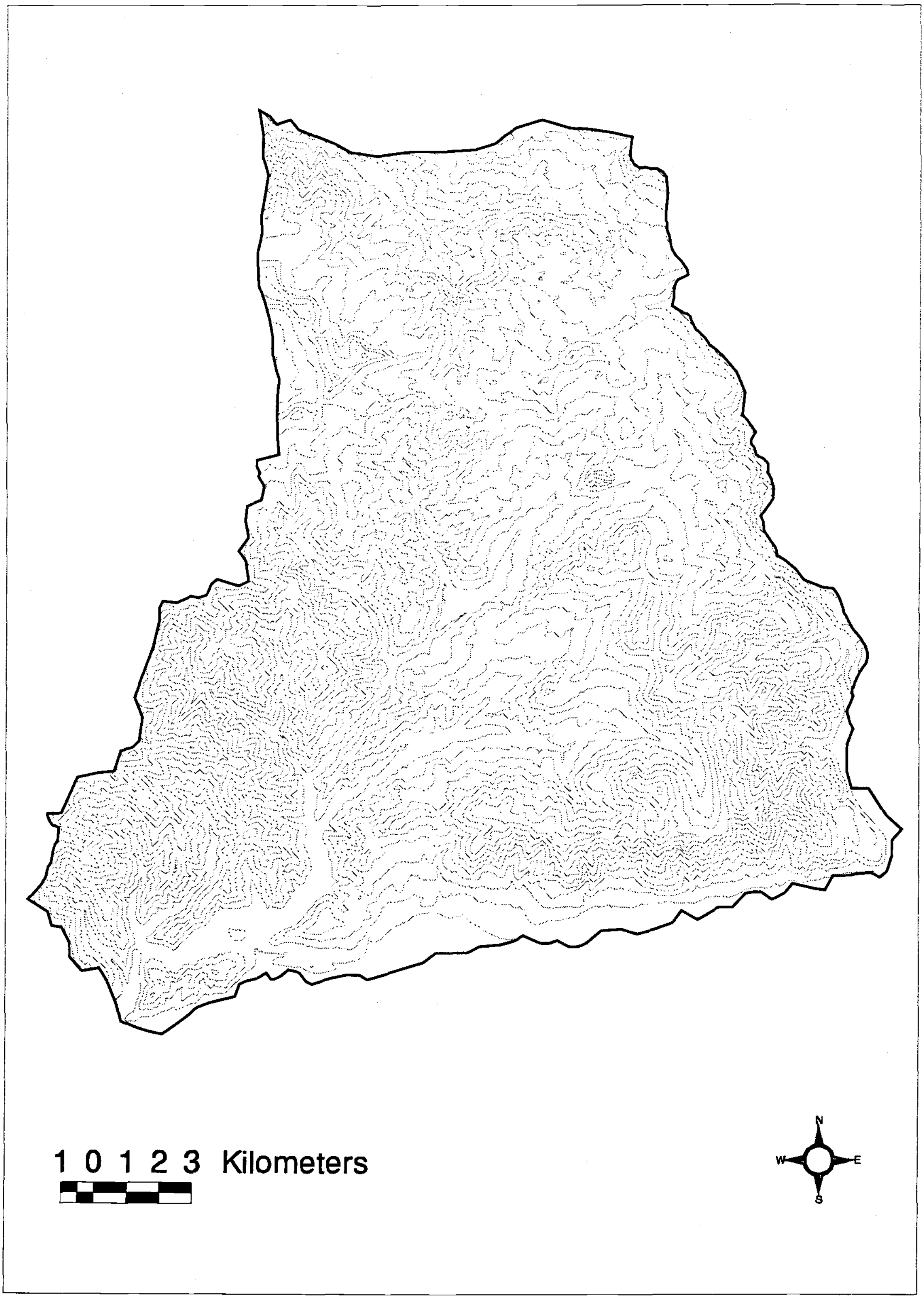


Fig. 4.3. Elevational contours (400 m) of the Blue River study area.



The study area has a temperate, maritime climate with cool, wet winters and warm, dry summers. Nearly 75 % of the annual precipitation occurs between November and March. A persistent snowpack may form above 1050 m, although there is much inter-annual variation in snow level (Bierlmaier and McKee 1989). Annual precipitation at the Andrews Forest varied from about 1400 mm to about 3100 mm over the 1973 to 1991 period, averaging about 2300 mm (Bierlmaier and McKee 1989, Greenland 1994).

Despite abundant annual precipitation, periods of extended drought commonly occur during the summer months. The combination of summer drought, east wind events, and lightning storms lead to a favorable fire climate for the region during certain years. Adiabatic, dessicating east winds occur when thermal low-pressure cells develop along the coast as a high pressure ridge settles over eastern Oregon, producing warm, dry winds blowing westward across the Cascades. These winds may hasten fuel moisture loss, creating favorable conditions for fires, or may cause an existing low-intensity fire to become more intense. Dominant winds during the summer months trend from the southwest, and do not have the same drying influence or intensity. Lightning storms, infrequent compared to other mountainous regions of the American West, were sufficient to ignite about 60 % of all recorded fires in the central western Cascades (Teensma 1987). Average annual lightning strike density for the study area for the 1985 to 1994 period was 1 strike per 50 hectares (ha).[1]

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[1] Lightning strikes were detected by electronic triangulation, and these data were obtained from the Western Regional Climate Center, Reno, Nevada, U.S.A.

Plant community types may play an important role in influencing the spatial heterogeneity of fire regimes (Agee 1993). Most of the study area is covered by two major vegetation zones (i.e., forest series): the western hemlock (*Tsuga heterophylla*) zone, between approximately 350 m and 1000 m; and the Pacific silver fir (*Abies amabilis*) zone, above approximately 1000 m (Franklin and Dyrness 1973). Within the western hemlock zone, dominant tree species include western hemlock, Douglas-fir (*Pseudotsuga menziesii*), and western redcedar (*Thuja plicata*). Occasional tree species include incense-cedar (*Calocedrus decurrens*), western white pine (*Pinus monticola*), sugar pine (*Pinus lambertiana*), and grand fir (*Abies grandis*). Douglas-fir, an early-seral species that may persist for a millennium in the absence of major disturbance, is by far the dominant tree species in this zone. Major understory species include swordfern (*Polystichum munitum*) and oxalis (*Oxalis oregana*) on wet sites; Oregon grape (*Berberis nervosa*), salal (*Gaultheria shallon*), and vine maple (*Acer circinatum*) on mesic sites; Pacific rhododendron (*Rhododendron macrophyllum*) on cold sites; and oceanspray (*Holodiscus discolor*) on dry sites.

Within the Pacific silver fir zone dominant tree species include Pacific silver fir, Douglas-fir, noble fir (*Abies procera*), and western hemlock (Franklin and Dyrness 1973). Major understory species include devils-club (*Oplopanax horridum*) on the wettest sites; coolwort (*Tiarella unifoliata*), cutleaf goldthread (*Coptis lachiniata*), and vine maple on mesic sites; and beargrass (*Xerophyllum tenax*) on dry sites. Douglas-fir and noble fir are the important early-seral tree species in this zone.

Some of the driest, low-elevation sites within the study area are occupied by plant communities in the Douglas-fir forest series, where Douglas-fir is considered to be the dominant climax species. Other tree species present include incense-cedar, sugar pine, Pacific madrone (*Arbutus menziesii*), and giant chinkapin (*Castanopsis chrysophylla*). Uncommon vegetation zones in the study area include the mountain hemlock (*Tsuga mertensiana*) zone, which occupies the highest elevations, and the grand fir zone, scantily represented in certain rainshadow environments (McCain and Garza, personal communication).

Despite the great variety of forest community types represented, Douglas-fir is by far the dominant tree species within the study area. It was absent from only two of 137 sites sampled in this study. Shade-intolerant Douglas-fir trees have thick bark when mature and are able both to survive surface fires and to colonize following stand-replacement fires (Minore 1979, Agee 1993). However, young Douglas-fir trees are very vulnerable to fire. Noble fir is also a shade-intolerant, early-seral species, joining Douglas-fir as an important post-fire colonizer at higher elevations. On certain mesic slopes at moderate and high elevations, I observed western hemlock to have formed dense, nearly pure stands following stand-replacement fire. On wetter sites, western hemlock also may respond to partial stand-replacement fires with abundant regeneration. Pacific silver fir and western hemlock are the most fire susceptible tree species in the study area, while western redcedar, incense-cedar, noble fir, mountain hemlock, and western white pine are far less fire resistant than Douglas-fir (Minore 1979).

Human activities may have played an important role in the fire history of the study area. Prior to Euro-American settlement, the Molala lived in this area, wintering along lower-elevation rivers and streams, and moving upland during the summer to hunt, fish and gather vegetable foods (Minor and Pecor 1977). They may have maintained permanent winter settlements near the confluences of major streams, such as the McKenzie River-Deer Ck., Blue River-Tidbits Ck., Blue River-Lookout Ck., and S. Santiam River-Squaw Ck. stream junctions. The Kalapuya peoples were associated primarily with the Willamette Valley and its major tributaries, but may have utilized the uplands of the Cascades for summer food-gathering activities as well (Minor and Pecor 1977). Native peoples may also have travelled through the study area en route to obsidian sources in the High Cascades. The role of native peoples in influencing the presettlement fire regime of major river valleys in the Oregon Cascades is little known and controversial (Burke 1979, Teensma 1987), although it is likely that they were important for forests in major river valley and foothill environments (Boyd 1986).

Native populations were decimated by a series of epidemics from 1782 (smallpox) to 1833 (malaria), resulting from contacts with early fur traders in neighboring areas (Mackey 1974). Since the McKenzie and South Santiam river valleys were not well-settled until the mid-1850s (Burke 1979), it is likely that the early 1800s represented a period when the study area was minimally influenced by humans. From the 1850s to 1893, when the Cascade Forest Reserve was set aside, the lower elevations of the study area were heavily utilized by a succession of ranchers, farmers, homesteaders, and travellers, while the upper elevations were locally utilized by herders and miners (Burke 1979). The McKenzie and South Santiam valleys became primary travel corridors through the Cascades. Small parcels within the southwestern portion of the study area were logged during the early 1900s. All of these activities have been (and still are) associated with a high incidence of anthropogenic fire.

4.3. Methods

4.3.1. Field Methods

Fire scar and tree origin years of primarily Douglas-fir trees were obtained from field counts of tree-rings on 4478 cut stumps in 137 clearcuts (Fig. 4.1). Fire history is most efficiently sampled in clearcuts in the central western Cascades because the dominant tree species, Douglas-fir, often survives fire with small scars, associated with bark furrows, healing completely within 5 to 20 years. Also, Douglas-fir trees grow to large diameters; diameters at breast height (d.b.h.) of 2 m are not uncommon. Thus, fire scars in standing forests are difficult to locate and, once located, are difficult to date using tree coring procedures. In clearcuts, numerous trees can efficiently be examined for evidence of past fires.

In an effort to sample extensively over the entire study area, I sampled one randomly selected clearcut in every legal section where at least one recent (i.e., less than approximately 12 years old) clearcut was available. There are 172 legal sections across the study area, typically 2.79 km^2 (1 mi^2), although areas vary. Mean sampling density was 0.3 sites per km^2. Thirty-five sections were not sampled because they did not contain harvest units, were harvested too long ago for stump surfaces to be suitable for ring counting, or have already been harvested twice and are now on a second rotation, making evidence of pre-harvest disturbance history unavailable. Undersampled portions of the study area include the area from Lookout Mt. south to the McKenzie River, the extreme southwesternmost portion (Simmonds Ck.), and the northernmost portion adjacent to the South Santiam River.

For 47 of the sites, sampled clearcuts were old (pre-1984) and brushy, or else dangerously steep, precluding the systematic sampling of plots. At these sites, fire history was sampled "opportunistically" wherever stumps with fire evidence were found, over a two to four ha area. Sampling continued until it was apparent that a complete fire history had been sampled, which usually required from 10 to 30 stumps per site.

For the remaining 90 sites, fire history was sampled for a 4-ha square area bounded at the corners by the centers of four, intensively sampled 0.1-ha circular plots. The 4-ha area was approximately delineated by pacing, and at some sites, logistical and safety constraints prevented sampling the full area or number of plots. The actual area sampled at a site probably ranged from three to five ha. Four plots were sampled at 77 of the 90 sites, while the remaining 13 sites were sampled using from two to five plots. There was no significant difference between the number of fires detected for sites with different numbers of plots sampled, using an ANOVA analysis ($F_{(4,85)} = 0.9985$; $p = 0.4130$). Also, regression analysis showed no trend in the number of fires detected as a function of the number of trees aged at a site, when opportunistic sites were excluded ($F_{(1,88)} = 0.7787$; $p = 0.3799$).

Within each 0.1-ha plot, I sampled all Douglas-fir stumps and stumps of other species that had fire scars. I also measured diameters at stump height and tallied by species all stumps, snags, and standing trees present. For a 0.01-ha plot at the center of each 0.1-ha plot, I sampled all stumps regardless of species. Information from the 0.01-ha plots was useful for reconstructing western hemlock origin years. For the approximately 4-ha area between the corner plots, I sampled only old stumps, or those with many scars from previously unsampled fire years.

Fire scars and tree origin years were dated in the field by counting tree-rings under appropriate magnification (using a 3x, 10x, or 16x hand lens), after preparing the stump surface with hand tools. Scrapers were used to remove pitch and debris, a surform scraper was used to expose a new surface where necessary, and a wire brush was often used to abrade the softer spring wood, accentuating the denser, more resistant latewood. Stump surfaces were still rough after preparation, and it is likely that there were counting errors (see Chapter Two). Crossdating was not employed to correct scar and origin year estimates using correlations among ring widths and other tree-ring features (Stokes and Smiley 1968), because of logistical constraints inherent in a study whose objectives require sampling many trees at many sites to achieve a desired grain and extent for developing a landscape-level representation of past fire patterns.

The following data were recorded or computed for each sampled stump: height (cm), diameter at stump height (cm), origin year, reliability of the origin year estimate, the average width of the first three rings (mm), the radius at age 40 (cm), the presence of any scar(s), the position of scar(s) relative to the slope direction (i.e., upper, side, lower), the compass bearing of scar(s) from the pith outwards, the percent circumference of the cambium killed by the scarring event(s), the radius from the pith to the scar(s) (cm), the age of the scar(s), and the reliability of the scar age estimate. Pitch rings (i.e., growth rings separated by a band of pitch) were sometimes dated, and measured similarly as scars. Field observations and previous studies have shown that pitch rings are often associated with fire years, and provide weak evidence of fire (Weisberg, unpublished manuscript, Weisberg 1997). The origin year was estimated by first counting the number of tree-rings from the pith to the most recent growth ring, and subtracting this number from the harvest year. Then the average width of the first three rings was used to estimate the age of the tree at stump height, according to the formulas (Morrison and Swanson 1990):

$$AGE = 0.1852 * (\text{Stump Height} / \text{Average Width}) \text{ for Average Width} > 2 \text{ mm},$$

and

$$AGE = 0.1852 * (\text{Stump Height} / 2) \text{ for Average Width} <= 2 \text{ mm}.$$

The origin year estimate was corrected by adding the estimated age of the tree at stump height. Although this formula was developed for Douglas-fir forests of a nearby study area, it is likely a coarse approximation of the number of years required for a tree to grow to stump height. Scar year estimates are therefore more accurate than origin year estimates. Origin years were usually counted once, and scar years recorded as the average of two counts.

4.3.2. Environmental Variables

The following environmental variables were obtained for each site and considered in all statistical models: elevation, aspect, slope steepness, hillslope position, and forest series. Approximate site locations were digitized into the ARC/INFO geographical information systems (GIS) software, and elevation was obtained at 30 m resolution from a digital elevation model (d.e.m.). Slope aspect was measured in the field, and linearized into two continuous variables representing "northness" and "northeastness" using the following equations:

"northness" = $\cos((\text{Aspect} / 360) * 2 * \pi)$

"northeastness" = $\cos(((\text{Aspect} - 45) / 360) * 2 * \pi)$

Slope steepness was evaluated in the field as low, moderate, or high, over the scale of the 4-ha site. Hillslope position was calculated from the d.e.m. using an ARC/INFO program (i.e., slopeposition.aml) that uses hydrologic modeling to calculate the landscape area draining into each pixel. Forest series was obtained from a spatial database of modeled plant association groups available from the Willamette National Forest. Elevation and forest series were fairly highly correlated with each other ($r = 0.5538$), as were "northness" and "northeastness" ($r = 0.7650$). Each statistical model using the environmental variables as predictors differed in whether elevation or forest series, or northness or northeastness, was used to fit the model, depending on which factor was most strongly associated with the response variable. All second-order interactions between pairs of the above variables were examined in fitting each model, since it was expected that several of these factors would have interactive effects in influencing fire patterns. Prior to statistical analysis, all continuous variables (i.e., elevation, northness, northeastness, hillslope position) were aggregated to an approximately 4 ha scale using a rectangular moving window averaging filter.

4.3.3. Fire History Reconstruction

In light of the coarse temporal resolution of this study, fire scar evidence was summarized as “fire episodes”, ranging over a period of multiple years, that might represent a single event or multiple fires closely occurring in time and space. Fire episodes were reconstructed using primarily fire scar data. Tree origin years were used as corroborating evidence, or to decide if a fire had occurred at a site where neighboring sites had scar evidence for a particular fire episode.

Since not all scars are of fire origin, a set of criteria was used to determine whether or not evidence for a fire at a site was sufficient to define it as a fire episode (Table 4.1). Criteria differ slightly depending whether a site was intensively or opportunistically sampled (Table 4.1). Estimated scar years from different trees at a site were first clustered into the same potential fire episode if they were within 8 years for the 1800 - 1996 period, 12 years for the 1700 - 1799 period, or 16 years for the pre-1700 period. Different time brackets were necessary for different temporal periods since scar year estimates were fewer and subject to more counting error for earlier years. An unfortunate consequence of decreased resolution in discriminating and dating earlier fires was that earlier fire episodes tended to be larger and contain more patches than later ones, suggesting that multiple fires were included in the earlier fire episode reconstructions. For example, fire episode reconstructions for two periods of similar length (i.e., 15 - 17 years) showed seven fire episodes from 1873 to 1890 (Fig. 4.4A) and one fire episode from 1609 - 1624 (Fig. 4.4B). It is possible that the earlier period experienced multiple fires that could not be differentiated with the dating resolution of this study.

Pitch rings were counted as scars if two fire scars dated to the same approximate year. The first two scars dating to an approximate year on tree species other than Douglas-fir were given half the weight of Douglas-fir scars; subsequent scars were given equal weight.

Measures used to determine sufficient criteria for a fire episode included the number of scars dating to within a limited time period at a site, the number of nearby sites

Table 4.1. Criteria for identification of a fire episode at a site. Fulfillment of any of the following six conditions results in a cluster of scar years being classified as a fire episode.

Conditions:

1. ≥ 5 Scar Is *OR* ≥ 4 Scar Es

2. (4 Scar Is *OR* 3 Scar Es) + one: CFNS, 2SA, MSY, MR, OC
OR + two: (MSU, MNR) *AND* BA

3. (3 Scar Is *OR* 2 Scar Es) + one: CFNS, MR, OC
OR + two: (2SA, MSY, MSU, MNR) *AND* BA

4. (2 Scar Is *OR* 1 Scar Es) + one: MR, OC, CFNS3
OR + two: (CFNS, 2SA, MSY, MSU, MNR) *AND* BA if pre-1800
OR + three: (CFNS, 2SA, MSY, MSU, MNR) *AND* BA if post-1800

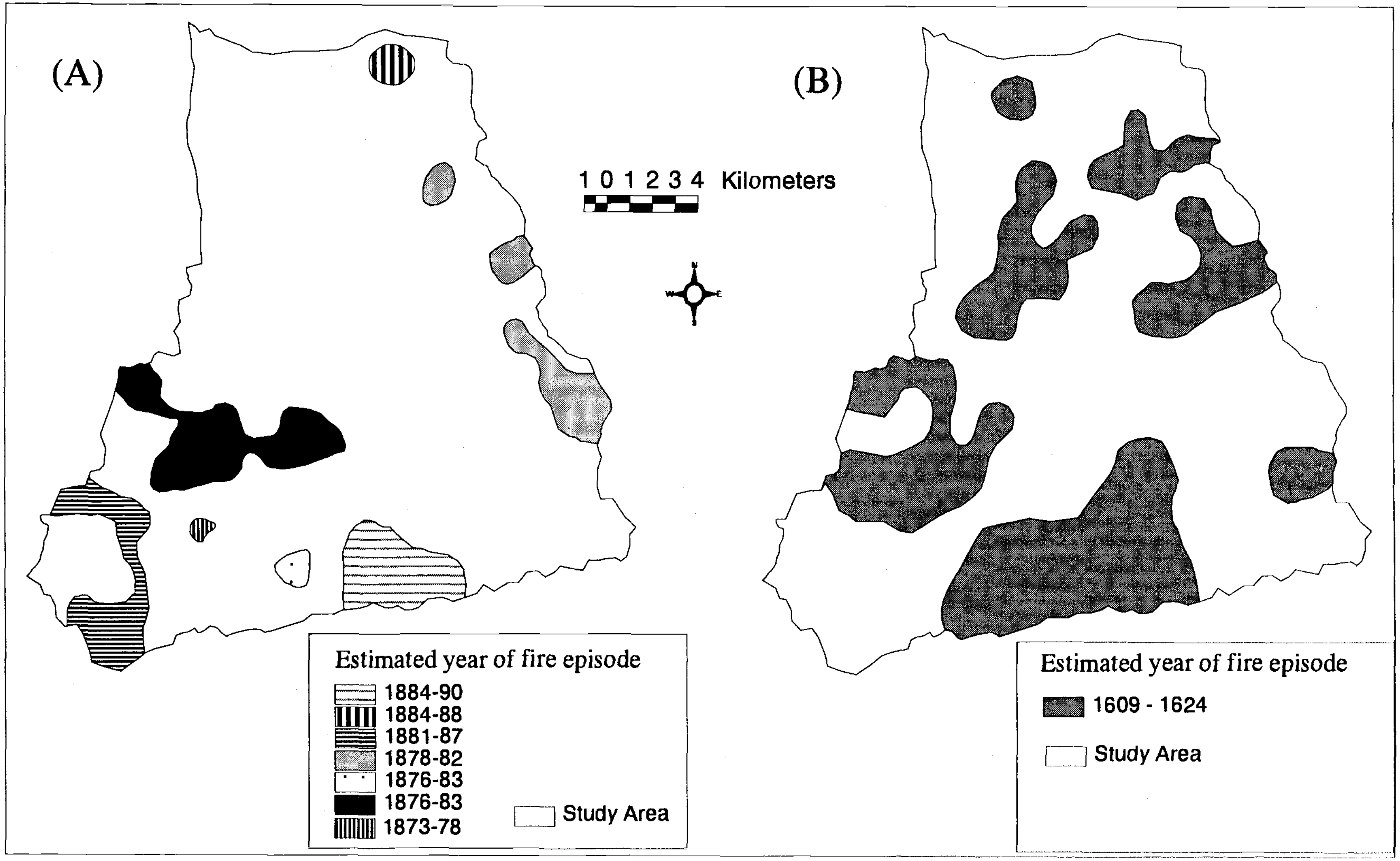
5. 1 Scar Is + one: (MNR *OR* MR *OR* OC) *AND* CFNS (CFNS not necessary if pre-1650 *AND* MR)
OR + CFNS3

6. 0 scars + one: MR *AND* CFNS, MNR *AND* CFNS2

Key:

BA	most scars are < 20% of the circumference and within 15cm of the pith
CFNS	a confirmed fire from a nearby (within 3 km) site
CFNS2	a confirmed fire from 2 nearby (within 3 km) sites
CFNS3	a confirmed fire from 3 nearby (within 3 km) sites
Es	opportunistic site (no plots and less than 30 stumps)
Is	intensively sampled site (plots, and at least 30 stumps)
MNR	a minor regeneration cohort (PropReg < 30%) follows the scar year
MR	a major regeneration cohort (PropReg ≥ 30%) follows the scar year
MSU	the majority of scars are on the uphill sides of the stumps
MSY	multiple scars are present in the same year
OC	a scar occurs on an open catface and charred wood or bark is discernible
2SA	a scar along the same radius of a previous scar

Fig. 4.4. Reconstructed fire episodes from: (A) 1873 - 1890, and (B) 1609 - 1624.

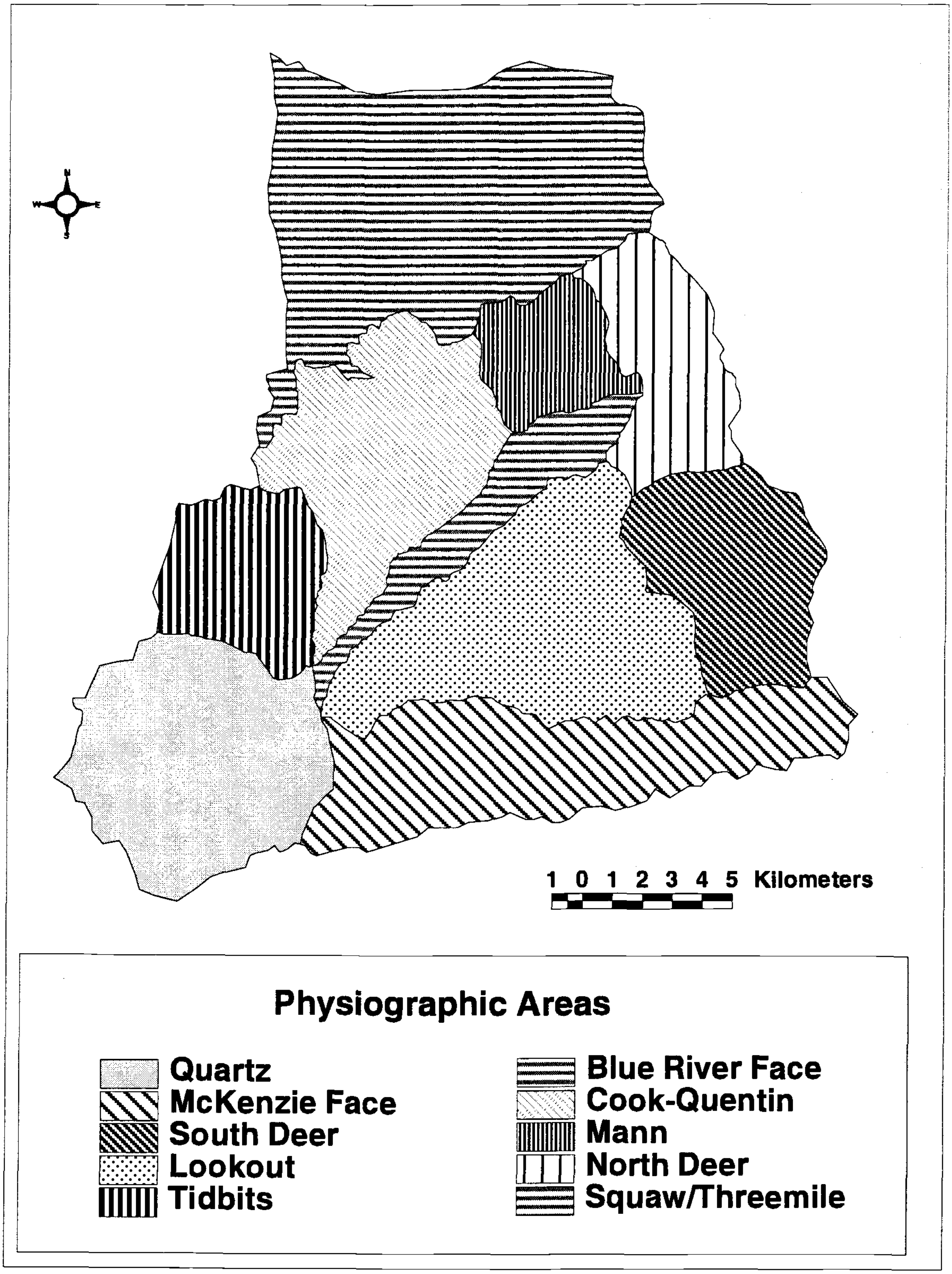


with confirmed fires of similar years, the presence of regeneration cohorts in years following the estimated scar year, and scar characteristics such as percentage of cambial circumference damaged, distance from the pith, presence or absence of an open catface with evidence of charring, and alignment of healed-over scars with other such scars along a common axis assoicated with a bark furrow. Scars oriented along a common radius representing a point of weakness in the bark are likely to be fire scars, while large scars close to the pith are more likely to result from bear or antler damage. Open catface scars are rarely found on Douglas-fir trees in the study area, due to their ability to heal rapidly, and rapid decomposition rates.

I divided the study area into ten contiguous "physiographic areas" to facilitate aggregation of fire evidence between sites (Fig. 4.5). These areas were delineated to reflect similar aggregations of landforms (e.g., steep, sharply dissected topography with short slopes in the case of the Quartz Ck. area), slope facets expected to have experienced a common fire history (e.g., the elongate, north-facing slope over Blue River, highly exposed to east winds that might carry high-severity fires) and, in some cases, watershed boundaries (e.g., Lookout Creek watershed). In a very general way, I intended that the relative size of each physiographic area should reflect the relative sampling intensity.

After deciding for each site the range of years over which each fire episode had occurred, I combined the information from multiple sites was into a single, master fire chronology. I first constructed a pooled fire chronology for each physiographic area, using scar years to delineate fire episodes, and tree origin years only to indicate the occurrence of an already established episode at a site. Then I pooled similar fire episodes between adjacent landscape areas, adjusting fire year estimates to conform to the pooled

Fig. 4.5. Physiographic areas of the Blue River study area, used to aggregate fire evidence for delineation of fire episodes



variation in scar counts. Fire episodes were not joined between landscape areas where differences in fire episode year estimates differed more between areas than within areas.

After joining potential fire episodes between landscape areas, I had obtained a single master fire chronology for the study area, where ranges of scar year estimates were used to define fire episodes. For each episode, I averaged scar year estimates to obtain an estimate of fire year that was used in subsequent analyses. I attempted to match 19 post-1910 reconstructed fire episodes with historical fire records as summarized in Burke (1979). Nine fire episodes corresponded to known historical events (within the same quarter-section) and were thus dated precisely. The average difference between estimated fire years obtained by averaging scar year estimates, and precise fire years from historical records, was 1.67 years (range: 0 to 5 years; s = 1.58 years).

The master fire chronology was again adjusted after sites recording fire for each episode were plotted using GIS, allowing me to check for mistakes in combining potential fire episodes between sites, and between landscape areas. The final master fire chronology records estimated fire occurrence and interpreted severity for every reconstructed fire episode for every site in the study area. This chronology was used in various ways to analyze reconstructed fire episode intervals (i.e., "fire intervals"), fire severity patterns, and fire episode extent.

4.3.4. Fire Frequency Characterization and Fire Interval Analysis

Fire frequency was measured in a variety of ways, reflecting the inability of any one method to provide a definitive summary. Fire interval distributions were analyzed for the 1475 to 1996 period using the following measures, calculated using the FHX2 software (Grissino-Mayer 1997): mean fire interval (MFI), Weibull Median Probability Interval (WMPI), maximum fire interval (maxFI), and coefficient of variation (CV). The first two methods describe the central tendency of fire frequency, while the last two describe its variability. The Weibull distribution is generally a better approximation for fire interval distributions, often skewed towards smaller values, than the normal distribution, implied by the use of the arithmetic mean to describe central tendency. Most of the fire interval distributions used in this study were not described well by a normal distribution, and all were fitted by a Weibull distribution. The WMPI is the interval where 50% of all fire intervals are less, and 50% more, according to the best Weibull fit to the data (Grissino-Mayer 1997). However, use of the WMPI alone represents a loss of information about the especially long fire-free intervals that, while infrequent, may be ecologically very important. The WMPI and CV were calculated for the 74 sites with at least three fire intervals, while the MFI and maxFI were calculated for the 80 sites with at least three fire intervals, one fire interval of at least 200 years, or two fire intervals of at least 150 years. The WMPI and CV may be biased towards smaller values since sites with long fire records but fewer than three fire intervals cannot be included in these calculations.

The MFI and maxFI were also calculated for fire intervals that did not include low severity fires or underburns. The MFI between non-low-severity fires (MFI.nlow) and maxFI between non-low-severity fires (maxFI.nlow) could be calculated for 76 sites, according to the above criteria for number of intervals required. For all of the fire interval distribution measures, the period between the last fire and the present was considered a fire interval if it was at least 100 years long, a value expected to be close to the mean fire interval (Teensma 1987, Morrison and Swanson 1990). Omission of the last, truncated fire interval biases fire frequency descriptors towards increased frequency if the last interval is long relative to average interval length; inclusion of the last, truncated fire interval leads to bias towards increased frequency if that interval is relatively short.

Fire frequency was also calculated using the natural fire rotation (NFR), which is the ratio of the length of time period to the proportion of the study area burned in that time period (Hemstrom and Franklin 1982). The NFR, representing the number of years required to burn an area the size of the study area, was calculated for different time periods separately using fire episode areas from either subjectively reconstructed fire episode boundaries, or from the ratio method, described below. The ratio method allowed separate NFR estimates for all fires, and for fires excluding those known to be underburns or of low severity. Fire frequency was also analyzed using GIS overlays of fire episode polygons to create maps where each land unit (i.e., a 100 m pixel) was represented by the number of fire episodes to have burned over it. As with the NFR, this method depends heavily upon the accuracy of the fire event reconstruction.

The NFR and mapped fire frequency methods may be preferable to site-level fire frequency measures (e.g., MFI, WMPI, maxFI) because: (1) they are direct calculations, not parameters of statistical distributions estimated from a potentially inadequate sample; and (2) they combine fire frequency and size to provide a more unified description of past fire behavior for a given area. The NFR is most useful where a high density of fire history samples allows fine-scale reconstruction of fire event boundaries that include smaller patches of unburned forest within the outer fire perimeter. Advantages of site-level frequency measures include: (1) they are more useful than the NFR, but not the mapped frequency method, for evaluating spatial heterogeneity of fire frequency; and (2) they do not require accurate delineation of fire boundaries, which is often unobtainable.

4.3.5. Fire Severity Characterization

Fire severity, defined here as the magnitude of fire-caused tree mortality, was estimated for the effects of each fire episode upon the overstory vegetation of each site, according to a dichomotous key (Table 4.2). The calculation used for determining low, moderate, and high severity fire was the Proportion of Regeneration Index (PropReg), where the basal area of Douglas-fir or noble fir regeneration during the 40 years following a fire, relative to the basal area of Douglas-fir or noble fir from that period combined with earlier time periods, was used to coarsely represent the proportion of canopy killed by fire (Table 4.2). Prior to calculating basal area, diameter at breast height was calculated from diameter at stump height using equations from Curtis and Arney (1977). Basal area was used instead of stem density to remove some of the bias associated with fully stocked young stands having higher stem density than older stands, so that more recent fires of the same severity have more abundant regeneration. Opportunistically sampled stumps were not included in this calculation.

The first five decisions of the key are an attempt to remove some of the effects of the timing of fires upon fire severity. For example, a high-severity fire, represented by scar evidence on a few surviving trees, might have no Douglas-fir regeneration dating from it if it was followed closely by another fire that killed all of the young, post-fire regeneration. Where a fire was followed closely in time by another fire, it was classified

Table 4.2. Fire severity key, for estimating severity of individual fires at individual sites.

---

1. Fire is not followed chronologically by another fire within 50 years. The post-fire age cohort is not the oldest cohort at the site with trees over 200 years old ------------------- **4**

1. Else -- **2**

---

2. Greater than 90% of the total stand PSME BA at the time of sampling originates prior to the fire --------- **Low Severity (if regen.) or Low Severity/Underburn (if no regen)**

2. Else -- **3**

---

3. PropReg > 30% if over 200 years old, > 50% if between 100 and 200 years old, or >70% if less than 100 years old -- **4**

3. Else --- **Fire Severity Unknown**

---

4. Fire closely (within 50 years) follows another fire that is of Unknown, High, or Moderate severity --- **5**

4. Else -- **6**

---

5. Little or no evidence of regeneration dating from after the previous fire ---------------**6**

5. Substantial regeneration from the preceding fire survives (PropReg > 10%) -------------
----------------------------- **Low Severity** (if regeneration from this fire) **or**
Low Severity/Underburn (if no regeneration from this fire)

---

6. There is any amount of regeneration from this fire; a distinct cohort exists ----------- **7**

6. There is no regeneration from this fire, only scar evidence; there are no distinct cohorts even of shade-tolerant species. Scars mainly on TSHE, THPL, ABAM or young trees ----
---**Underburn**

Table 4.2. *Continued.*

---

7. No, or very few, trees predate the fire, and there is much regeneration of a post-fire seral species dating from within 40 years after the fire (PropReg ≥ 70%)-- **High Severity**

7. Else -- **8**

---

8. There are more than a few fire-resistant (i.e., Douglas-fir, incense-cedar) survivors of (≥ 10% basal area at the time of sampling), but virtually no survivors of fire-susceptible species (e.g., western hemlock, western red-cedar, noble fir, Pacific silver fir, Douglas-fir < 60 years old), and 30% ≥ PropReg ≥ 70% ---------------------------- **Moderate Severity**

8. Else-- **Low Severity**

ProgReg = Proportion of Regeneration Index of Fire Severity =
(Proportion of Regeneration between the fire year and 40 years following) / (Proportion of Regeneration during the time period from 40 years following the fire to the oldest tree origin year in the stand);
in basal area units (m^2/ha);
applied only to Douglas-fir and noble fir.

as having unknown severity unless most of the stand basal area predated it, in which case it was low severity, or unless it had substantial post-fire regeneration surviving, in which case it moved further down the key. The fire severity key allows low-severity fires to have a PropReg value of up to 0.30, while underburns are defined as lacking a regeneration cohort of any species (Table 4.2).

Since it was not possible to calculate PropReg for the earliest fire recorded at a site (as an age cohort), the oldest fire was considered to be of unknown severity when the oldest trees were at least 200 years old (Table 4.2). To test the possibility that this decision biased analyses of topographic influences on the proportion of high severity fires to have occurred at a site (PROPHIGH), I used the alternative criterion that the oldest fire at a site was always of high severity, for comparative purposes in some analyses.

I calculated two additional measures that combine frequency and severity. The ratio of the number of fire scars observed on Douglas-fir to the number of Douglas-fir trees sampled at a site (SCAR.ratio) was found by independent means in a nearby study area to be greater for sites that had experienced more frequent, lower severity fire (Weisberg 1997). The number of pre-harvest age cohorts at a site was also likely to be greater for sites with more frequent, lower severity fires. Age cohorts were distinguished by the presence of at least two consecutive decades of Douglas-fir or noble fir regeneration, consisting of at least four trees (or three trees if prior to 1700), and separated by at least two decades from temporally adjacent cohorts.

4.3.6. Fire Extent Characterization

Fire extent was characterized using two methods: the polygon method, where fire boundaries were reconstructed; and the ratio method, where fire extent was calculated using the ratio of the number of sites recording the fire to the number of sites with trees old enough to have possibly recorded the fire (Teensma 1987, Morrison and Swanson 1990). For the polygon method, boundaries were placed halfway between sites with and without fire evidence. Sites with no trees old enough to have recorded the fire episode were not included as sites without evidence. At the periphery of the reconstructed fire episode, boundaries were limited to within 2 km of the nearest site with evidence. If only one site recorded the fire episode, the reconstructed boundary was kept within 1-km of that site. Therefore, the minimum area assigned to fires occurring at a single site more than 1 km from the study area boundary or any other site was 3.14 km^2. In a few cases, sites were located within 1 km of each other. The smallest fire size estimated was 0.74 km^2, for a site close to another site and to the study area boundary.

Finally, fire episode boundaries were traced along major topographic features that could act as fire breaks (e.g., major ridges, large streams) where sites with and without evidence were consistently found on opposite sides of those features. Fire episode boundaries, considered to be very crude approximations of actual fire perimeters, were digitized into GIS coverages. Fire episode areas were determined by querying the ARC/INFO database.

Using the ratio method, fire extent was calculated as:

SIZE = (NSF / (NSNF - NSE)) * 44, 884.14;

where SIZE = estimated fire episode size (ha)

NSF = the number of sites to record the fire

NSNF = the number of sites not to record the fire

NSE = the number of sites with no trees old enough to have recorded the fire

This method incorporates less information than the polygon method, but has the advantage of greater objectivity. The smallest fire size estimate obtainable using the ratio method was 3.3 km^2.

4.3.7. Temporal Comparisons

Fire frequency, severity, and size were analyzed for potential changes over time that might be related to variations in climatic or human influences. Natural fire rotation was compared between centuries. The number of fires to have burned over each 1-ha landscape unit was calculated and mapped by overlaying reconstructed fire polygons. I compared fire-polygon-based fire frequency maps between centuries and between pre-settlement (1588 - 1849) and post-settlement (1850 - 1996) periods.

I also examined plots of cumulative fire frequency for sharp breaks in slope in an attempt to partition the fire record into time periods of different fire regime. I evaluated the cumulative frequency of fire episodes, fire patches, and fire occurrences at sites. Since there were more patches per fire episode for earlier fires (Fig. 4.4), fire patch frequency was less biased towards methodological error than fire episode frequency. The cumulative frequency of fire occurrences was a combined measure of fire extent and frequency, analogous to the NFR.

I compared temporal variations in fire severity and size by examining plots of these variables as they changed over 30-year periods, and over 20-year periods with a 60-

year moving average. The 30-year and "smoothed" 20-year resolutions were believed to bracket the degree of counting error variability around the fire year estimate, and to minimize error and uncertainty in fire episode delineation from falsely separating one fire into multiple episodes, or combining multiple fires into a single episode. To calculate fire extent, I summed the estimated area burned for each reconstructed fire episode occurring within the 20 or 30 year time period. Results are provided for both ratio and polygon methods of fire extent reconstruction. I multiplied the proportion of fire occurrences within each severity class (i.e., high, moderate, low or underburn, unknown) for fires within each time period by the estimated area burned to obtain the estimated area burned within each severity class for each time period.

4.3.8. Spatial Comparisons

Topographic influences on fire regime were investigated over fine scales (i.e., within-site) by comparing the fire histories of upper and lower plot pairs at each of 76 sites, excluding 14 sites where either fewer than four plots were sampled, or slope gradients were insufficiently steep. Although at each of the 76 sites upper and lower plots were separated by approximately 200 meters, the plots are not always representative of qualitatively different slope positions (i.e., near-ridge *vs.* near-stream); they are indicators of relative slope position. For each site, the difference between upper and lower plots was calculated for: oldest Douglas-fir age, average Douglas-fir age, and oldest fire recorded. These differences were displayed in histogram form and analyzed graphically. Also, the chi square test was used to test whether fire occurrence was independent of relative slope position. For each fire recorded at a site, fire occurrence was tabulated for the following contingencies: upper sites record the fire, lower sites do not; lower sites record the fire, upper sites do not; both pairs of sites record the fire. The frequency of fires in the first two contingencies was evaluated against the null hypothesis of an even split between upper and lower sites.

The spatial variation of fire frequency and severity at the between-site scale was analyzed statistically over multiple steps. First, principal components analysis (PCA) was used to simplify the set of highly correlated fire history variables into a smaller set of uncorrelated variables that maximized the variance, by selecting the fire history variable with the highest loading on each of the first four principal components (PCs). The PCA proved useful in examining relationships between these variables. On the basis of these relationships, the WMPI, maxFI.nlow, CV, proportion of low severity fires (PROPLOW), and SCAR.ratio were chosen as response variables for multiple linear regressions against environmental predictors. A stepwise method was used to help select the model with the smallest Akaike's Information Criterion (AIC), proceeding in both directions and stepping through all second-order interactions (Hastie and Pregibon 1993). All statistical analyses were conducted using Splus software (MathSoft, Inc. 1995, Version 3.3).

I treated predictive models from regression analyses as algorithms to generate maps of predicted fire regime descriptor variables in the GRID module of ARC/INFO. Resulting continuous raster coverages were reclassified to five equal interval classes for display purposes, although continuous coverages were used for further data analysis. Also, residual values from regression analyses were calculated for each site with respect to each of the response variables, and plotted using ARC/INFO. Mapped residuals were visually examined for patterns relating to factors not included in the regression analysis, especially east wind exposure and human ignition potential. Spatial patterns of residuals were examined for autocorrelation using the Moran's I statistic to plot omnidirectional correlograms (Legendre and Fortin 1989). Correlograms were flat and, using 95% confidence intervals for Moran's I as a test for significance (Sokal and Oden 1978), residuals were not spatially autocorrelated over any lag distance for any of the four regression analyses.

4.3.9. Fire Regime Characterization

To characterize and map fire regimes across the study area, it was necessary to combine information from many fire history variables into a single coherent classification. Fire regimes are usually delineated according to fire frequency and severity (Heinselman 1973, Agee 1981, Kilgore 1981). Based on the results of univariate analyses for fire frequency and severity variables, where fire frequency was more closely associated with topography than was fire severity, I decided to use a linear combination of fire frequency variables to delineate areas of different fire regimes. These areas were then analyzed with regard to many variables describing fire frequency, severity, the number of shade-intolerant age cohorts, and rate of shade-intolerant cohort establishment, allowing for a broader interpretation of fire regime units.

The results of a second PCA, using only fire frequency variables, suggested that much of the variation in fire frequency was captured by the first PC, whose linear combination resembled the average of WMPI, MFI.nlow, and maxFI.nlow. After standardization to unit variance, these variables were averaged and the resulting linear combination (FREQ.comb) was modelled as a response to topographic variables using regression analysis. The regression equation was used to predict FREQ.comb over the study area as a raster GIS coverage, which was reclassified into three classes, each occupying an approximately equal area. To reduce fine-scale variation, I merged patches of less than 50 ha into adjacent classes using the MERGE version 4.06 program (Ma 1995).

4.4. Results

4.4.1. Fire History Evidence

Only 775 of 1283 sampled scars were considered fire scars in the master fire chronology. The 40% not used were either scars from non-fire sources of injury (e.g., bears, antlers, windthrow, root rots, insects), were from fires too small and low-severity to have scarred more than a few trees in the sample site, or were erroneously dated so as to appear unassociated with other scars that actually occurred in the same year. Eighty-five per cent, or 644 of 775, fire scars were on Douglas-fir trees. On average, 5.66 (s.d. = 4.97) fire scars were sampled at each of the 137 fire history sites. A small number of pitch rings was used to reconstruct fire history (Table 4.1). I used 76 of 189 sampled pitch rings as fire evidence, and the mean number of pitch rings used per site was 0.55 (s.d. = 0.85).

I reconstructed 94 fire episodes for the 521 year period from 1475 to 1996. Scattered Douglas-fir regeneration, possibly indicating earlier fires, was found from ca. 1460, 1430, 1410, 1390, 1340, 1320, 1270, and 1230.

4.4.2. Fire Regime of the Study Area

4.4.2.1. Fire Frequency

Fire frequency was described using various measures as site-level averages, natural fire rotations for the study area, and as maps of the number of fires projected over each 1-ha unit of the study area. Site-level estimates for mean fire interval, Weibull median probability interval, maximum fire interval, and the coefficient of variation for fire intervals were highly variable and differed greatly depending on whether or not low-severity fires were included in the calculations (Table 4.3). By excluding low-severity fires, the number of sample sites available for the WMPI calculation was reduced by half, since few sites had a long enough record to capture at least three intervals between moderate, high, and unknown severity fires

Natural fire rotation provided an alternative way to characterize fire frequency over the study area. Depending on the fire size reconstruction method employed, natural fire rotation for the 1588 to 1996 period was 96 or 137 years (Table 4.4). The polygon method yielded greater estimates for NFR because it estimated fire sizes to be smaller. Excluding low-severity fires and underburns, the NFR (ratio method) was estimated as 133 years. NFR estimates also varied according to the time period considered. Fires were relatively frequent and/or widespread during the 1500s and 1800s, were less prevalent in the 1600s and 1700s, and were rare, especially when low-severity fires were excluded, during the 1900s (Table 4.4).

Fire frequency variation in space and time was also shown by mapping the number of reconstructed fires to burn each 1-ha unit of the study area for the whole period

Table 4.3. Summaries of selected fire history descriptor variables calulated at the site level. For each variable, the first row (bold type) shows the mean; the second row (italics) shows first the standard deviation, then the sample size; the third row (parentheses) shows the 95 % confidence interval around the mean; and the fourth row (square brackets) shows the range.

Fire History Variable	All Fires (1475 - 1996)	Excluding Low Severity Fires
Mean Fire Interval (yrs.)	**97** *(57, 80)* (84 - 109) [22 - 407]	**197** *(112, 76)* (172 - 222) [63 - 461]
Weibull Median Probability Interval (yrs.)	**73** *(29, 74)* (67 - 80) [15 - 157]	**91** *(30, 37)* (81 - 100) [47 - 159]
Maximum Fire Interval (yrs.)	**179** *(66, 80)* (164 - 193) [64 - 407]	**291** *(96, 76)* (269 - 312) [117 - 461]
Coefficient of Variation (Fire Intervals)	**0.75** *(0.29, 78)* (0.69 - 0.82) [0.08 - 1.54]	**0.82** *(0.31, 63)* (0.75 - 0.90) [0.01 - 1.38]
Douglas-fir Fire Scar Ratio	**0.19** *(0.18, 90)* (0.15 - 0.23) [0 - 0.86]	NA
Proportion of Underburns and Low Severity Fires	**0.42** *(0.25, 90)* (0.36 - 0.47) [0 - 0.86]	NA

Table 4.4. Natural fire rotation, calculated for different time periods in three different ways. Natural fire rotation was not calculated for the pre-1588 period using the polygon method because fire boundaries for this period could not reliably be reconstructed.

Time Period	**Ratio Method** (all fires)	**Ratio Method** (excluding low severity)	**Polygon Method** (all fires)
1475 - 1996	78	102	NA
1588 - 1996	96	133	137
1500s	53	55	NA
1600s	111	146	133
1700s	143	198	135
1800s	58	89	76
1900s	204	548	246

of record, for particular time periods, and for individual centuries (Figs. 4.6 - 4.8). Patterns shown in these maps should be interpreted very generally, and in light of the artificially low fire frequency shown for areas sampled with relatively few sites, since fire boundaries were not reconstructed further than 2 km from the nearest site with evidence. For the 1588 - 1996 period, fires were very frequent for portions of the south-facing, low-elevation slope over the McKenzie River, lower Cook Ck. and upper Quentin Ck., and the northeastern part of the study area in the Three Ck. watershed (Fig. 4.6). Fires were relatively infrequent, after taking sampling density into account, in the Tidbits Mt. area, on the north slope over Lookout Ck., in the headwaters areas of McRae and Carpenter Cks., and in portions of the high-elevation, low gradient topography in the upper Squaw Ck. watershed. Little difference in fire pattern was evident between the presettlement (1588 - 1849) and postsettlement (1850 - 1996) cultural periods (Fig. 4.7). Differences in fire pattern between the 1600s, 1700s, and 1800s were not consistently associated with topographic features of the landscape (Fig. 4.8), although many of the fires in the 1800s were concentrated along Blue River and the lower portion of the Deer Ck. watershed, both areas that are exposed to east winds. Fires in the 1900s have been limited to areas of concentrated human use, such as settlement and transportation-related activities on the south-facing slope over the McKenzie River and on portions of the South Santiam River, early logging and mining in the Quartz Ck. watershed, and sheepherding at the higher elevations along the divide between the Blue River and Squaw Ck. watersheds. All of these activities have been linked to the increased occurrence of anthropogenic fire (Burke 1979).

Fig. 4.6. Number of reconstructed fires for each one hectare landscape unit, 1588 - 1996.

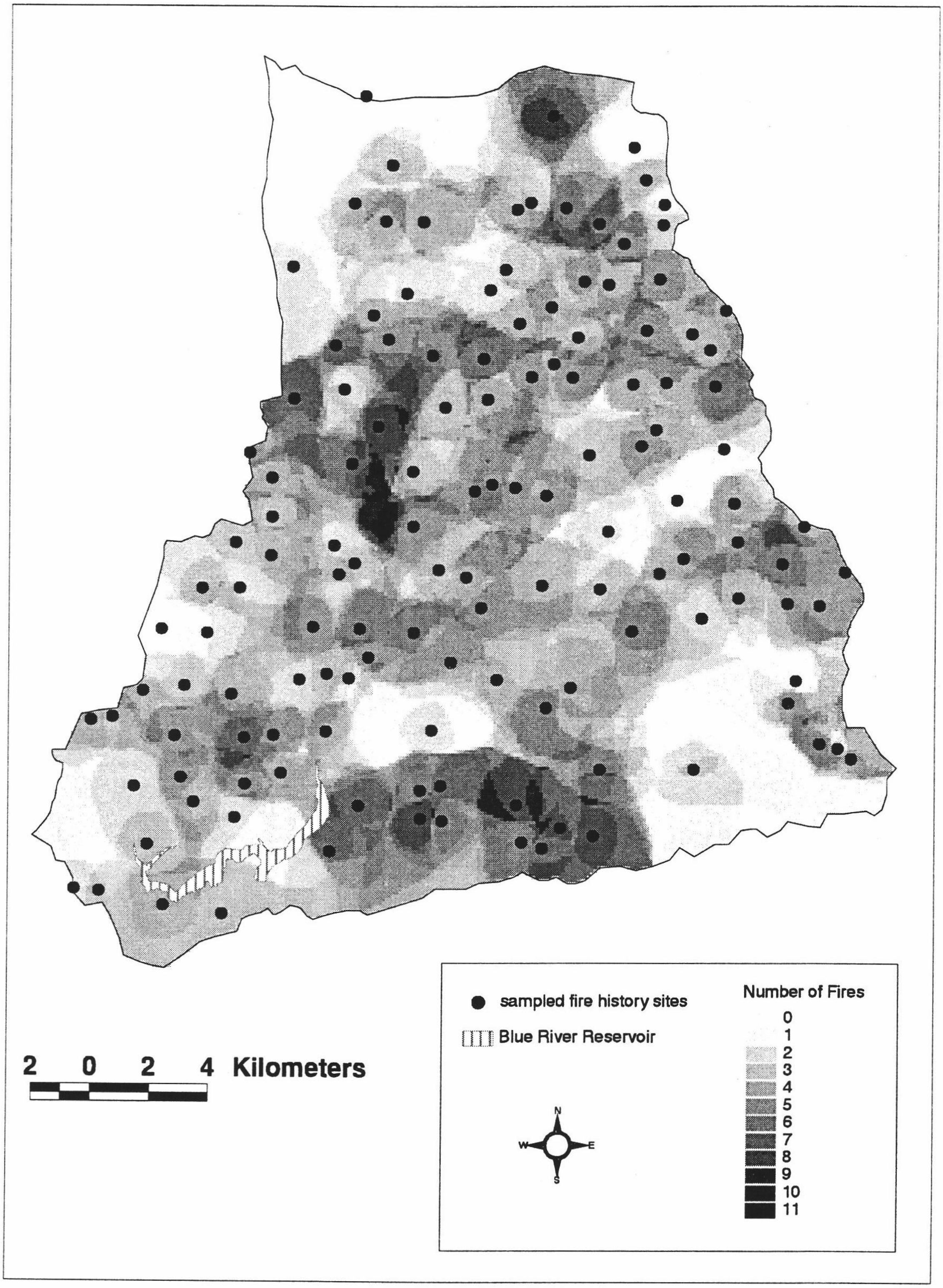


Fig. 4.7. Number of reconstructed fires to have burned over each one hectare landscape unit, for the (A) 1588 - 1849 and (B) 1850 - 1996 time periods.

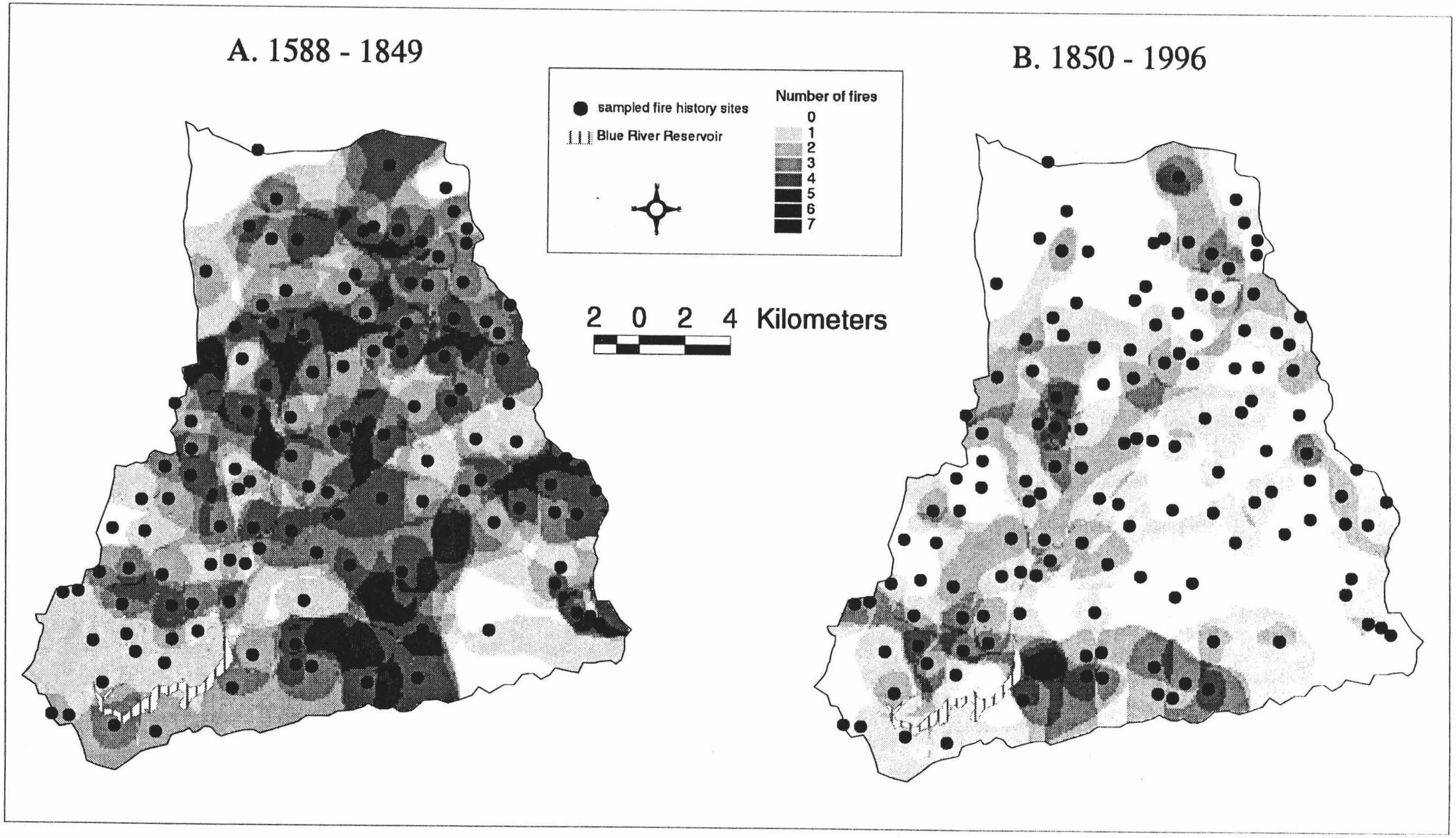
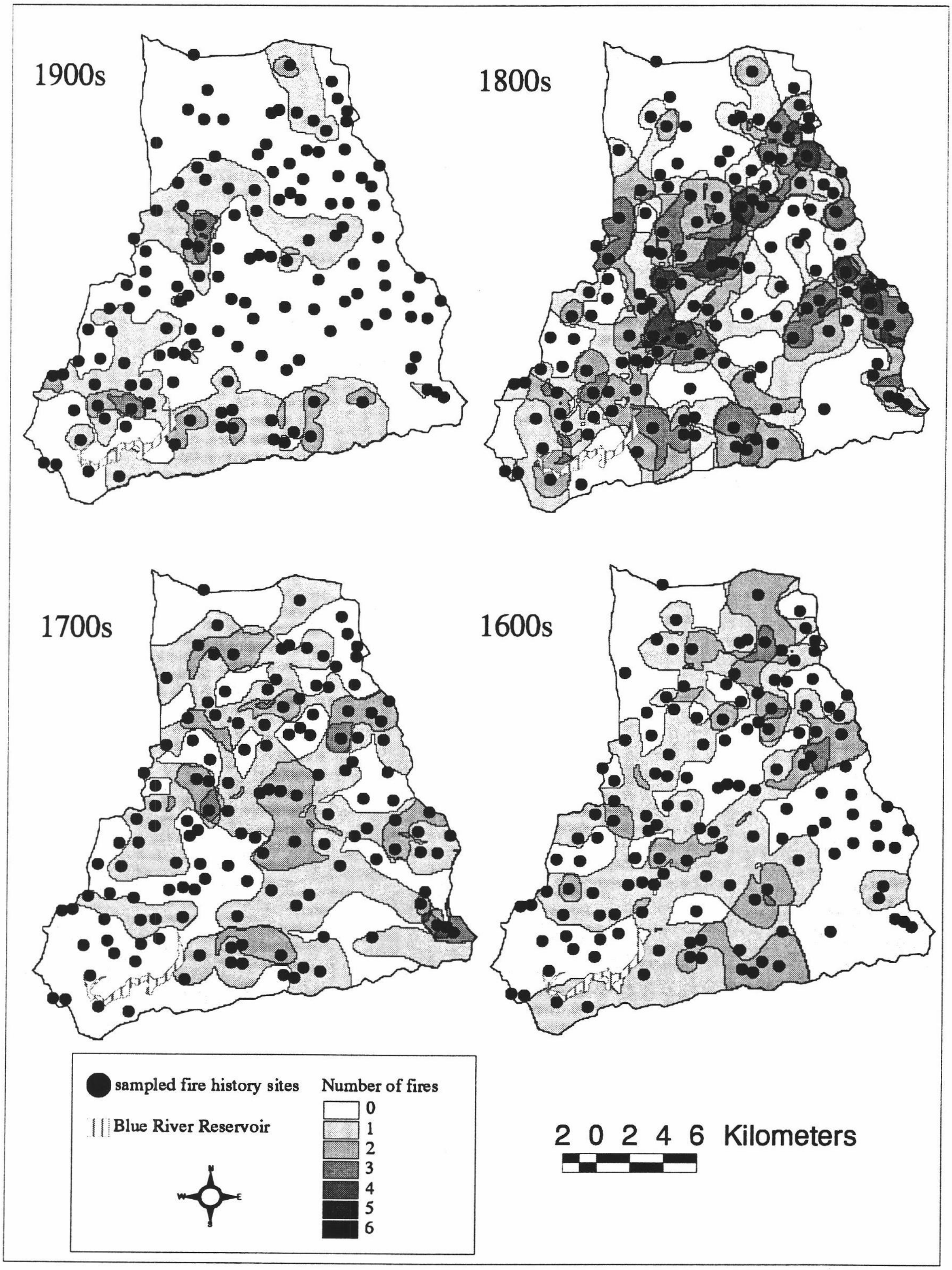


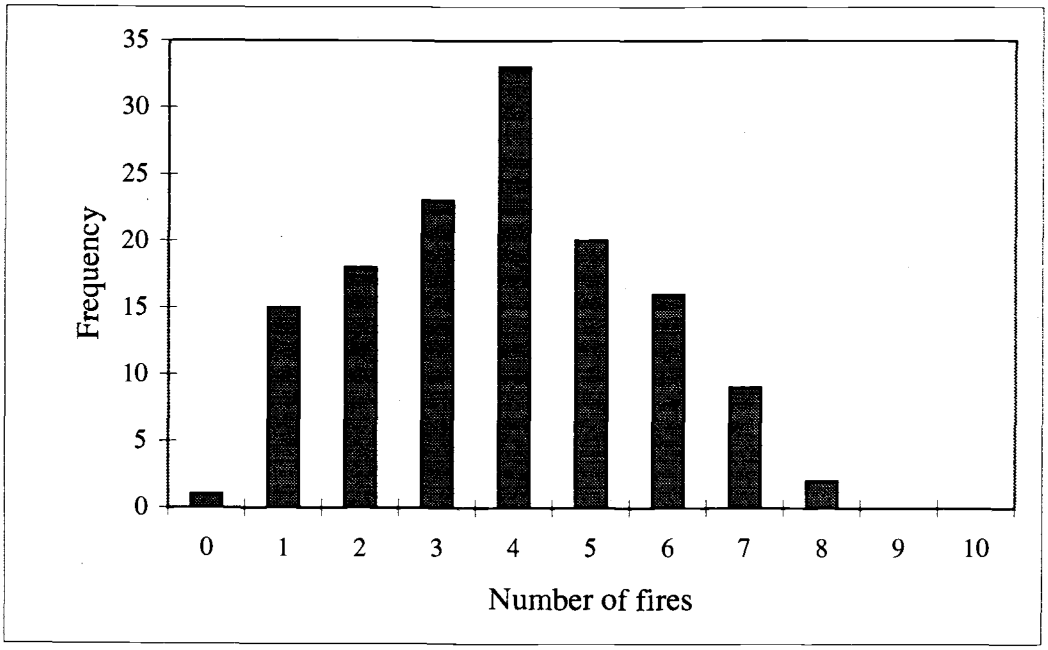
Fig. 4.8. Number of reconstructed fires to have burned over each one hectare landscape unit, by century.



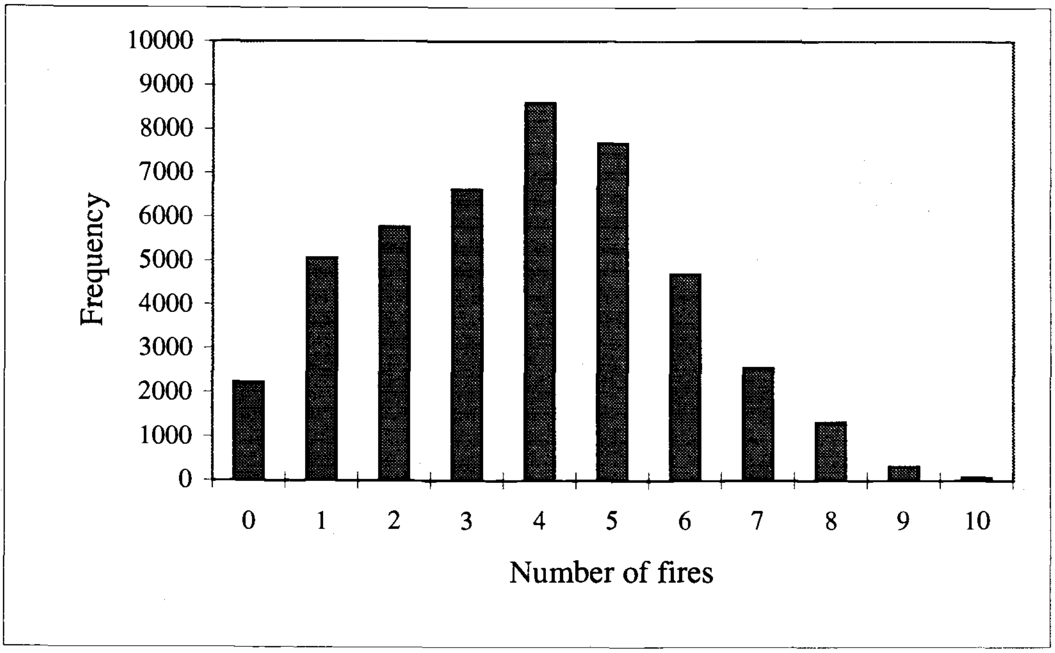
Over the 1588 to 1996 period, there was wide variability in the number of fires reconstructed for each 1-ha landscape unit (Fig. 4.9a). On average, each such unit experienced about four fires, with a range from 0 to 11 fires. Only 2224-ha (5 % of the study area) had no detected fires during this time period, and nearly all of this area had burned since 1470. The distribution of number of fires recorded at each fire history site was quite similar to the reconstructed study area distribution, lending support to its usefulness for describing spatial patterns of fire frequency (Fig. 4.9b). Distributions of numbers of fires per 1-ha unit by century show that the 1800s differed from the other three centuries by having experienced a higher occurrence of repeat fires on the same units (Fig. 4.10).

Another perspective on temporal changes in fire frequency resulted from analysis of cumulative frequency for reconstructed fire episodes, patches, and occurrences at sites (Fig. 4.11). Relatively few fire episodes were reconstructed until ca. 1650, after which the occurrence of fire episodes was fairly constant until the onset of a period of greatly reduced fire episode frequency ca. 1940 (Fig. 4.11a). The cumulative frequency of fire patches shows a similar pattern, except that the earlier period of low frequency ended around 1620, and there was a period of markedly higher fire patch frequency from ca. 1810 to ca. 1940 (Fig. 4.11b). A greater resolution of temporal variation is apparent from the plot of cumulative fire occurrence (Fig. 4.11c). Fire occurrence frequency was high from ca. 1530 to ca. 1620, moderate from ca. 1620 to ca. 1840, very high from ca. 1840 to ca. 1910, reduced from ca. 1910 to ca. 1940, and very low from ca. 1940 to the present. For all of these plots, the initial period of low fire frequency is an artifact resulting from evidence erasure, where relatively few sites were available to record fire evidence from

Fig. 4.9. Number of fires to have burned each site, or reconstructed to have burned over each one hectare area, 1588 - 1996.



a. Number of observed fires for each of 137 sites



b. Number of interpolated fires to have burned each one ha area

Fig. 4.10. Number of fires to have burned each one hectare area, by century.

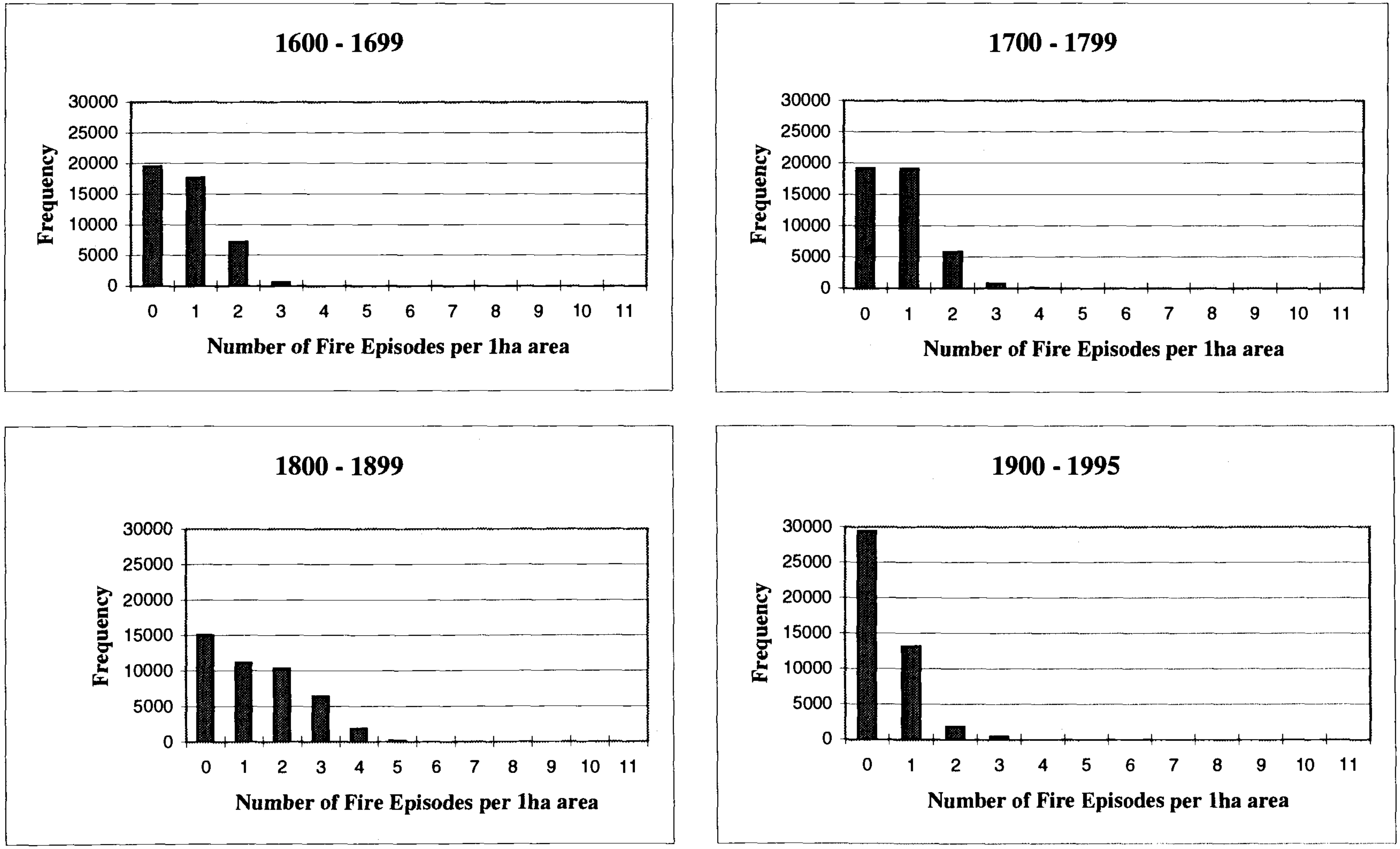
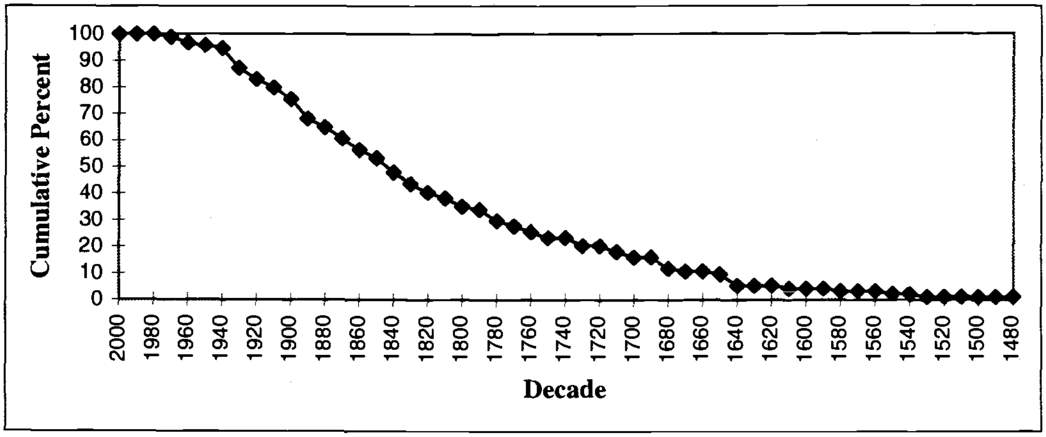
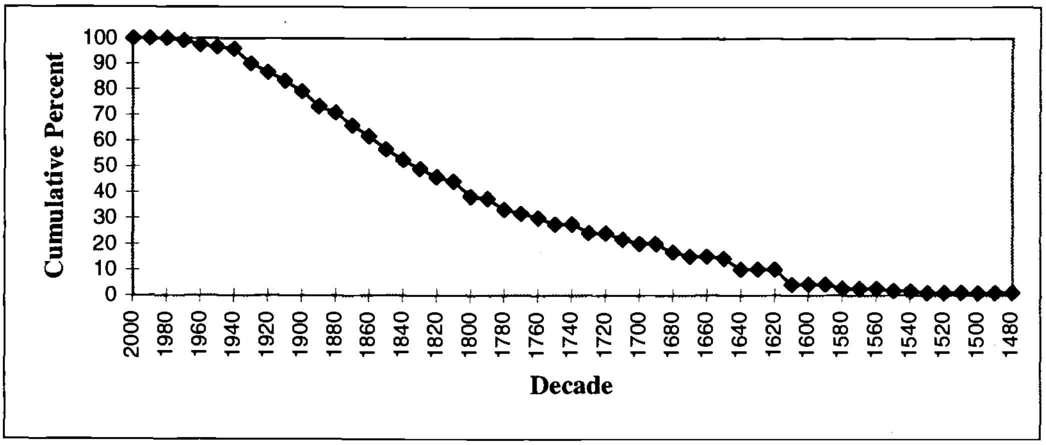


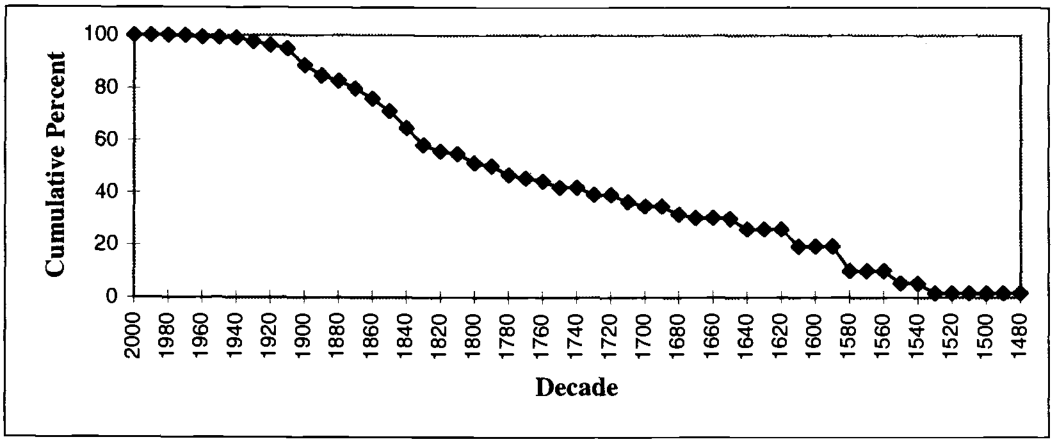
Fig. 4.11. Cumulative fire frequency by decade.



a. Fire episodes



b. Fire patches



c. Fire occurrences at sites

early in the record. The tendency for the rate of increase in cumulative fire frequency to increase gradually with increasing time towards the present also results from evidence erasure. The three plots together suggest a period of fewer, larger fires from 1530 (or earlier) until ca. 1610 - 1640; a period of low fire frequency from ca. 1620 - 1650 until ca. 1800 - 1830; a period of high fire frequency from ca. 1810 - 1840 until ca. 1910; a period of reduced fire extent from ca. 1910 to ca. 1940 until the present, and a period of very low fire frequency from ca. 1940 to the present (Fig. 4.11).

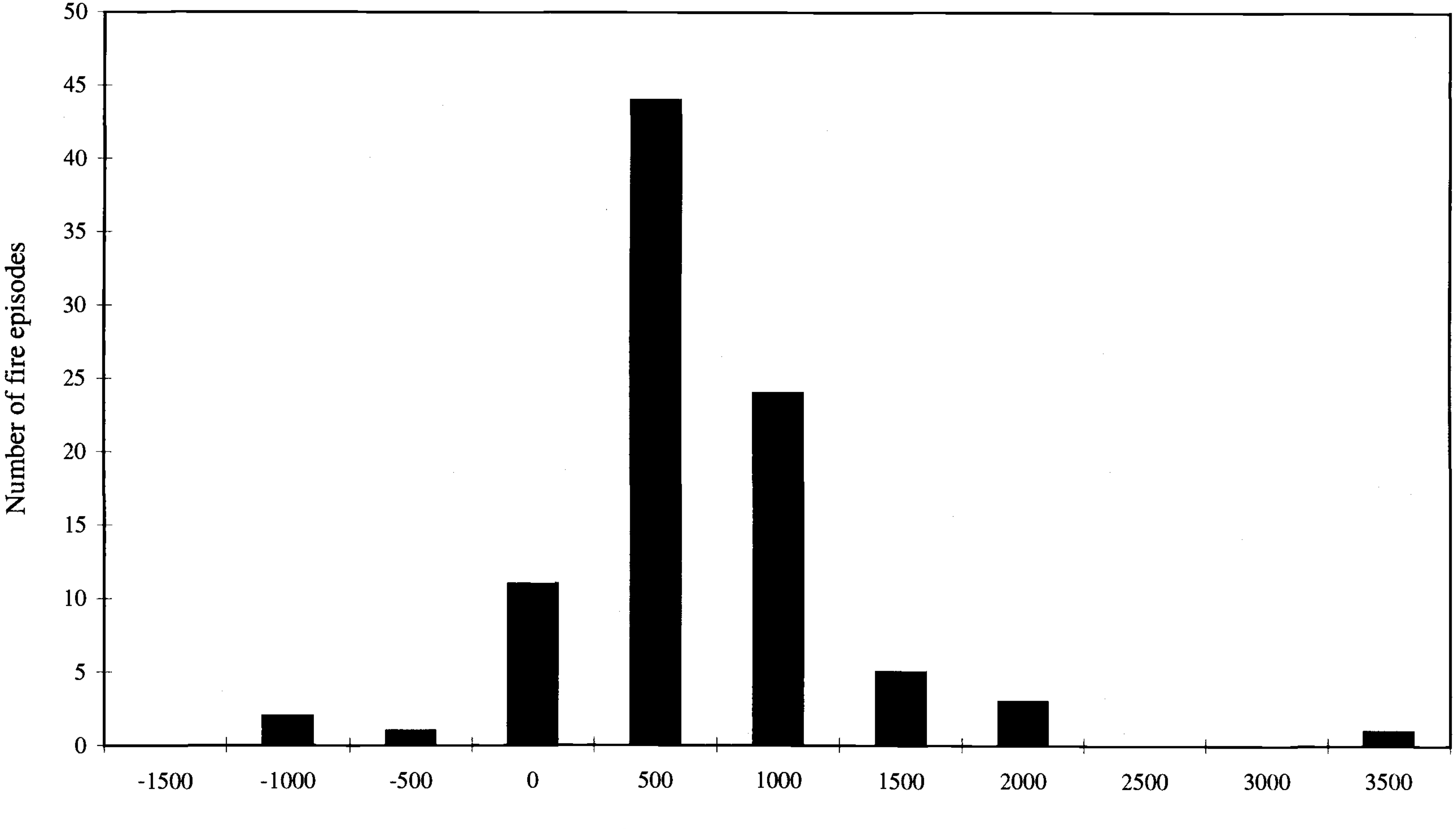
4.4.2.2. Fire Severity and Size

I detected many more low-severity fires than previous studies from within my study area (Teensma 1987, Morrison and Swanson 1990). The average proportion of fires that were low severity or underburns detected at a site was 42% (95% CI: 0.36 - 0.47) (Table 4.3). The average ratio of Douglas-fir fire scars to Douglas-fir tree number, considered an indirect measure of fire severity, was 0.19 (95% CI: 0.15 - 0.23).

The two methods for estimating fire extent yielded slightly different results. The ratio method yielded fire sizes that were typically greater than those estimated using the polygon method, although these differences were small (Fig. 4.12). The two measures were highly correlated ($r = 0.9878$), and the difference between them increased slightly with increasing fire episode size according to the relationship:

$$\text{ratio size} = 224.54 + (1.09 * \text{polygon size})$$

Fig. 4.12. Comparison of fire episode size estimates using the ratio and polygon methods. The frequency distribution of differences between the two methods is shown, using 500 ha intervals.

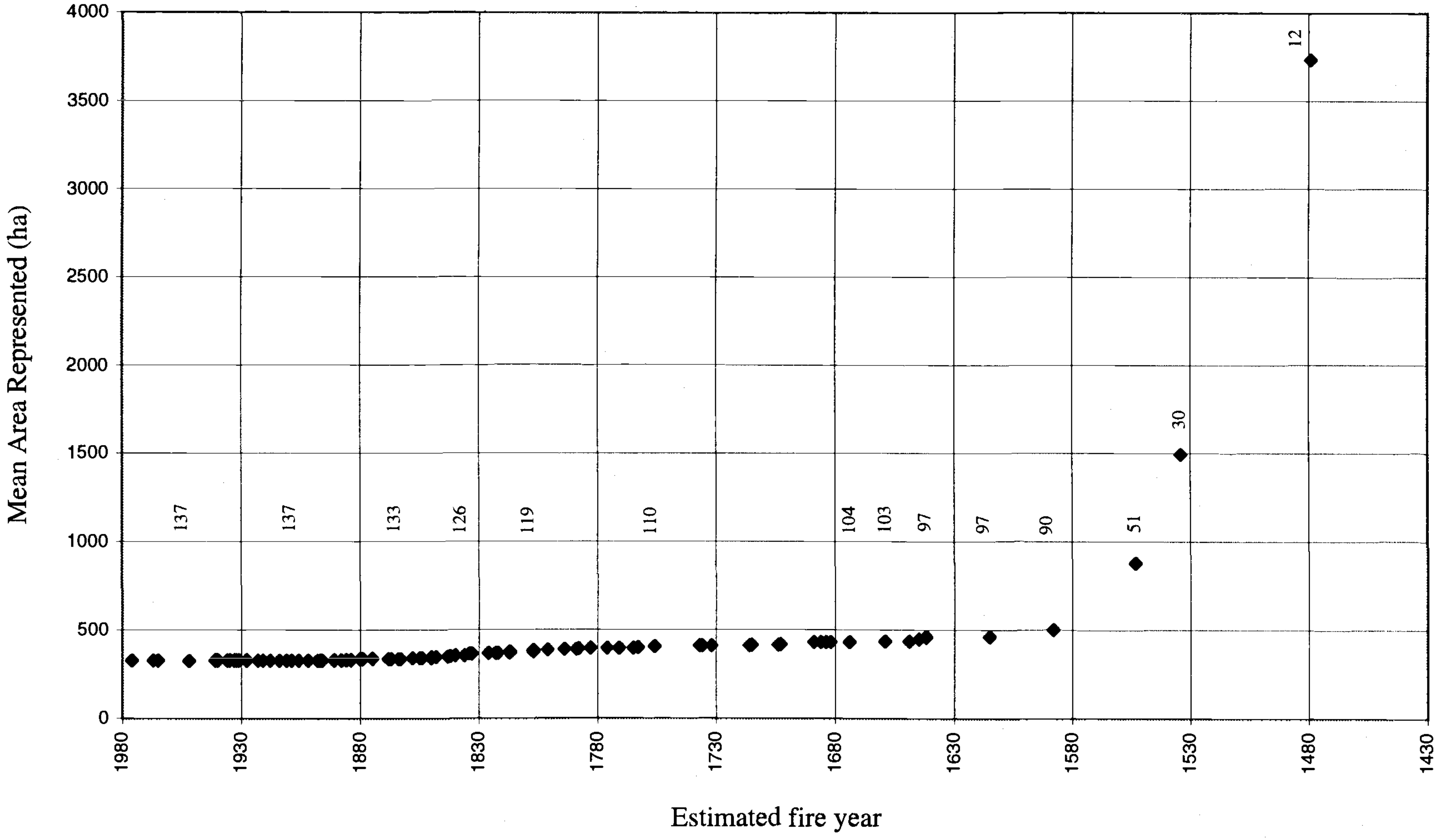


Polygon method size estimates were lower because of fire size reconstruction criteria limiting fire episode boundaries to within 2-km of sites with fire evidence. Apparently, the spacing of fire history sites resulted in many sites representing a greater area than this for the ratio method. The mean area represented by a site has changed over time, according to the frequency of complete evidence erasure at other sites (Fig. 4.13). The steep increase in mean area represented prior to the widespread 1588 fire episode suggests that fire episode extents for earlier than 1588 could not be reconstructed as accurately.

It is interesting that Teensma (1987), in a study covering the southeastern portion of my study area, found a greater proportion of sites with trees old enough to record pre-1580 fires than I did for the study area as a whole. The ca. 1480, ca. 1530, ca. 1550 (combining two episodes from Teensma (1987)), and ca.1590 fire episodes were recorded at 47 %, 31 %, 13 %, and 32 % of sites, respectively, in the Teensma (1987) study area, and at 7 %, 16 %, 20 %, and 39 % of sites in the greater Blue River study area. This discrepancy may be due to a greater proportion of the Teensma study area having older trees, to a bias towards harvesting the oldest old-growth stands before Teensma sampled fire history in clearcuts, or to sampling techniques in the current study that were less focused towards finding the oldest tree at each site.

I believe the polygon method provided a more accurate representation of past fire extent, since it incorporated information about the spatial arrangement of sites with positive and negative evidence for a fire episode. The ratio method only used information about the proportion of recording sites with evidence relative to the size of the study area. Neither method provided meaningful estimates of fire extent at the level of the individual

Fig. 4.13. The mean area represented by each site over time. Data labels refer to the number of sites with trees old enough to record fires of that year.

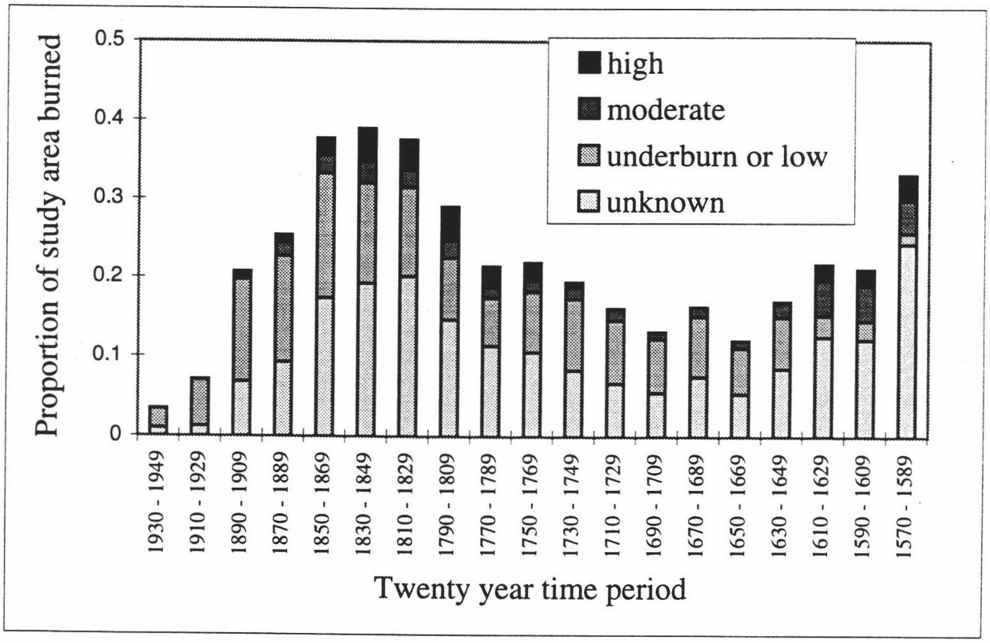


fire episode, because fire episodes may consist of from one to many fires occurring within several years or a few kilometers. Fire episodes were more likely to consist of multiple fires earlier in the fire record (Fig. 4.4), where there was less resolution in fire reconstruction due to a loss of recording sites (Fig. 4.13) and increased inaccuracy in ring counting. For this reason, I do not report fire sizes or show maps of reconstructed fire boundaries for individual fire episodes.

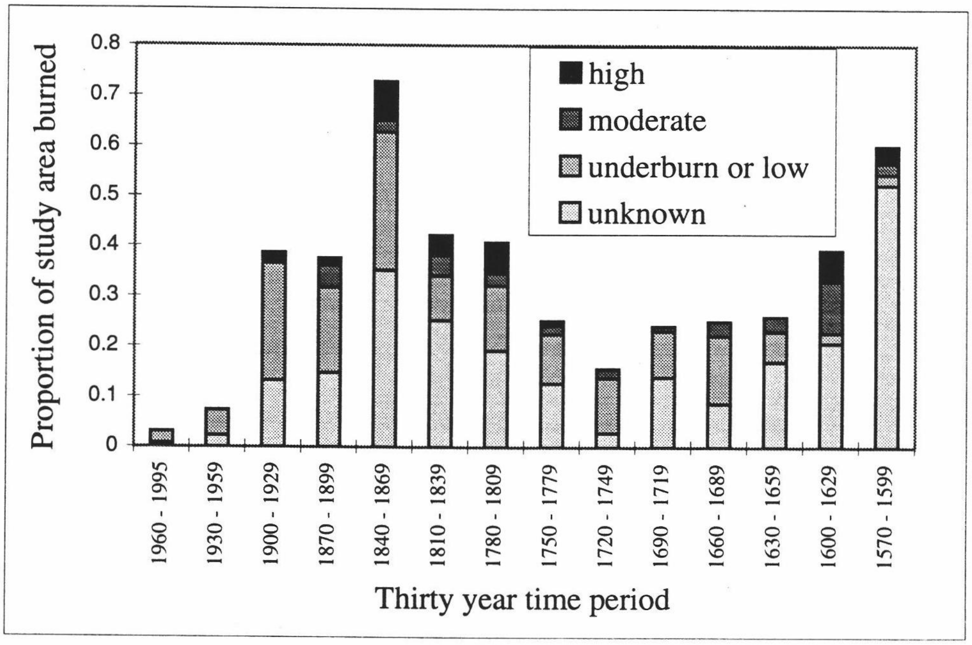
It is meaningful, however, to consider temporal patterns of burned area at the resolution of multiple decades, where inaccuracies in the resolution of discrete fires are of little importance. Regardless of whether the ratio or polygon method was used, there were definite changes in fire size and severity over time (Figs. 4.14, 4.15). Periods of widespread, high-severity fire occurred prior to ca. 1630 and from ca. 1780 to ca. 1930. The record of fire evidence erasure, reflecting the occurrence of high-severity fires over much of the study area, shows that most of the sampled sites had oldest trees with origin years ranging from ca. 1480 to ca. 1588 (Fig. 4.13). It is apparent that the earlier period of widespread, high-severity fire dominates the current stand age mosaic and fire record. This is not evident in Figures 4.14 and 4.15 because the effects of fires earlier than 1570 are not shown, and because most of the fires for the 1570 to 1630 period were reconstructed as having unknown severity. There is too little evidence remaining to accurately reconstruct pre-1570 fire episodes (Fig. 4.13).

Distinct periods of relatively low values of burned area and fire severity occurred over the 1588 - 1996 record (Figs. 4.14, 4.15). From ca. 1630 to ca. 1750, a relatively small area burned and no high-severity fires were recorded. From ca. 1750 to ca. 1789 the extent of burned area remained low, but a small amount of high-severity fire was

Fig. 4.14. Fire severity and size over time - ratio method

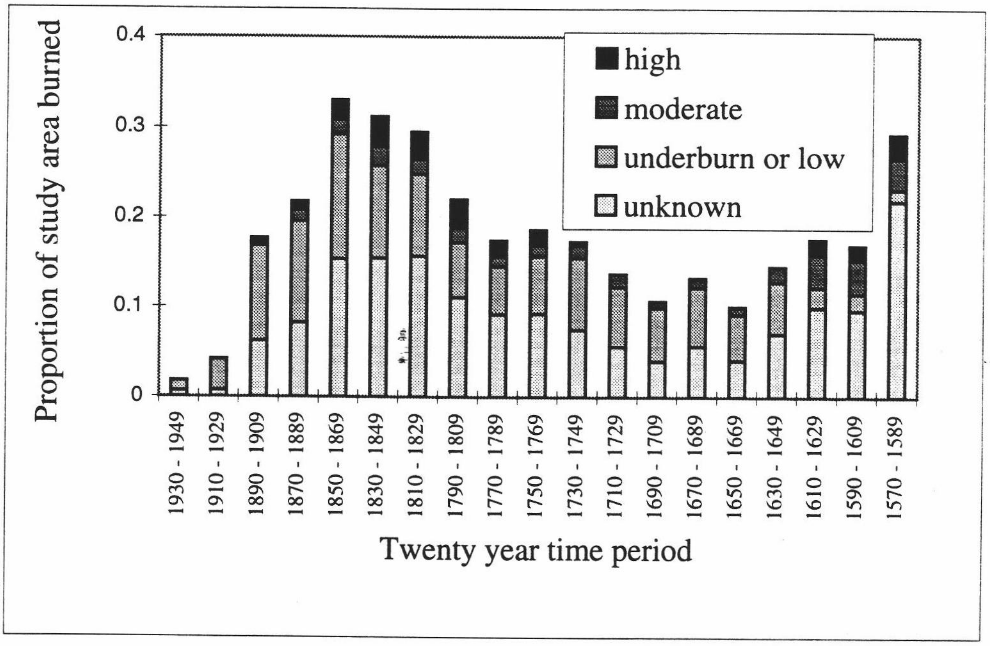


a. Moving Average (60 yrs.)

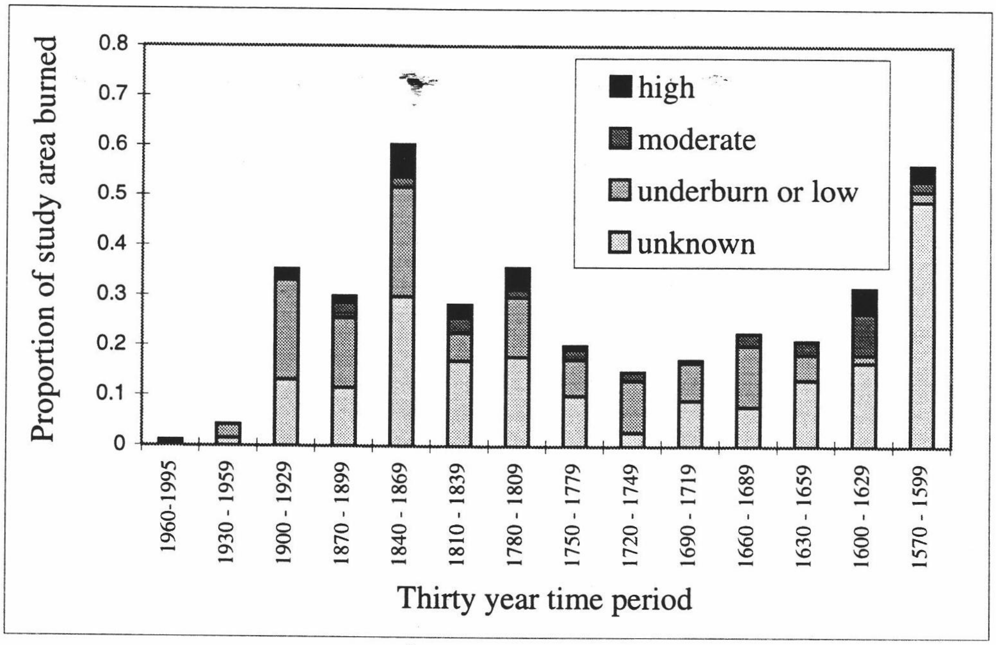


b. 30 Year Time Periods

Fig. 4.15. Fire severity and size over time - polygon method



a. Moving Average (60 yrs.)



b. 30 Year Time Periods

observed. Since ca. 1930 a very small proportion of the study area has burned, and all reconstructed fires have been of underburn, low, or unknown (but clearly not high) severity.

4.4.3. Spatial Variability in Fire Patterns

Descriptions of fire regime and fire pattern that apply to the study area as a whole integrate much variability from environmental, topographic and climatic influences on fuels and fire behavior. Environmental influences on fire regime may operate over multiple scales. I have endeavored to describe such variation over three scales: the within site scale of relative hillslope position; the within-basin scale of slope steepness, aspect, and hillslope position; and larger-scale gradients in elevation and vegetation. The latter two scales were combined into a single "between-site" scale for analytical purposes.

4.4.3.1. Within-site scale

Relative hillslope position appears to be a major factor influencing the length of the fire record and tree-age distribution at the within-site scale. Although for 62 % of sites the oldest fires recorded for upper and lower plots were the same, the oldest fire recorded was earlier for the lower plots for 79 % of the cases where they differed (38 % of cases) (Fig. 4.16). Similar relationships between relative slope positions are apparent from the difference histograms of both oldest and average Douglas-fir origin years (Fig. 4.17). Douglas-fir trees appear to be older at lower plots. Considering individual fire occurrences at different slope positions within sites, both lower and upper site pairs recorded evidence for 217 fires, whereas upper plots recorded evidence while lower plots

Fig. 4.16. Differences in ages of oldest recorded fires for plot pairs higher and lower on the hillslope, with plot pairs (n = 76) separated by 200 m.

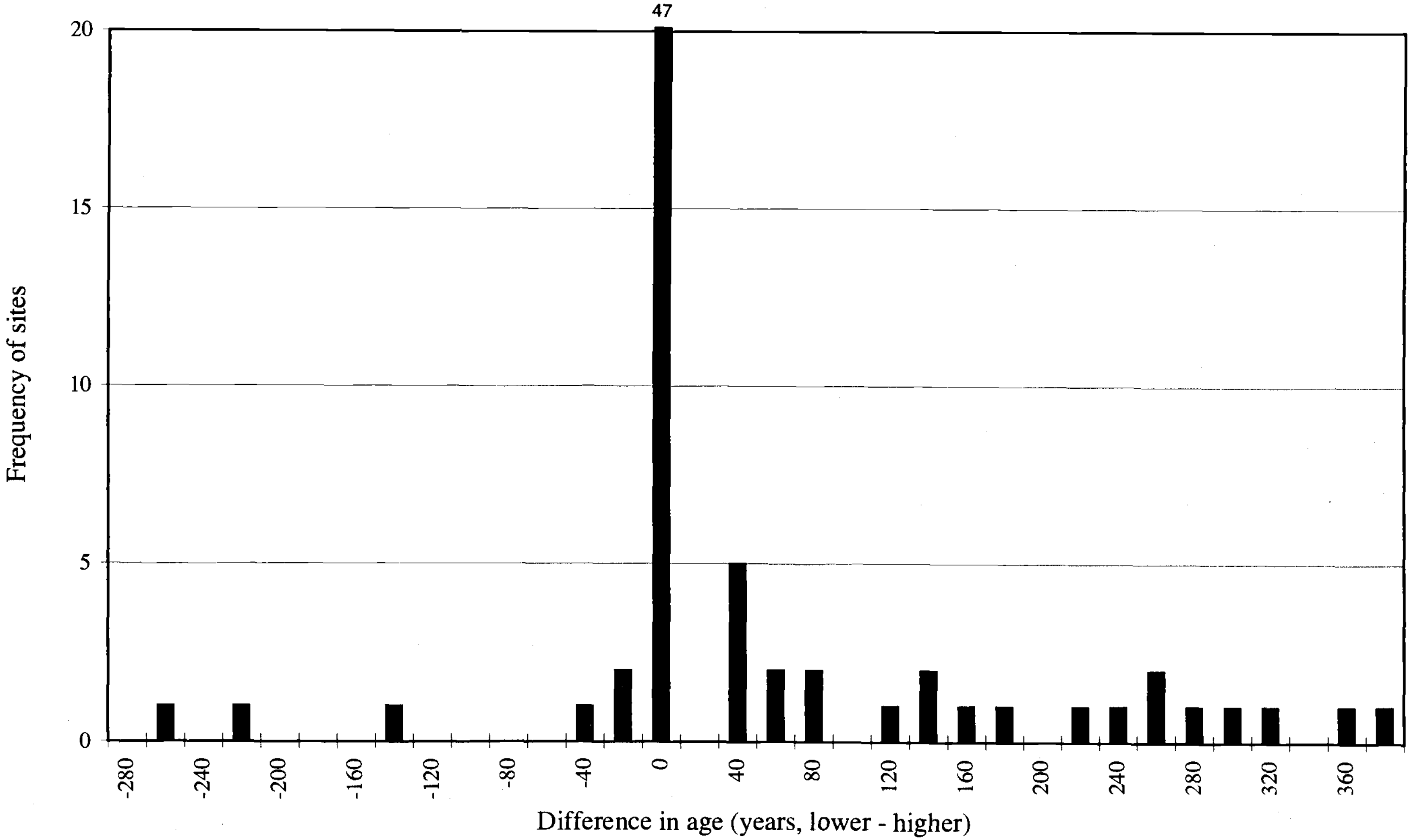
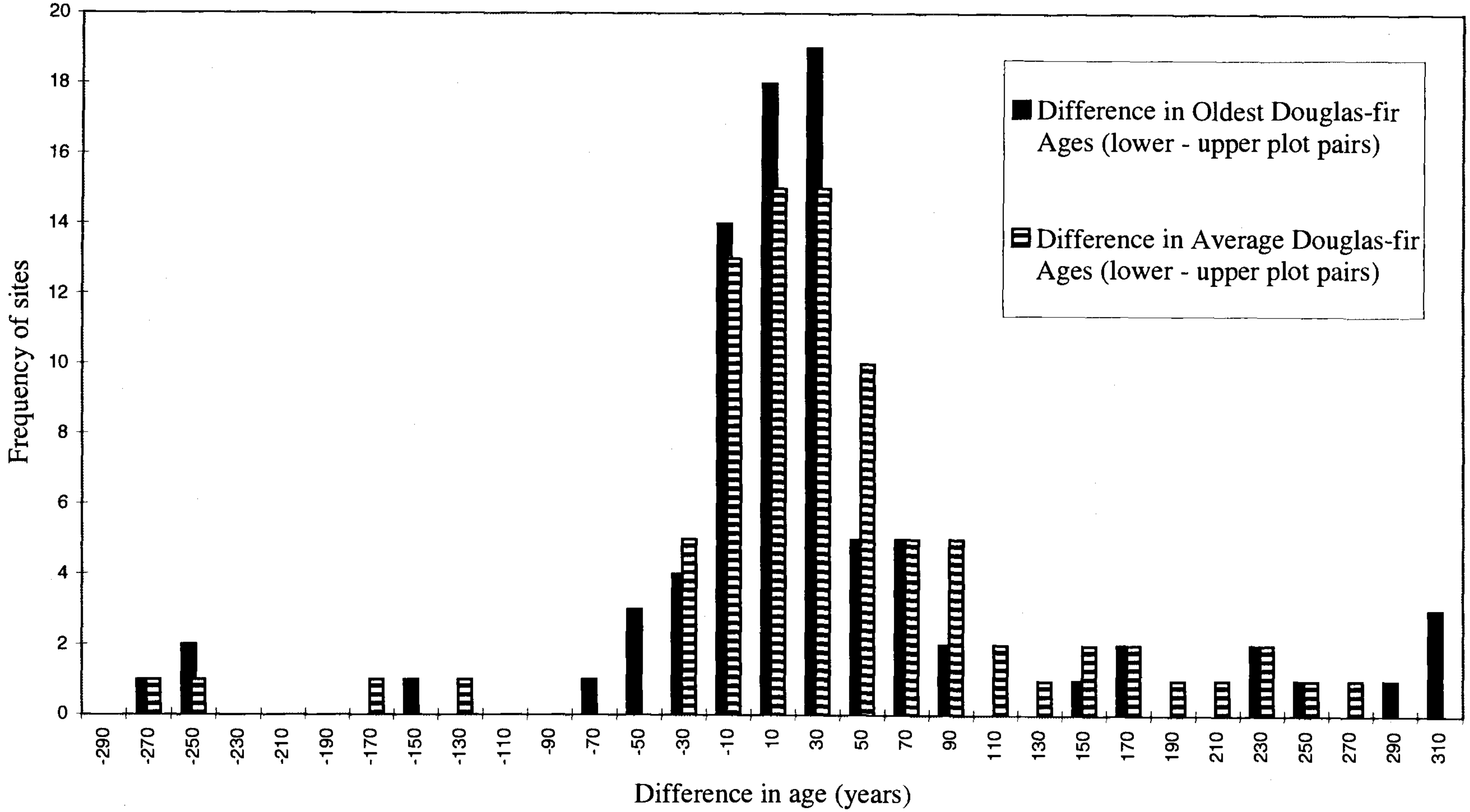


Fig. 4.17. Differences in oldest and average Douglas-fir ages for plots higher and lower on the hillslope, where plot pairs are separated by 200 m. Positive differences indicate that the lower slope plots have older trees.



did not for 47 fires, and lower plots recorded evidence while upper plots did not for 25 fires. These differences are significant ($X^2 = 6.72$, $p = 0.0095$), suggesting that fire frequency was greater for upper slope positions. However, these differences do not seem large enough to account for the difference in Douglas-fir tree ages between lower and upper plots. One might surmise that observed differences in Douglas-fir ages are due to fine-scale topographic influences on both fire frequency and severity.

4.4.3.2. Between-site scale

I used principal components analysis to select a subset of the fire severity and frequency variables for regression analysis against topographic variables (Table 4.5). The first PC explains 39% of the variance, and represents a common tendency for sites to have a positive association between the frequency of moderate and high severity fires, the frequency of all fires, and the proportion of low severity fires. The second PC represents variation in fire interval lengths at a site. The third PC represents the negative association between fire severity and fire frequency, while the fourth PC represents sites that had a low fire frequency and many scars, but a low proportion of low severity fires, suggesting that the high number of scars at these sites was due to relatively few moderate and high severity fires.

On the basis of the PCA, I chose maxFI.nlow, CV, SCAR.ratio, PROPLOW, and WMPI for further analysis. The first three were chosen because they loaded most highly on the first three principal components, respectively, and so represent relatively uncorrelated factors (Table 4.5). WMPI was chosen because it loaded most highly on PC 4 after SCAR.ratio, which had already been chosen. PROPLOW was chosen to include a

Table 4.5. Loadings of fire history variables on the first four principal components. Shown in parentheses is the amount of variance explained by each principal component. The loadings represent linear combinations of each variable comprising the component. Loadings less than 0.2 are not shown; loadings greater than 0.5 are shown in bold.

Variable	**PC 1** (0.39)	**PC 2** (0.24)	**PC 3** (0.20)	**PC 4** (0.10)
SCAR.ratio			**-0.649**	**0.750**
PROPLOW	0.411		-0.388	-0.324
PROPHIGH				
WMPI	0.387		0.467	0.475
CV	-0.235	**0.676**		
STDEV		**0.665**	0.286	
MFI			0.268	0.238
MFI.nlow	**0.541**			
maxFI.nlow	**0.545**	0.200		

SCAR.ratio = the ratio of the number of Douglas-fir fire scars to the number of Douglas-fir trees sampled at a site

PROPLOW = the proportion of low-severity fires at a site

PROPHIGH = the proportion of high-severity fires at a site

WMPI = the Weibull median probability interval of fire intervals at a site

CV = the coefficient of variation of fire intervals at a site

STDEV = the standard deviation of fire intervals at a site

MFI = the mean fire interval at a site

MFI.nlow = the mean fire interval at a site, excluding low-severity fires

maxFI.nlow = the maximum fire interval at a site, excluding low-severity fires variable that measured fire severity only; SCAR.ratio is influenced by both fire frequency and severity.

The Weibull median probability interval varied according to topographic variables representing climatic factors of temperature and moisture (Table 4.6). Higher WMPI values (i.e., lower fire frequency) were positively associated with higher elevations, north-facing slopes, and lower slope positions. The effects of slope aspect and slope position interacted such that fire frequency was especially low on north-facing, lower slopes, but varied little over slope aspect for upper slope positions (Fig. 4.18). The map of predicted WMPI illustrates these relationships graphically over the topographic heterogeneity of the study area (Fig. 4.19). Fire frequency followed an elevational gradient, but was low on north-facing slopes and along streams, and especially low where two or more of these factors overlap.

Spatial residual analysis for the Weibull Median Probability Interval regression model did not show consistent patterns of residuals that were related to variation in east wind exposure and human ignition potential (Fig. 4.20a). The model did not predict WMPI well for much of the Cook-Quentin area, underestimating fire frequency in the upper parts of these watersheds, and overestimating fire frequency in the middle and lower parts.

The maximum interval between fires of high, moderate, or unknown severity varied according to topographic predictors in a manner very similar to the WMPI (Table 4.7). Topographic variables explained more of the variation in maximum fire interval ($R^2 = 0.36$) than for any of the other four fire history variables modelled. The maximum fire interval was longer for higher elevations, more north-facing slopes, lower slope

Table 4.6. Regression model of Weibull median probability interval as a function of environmental variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect. Slope position is treated as an indicator variable with respect to "lower slope position" as a reference condition. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	47.09	16.70	0.0064	(14.26, 79.84)
Elevation	0.0358	0.0158	0.0265	(0.0048, 0.0668)
Northness	27.15	9.21	0.0045	(9.09, 45.21)
Midslope	-18.99	8.37	0.0266	(-35.40, -2.58)
Upper Slope	-10.04	8.46	0.2397	(-26.62, 6.54)
Northness:Midslope	-12.18	11.77	0.3045	(-35.25, 10.89)
Northness:Upper	-23.37	11.29	0.0425	(-45.50, -1.24)

$R^2 = 0.27$, $F(6, 65) = 3.99$, $p = 0.0018$

4.18. Predicted interactions for effects of cosine transformed slope aspect and slope position on the Weibull Median Probability Interval. Higher values for the transformed slope aspect indicate more north-facing slopes.

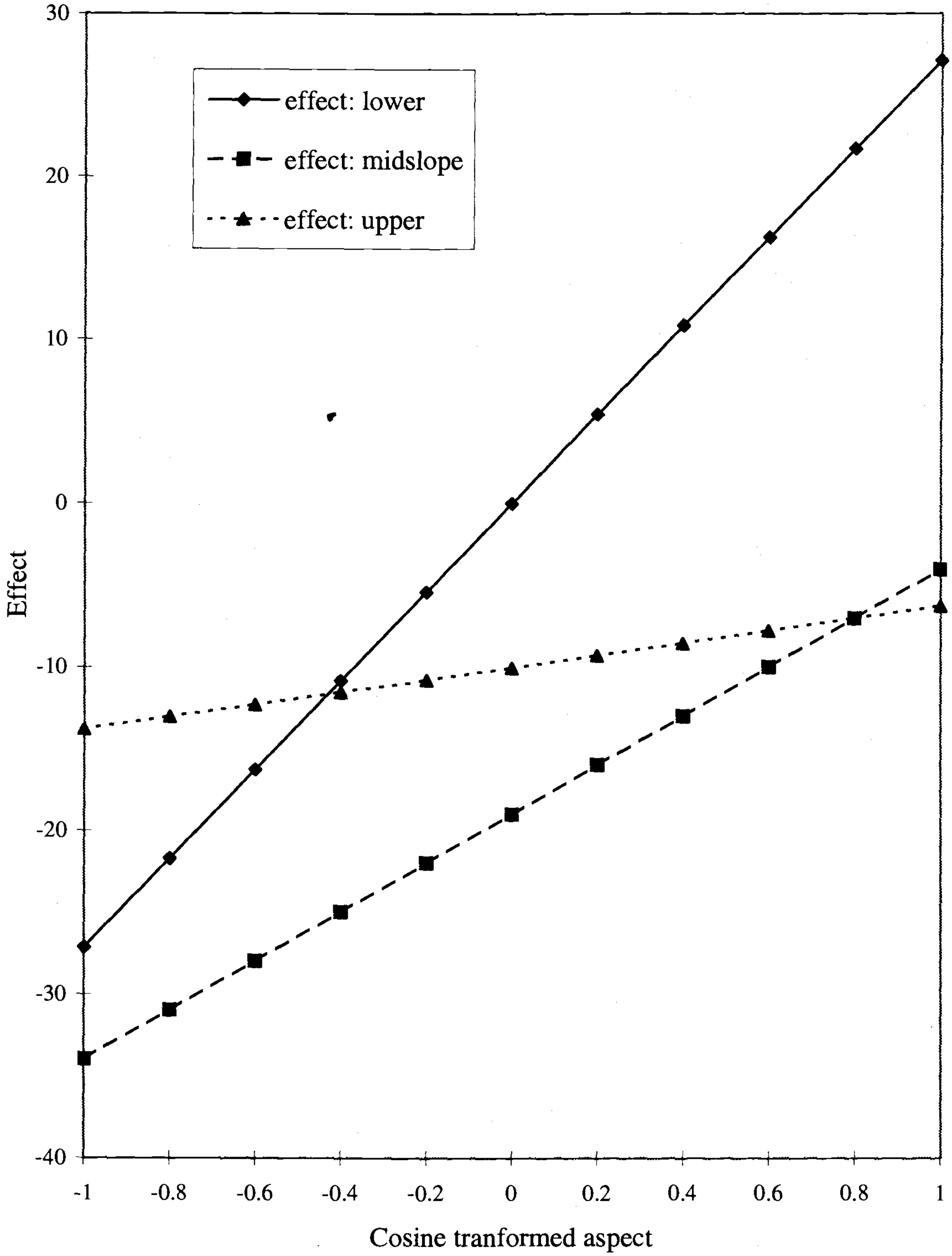


Fig. 4.19. Weibull median probability interval for all fires at a site, 1475 - 1996.

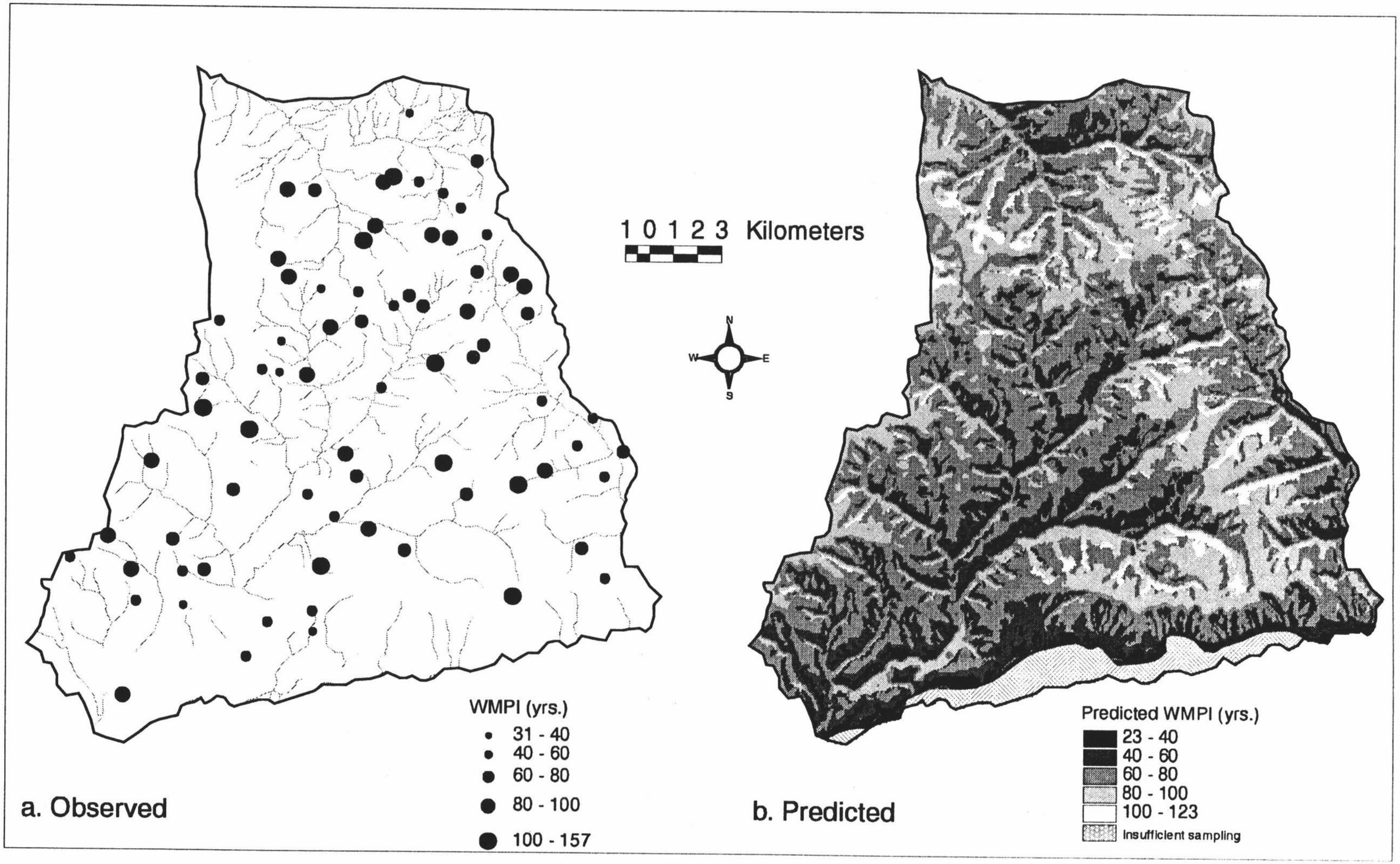


Figure 4.20. Residuals for the WMPI and maximum fire interval regression models. Positive residual values (circles) indicate that the regression model overestimates the value for a given site.

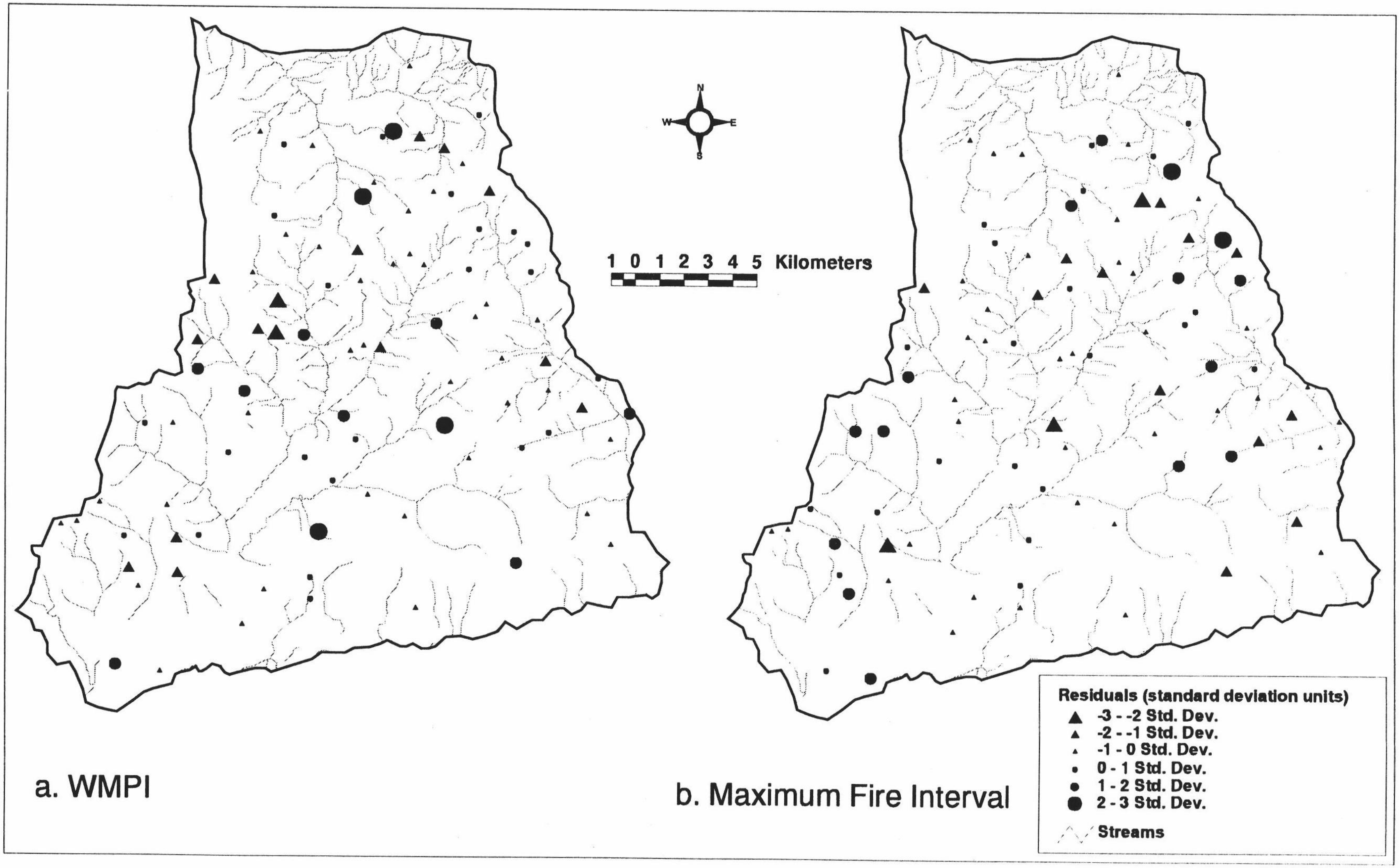


Table 4.7. Regression model of maximum fire interval between fires of moderate, high, or unknown severity, as a function of environmental variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect. Slope position is treated as an indicator variable, with respect to "lower slope position" as a reference condition. Slope steepness is also treated as an indicator variable where gradual slopes represent the reference condition. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	376.70	89.69	0.0001	(200.92, 552.49)
Elevation	0.0005	0.0849	0.9956	(-0.1659, 0.1669)
Northness	30.65	13.54	0.0270	(4.11, 57.19)
Midslope	-72.44	27.18	0.0097	(-125.71, -19.17)
Upper Slope	-68.59	26.16	0.0109	(-119.86, -17.32)
Moderately Steep	-186.83	129.89	0.1551	(-441.41, 67.75)
Very Steep	-310.01	126.49	0.0170	(-557.93, -62.09)
Elevation:Moderately Steep	0.1401	0.1184	0.2409	(-0.09, 0.37)
Elevation:Very Steep	0.2642	0.1217	0.0335	(0.03, 0.50)

$R^2 = 0.36$, $F(8, 65) = 4.67$, $p = 0.0002$

positions, and for gradual slopes at lower to middle elevations. The effects of elevation and slope steepness interacted such that steep slopes at high elevations had long maxFI.nlow, while sites on gradual slopes had high maxFI.nlow regardless of elevation (Fig. 4.21). The map of predicted maximum fire interval closely resembles that of predicted Weibull Median Probability Interval, although patterns follow the stream network less closely, due to the importance of slope steepness for maxFI.nlow (Figs. 4.19, 4.22). Residuals for the maxFI.nlow model did not show clear patterns related to variation in east wind exposure or human influences (Fig. 4.20b). For some reason, the regression model did not predict maximum fire interval as well in the western and eastern portions of the study area as it did in the central portion.

The coefficient of variation between fire intervals at a site did not vary significantly with combinations of topographic variables; no significant regression model could be derived. Variability in fire interval length appears to have been distributed randomly across the environmental heterogeneity of the study area.

Variables reflecting fire severity were more weakly associated with combinations of environmental variables than were variables reflecting fire frequency. The regression models for PROPLOW and SCAR.ratio had R^2 values of 0.14 and 0.09, respectively, compared to values of 0.27 and 0.36 for maxFI.nlow and WMPI. Sites with a high proportion of low-severity fires were associated with higher elevations and lower slope positions (Table 4.8), while sites with a higher ratio of Douglas-fir trees scarred to Douglas-fir trees sampled were associated with more north-facing and more gradual slopes (Table 4.9). The map of predicted PROPLOW shows a gradient of increasing values with increasing elevation, with a secondary influence of slope position (Fig. 4.23).

Fig. 4.21. Predicted interactive effect of elevation and slope steepness on the maximum interval between moderate, high, and unknown severity fires.

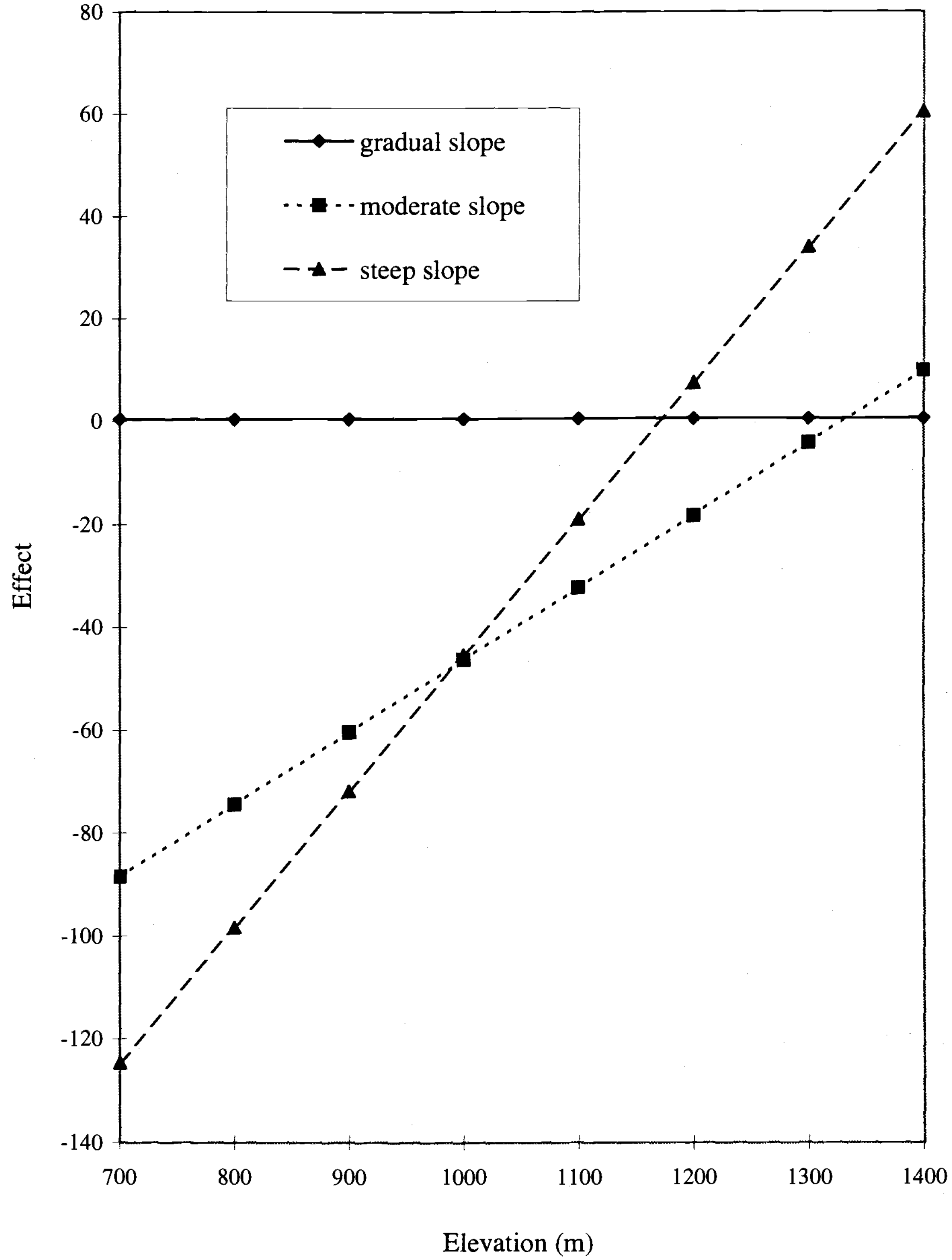


Fig. 4.22. Predicted maximum fire interval between fires of moderate, high and unknown severity, 1475 - 1996

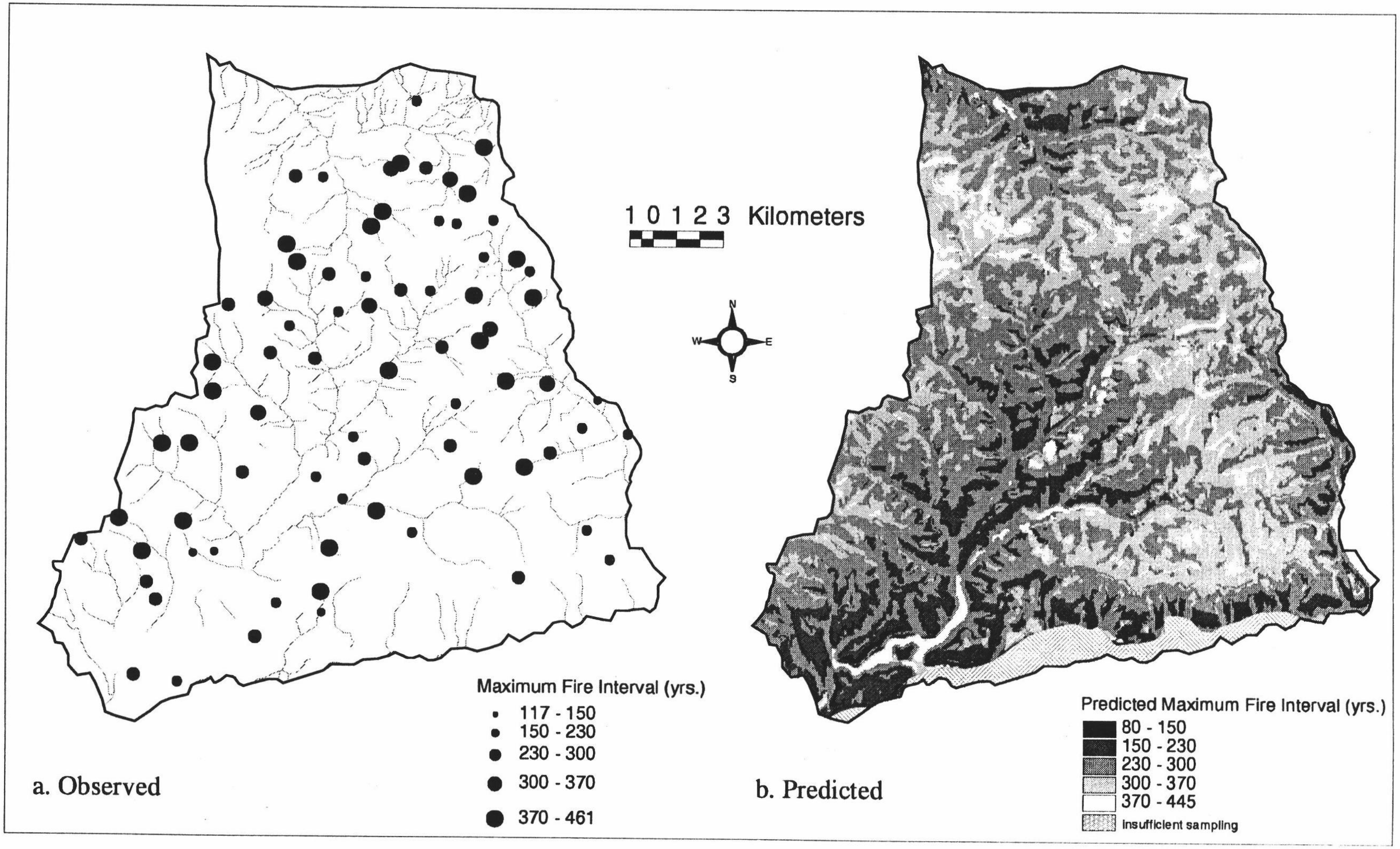


Table 4.8. Regression model of the proportion of low-severity fires at a site, as a function of environmental variables. Slope position is treated as an indicator variable, with respect to "lower slope position" as a reference condition.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	0.22	0.13	0.1082	(-0.03, 0.47)
Elevation	0.0003	0.0001	0.0351	(0.0001, 0.0005)
Midslope	-0.16	0.07	0.0235	(-0.30, -0.02)
Upper Slope	-0.04	0.07	0.5833	(-0.18, 0.10)

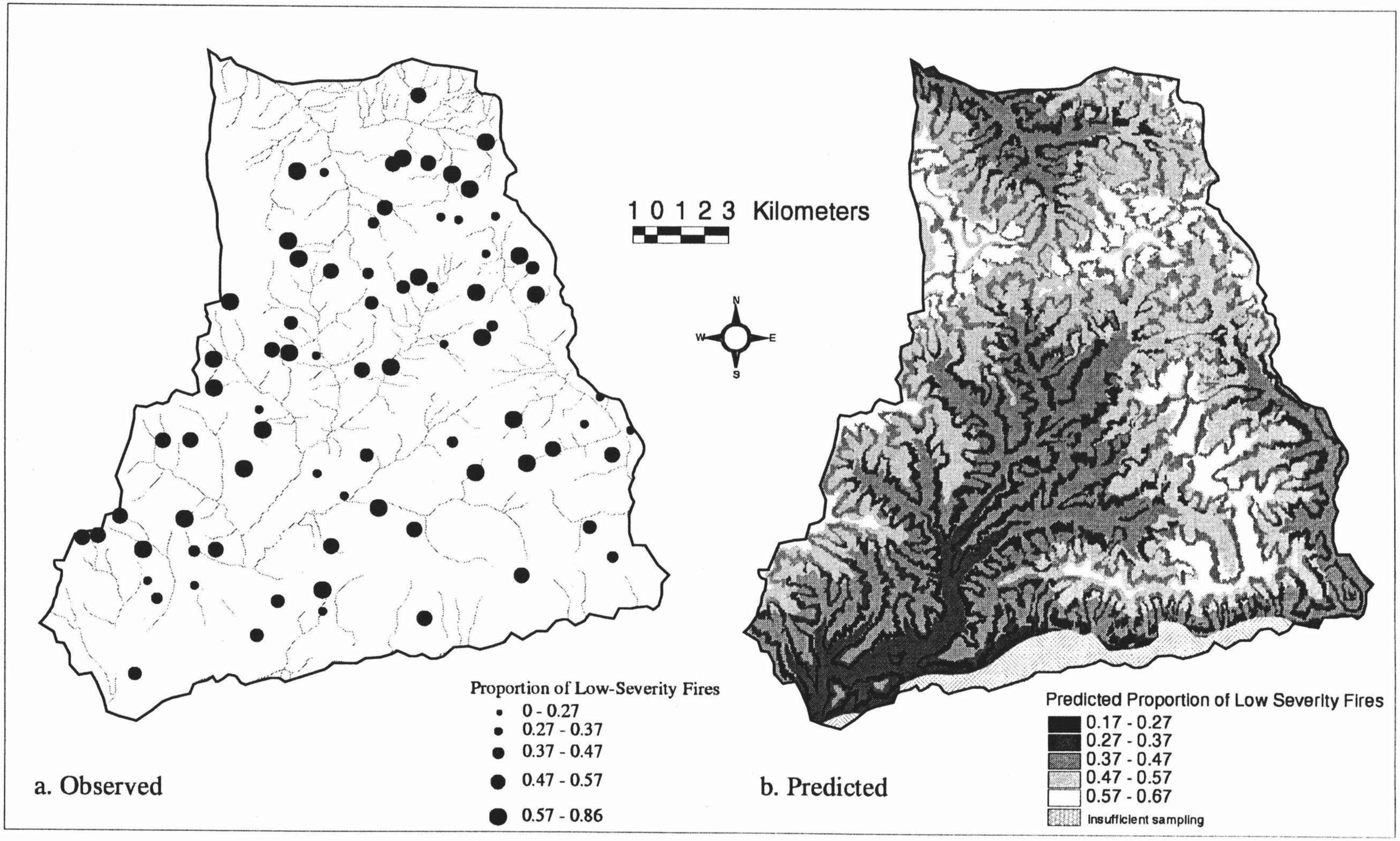
$R^2 = 0.14$, $F(3, 84) = 4.559$, $p = 0.0052$

Table 4.9. Regression model of the ratio of fire scars on Douglas-fir to the number of Douglas-fir trees sampled at a site, as a function of environmental variables. Slope steepness is treated as an indicator variable, with respect to gradual slopes as a reference condition.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	0.26	0.04	0.0000	(0.18, 0.34)
Northness	0.04	0.03	0.0892	(-0.02, 0.10)
Moderately Steep	-0.10	0.05	0.0345	(-0.20, 0.00)
Very Steep	-0.11	0.05	0.0264	(-0.21, -0.01)

$R^2 = 0.09$, $F(3, 82) = 2.76$, $p = 0.0471$

Fig. 4.23. Proportion of low-severity fires at a site, 1475 - 1996.


a. Observed

b. Predicted

Residuals show no clear pattern (Fig. 4.24b). The influence of slope steepness was far more evident than the effect of north slopes on increasing SCAR.ratio (Fig. 4.25). Most of the areas of low slope steepness are distributed patchily at higher elevations. Residuals from the SCAR.ratio regression model showed two sites at the headwaters of Deer Creek where the model greatly underestimated SCAR.ratio (Fig. 4.24a). These were *Abies*-dominated sites where a small number of Douglas-fir trees had survived multiple fires, perhaps due to favorable microtopography, or to a great disparity between the heights of the Douglas-fir crowns and the crowns of younger, *Abies* trees. These two sites were considered outliers and excluded from the regression analysis; residual values from these sites were calculated *post-hoc*.

4.4.4. Fire Regimes of the Study Area

The combined fire frequency variable (i.e., FREQ.comb) was greater, meaning fire frequency was less, for sites at higher elevations, more north-facing slopes, and lower slope positions (Table 4.10). Extrapolation of this variable to the study area topography generated a map of predicted fire frequency that may best be understood considering two spatial scales (Fig. 4.26). Slope position and slope aspect influences are important over within-basin scales, but are nested within a stong elevational influence on fire frequency over larger scales. At lower elevations, predicted fire frequency varies between high and moderate, depending upon slope position and aspect; at higher elevations, predicted fire frequency varies between moderate and low.

Average values for predicted WMPI, MFI.nlow, and maxFI.nlow are given in Table 4.11 for each of the three fire frequency classes (Fig. 4.26). A more reliable

Figure 4.24. Residuals for the fire scar ratio and proportion of low-severity fires regression models. Positive residual values (circles) indicate that the regression model overestimates the value for a given site.

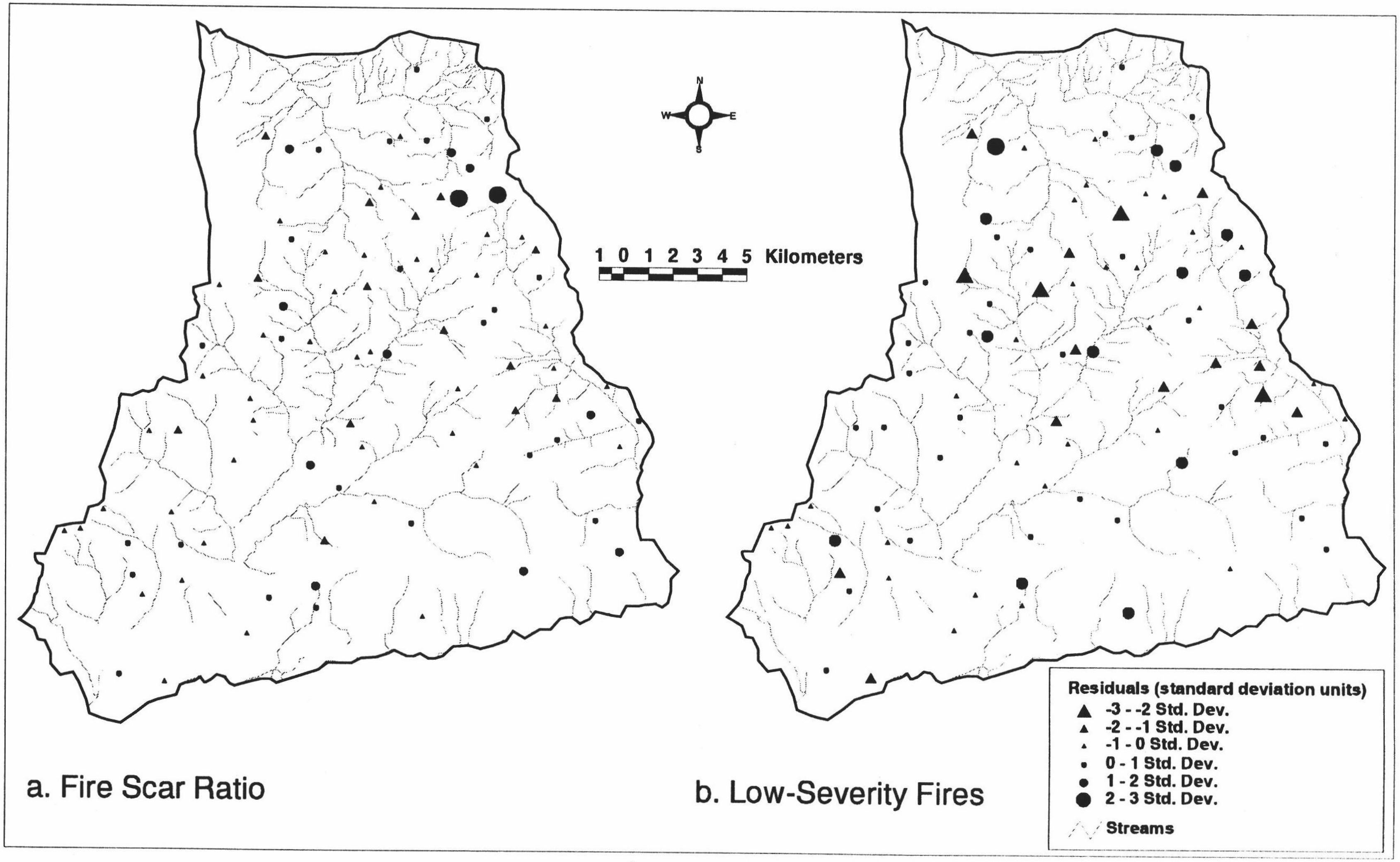
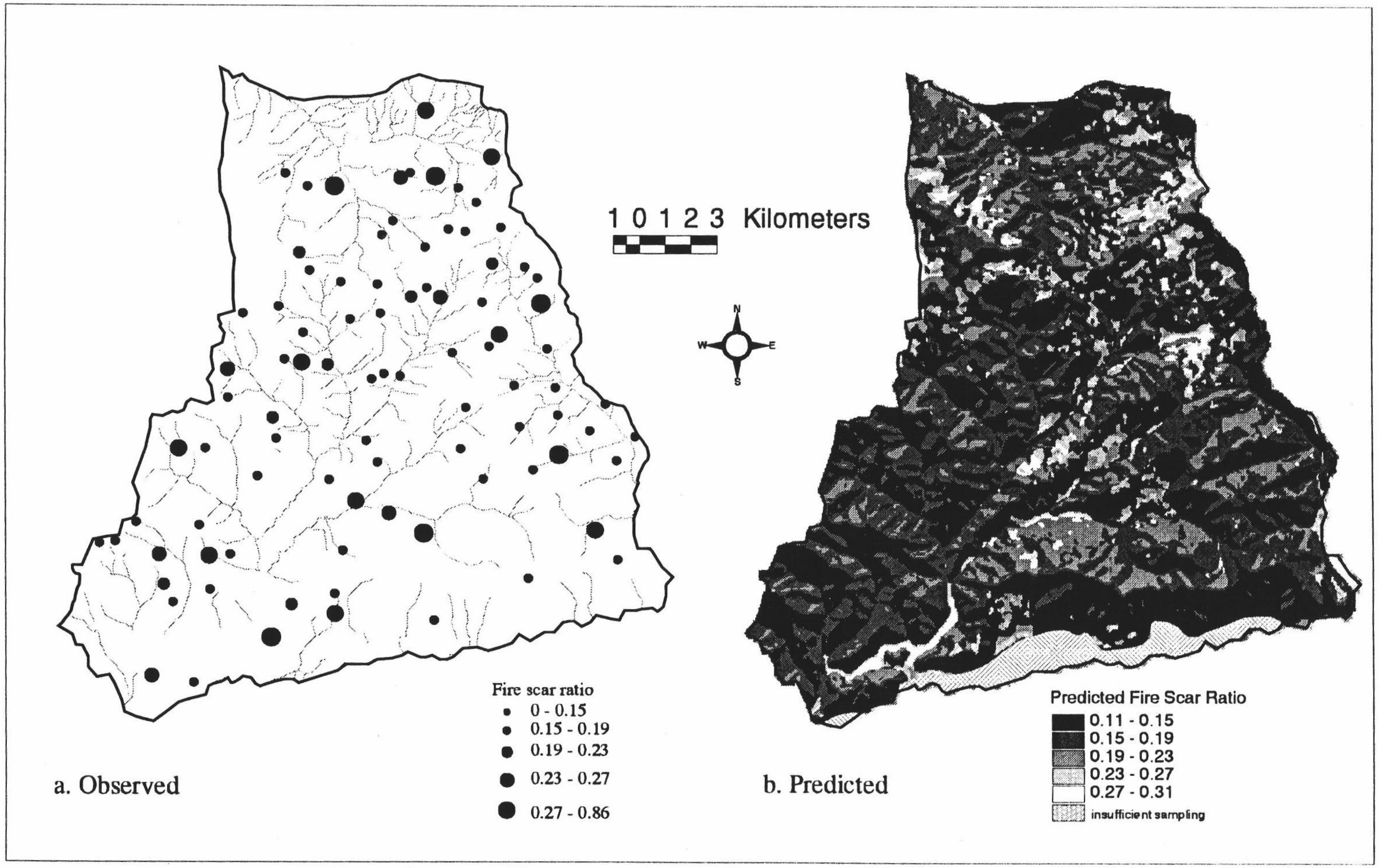


Fig. 4.25. Ratio of Douglas-fir fire scars to the number of Douglas-fir trees sampled at a site, 1475 - 1996.



a. Observed

b. Predicted

Table 4.10. Regression model of the average of standardized Weibull median probability interval, standardized mean fire interval between moderate and high severity fires, and standardized maximum fire interval between moderate and high severity fires, as a function of environmental variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect. Slope position is treated as an indicator variable with respect to "lower slope position" as a reference condition.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-0.99	0.44	0.0297	(-1.85, -0.13)
Elevation	0.0015	0.0004	0.0005	(0.0007, 0.0023)
Northness	0.30	0.12	0.0138	(0.06, 0.54)
Midslope	-0.85	0.23	0.0005	(-1.30, -0.40)
Upper Slope	-0.71	0.23	0.0034	(-1.16, -0.26)

$R^2 = 0.31$, $F(4, 73) = 8.14$, $p = 0.0000$

Figure 4.26. Fire frequency characterization for the Blue River study area. These classes are derived from a linear combination of Weibull median probability interval, the mean fire interval between moderate and high severity fires, and the maximum fire interval between moderate and high severity fires.

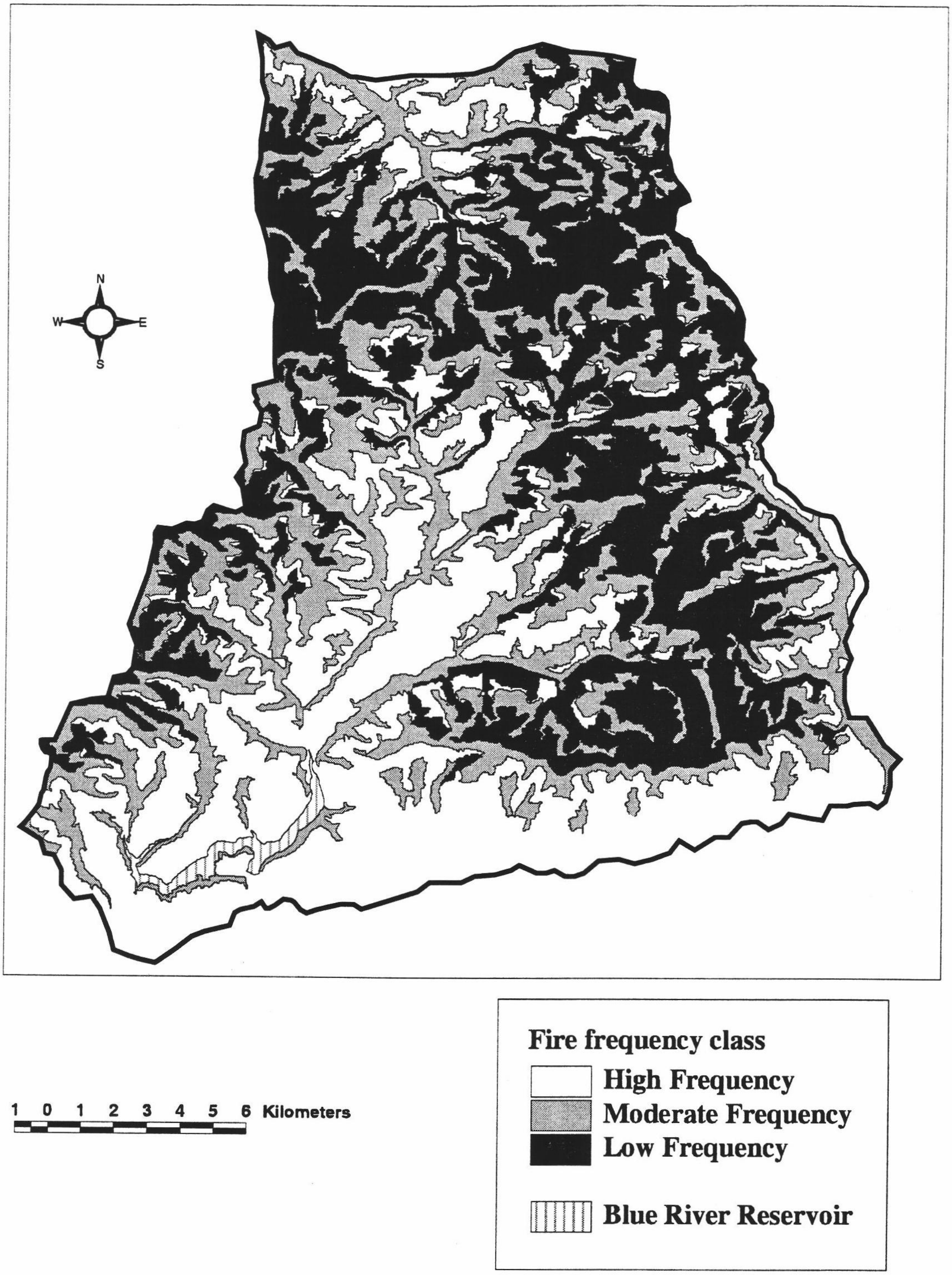


Table 4.11. Predicted fire frequency for the three fire frequency classes, according to the three variables used in the linear combination for distinguishing these classes. The fire frequency variables are summarized over the range of predicted values for 30 m pixels across the study area. WMPI = Weibull median probability interval; MFI.nlow = the mean interval between fires of moderate, high, and unknown severity; and MaxFI.nlow = the maximum interval between fires of moderate, high, and unknown severity. Shown for each variable are the mean (first row), the standard deviation (second row, in italics), and the range (third row, in square brackets).

Frequency Class	Number of pixels *(ha)*	WMPI (yrs.)	MFI.nlow (yrs.)	MaxFI.nlow (yrs.)
High	181110 *(16300)*	56 *12* [26, 104]	129 *26* [67, 263]	243 *51* [81, 408]
Moderate	161809 *(14563)*	72 *9* [43, 111]	176 *17* [94, 309]	286 *28* [187, 408]
Low	155723 *(14015)*	86 *12* [53, 123]	247 *37* [118, 409]	334 *27* [209, 445]

depiction of what mapped fire frequency classes mean for describing spatial variation in fire regime comes from considering how several fire frequency and severity measures differ among the three classes with regard to their observed values at sampled sites (Table 4.12). The high frequency class does have a higher fire frequency than the low frequency class over each of the four frequency variables shown, although confidence intervals for MFI overlap (Table 4.12). The moderate frequency class closely resembles the low frequency class for WMPI, is intermediate for MFI, and more closely resembles the high frequency class for MFI.nlow and maxFI.nlow. All three classes have similar values of SCAR.ratio. Despite high variability, sites in the low frequency class had a lower proportion of low severity fires than the high frequency class. The low frequency class also had the lowest frequency of low severity fires, although confidence intervals overlap between the three classes, as they do for the proportion of high severity fires (Table 4.12). Using the assumption that the oldest fire at a site was of high severity increased PROPHIGH by a greater amount for sites in lower frequency classes, although this difference was not statistically significant ($F_{(2, 86)} = 1.388$; $p = 0.2551$), and PROPHIGH values remained similar between the three classes (Table 4.13). The number of shade-intolerant (i.e., Douglas-fir, noble fir, incense-cedar) age cohorts established per century was greatest for the high frequency class, and least for the low frequency class (Table 4.12). An elevational or forest series gradient in age cohort number is apparent when mapped, such that higher elevations have fewer age cohorts (Fig. 4.27). Over 80% of sites within the low frequency class, but fewer than 60% of sites within the high frequency class, have only one or two age cohorts (Fig. 4.28).

Table 4.12. Observed values for selected fire history variables for different fire frequency classes. For each variable, the first row (bold type) shows the mean; the second row (parentheses) shows first the standard deviation, then the number of sites sampled; and the third row (italics) shows the 95 % confidence interval for the mean. Douglas-fir scar density is the ratio of the number of Douglas-fir fire scars sampled to the number of Douglas-fir trees sampled. Low severity fires (including underburns) are reported as both the proportion of all fires at a site, and the frequency per century of stand age.

Frequency Class	Douglas-fir Scar Density	Low Severity (prop.)	Low Severity (freq.)	High Severity (prop.)	WMPI (all fires)	MFI (all fires)	MFI (not low severity)	MaxFI (not low severity)	Age Cohorts per Century
High	**0.17**	**0.30**	**0.44**	**0.21**	**61**	**81**	**119**	**212**	**0.65**
	(0.13, 27)	(0.21, 27)	(0.32, 27)	(0.28, 27)	(22, 21)	(34, 23)	(46, 21)	(63, 21)	(0.17, 27)
	0.12, 0.22	*0.22, 0.38*	*0.32, 0.56*	*0.11, 0.31*	*52, 70*	*66, 95*	*99, 139*	*185, 239*	*0.59, 0.71*
Moderate	**0.22**	**0.44**	**0.62**	**0.09**	**68**	**97**	**209**	**307**	**0.59**
	(0.20, 31)	(0.05, 31)	(0.50, 31)	(0.21, 31)	(28, 27)	(67, 29)	(121, 27)	(85, 27)	(0.22, 31)
	0.15, 0.29	*0.35, 0.53*	*0.44, 0.80*	*0.02, 0.16*	*57, 79*	*73, 121*	*163, 255*	*275, 339*	*0.51, 0.67*
Low	**0.18**	**0.49**	**0.56**	**0.16**	**89**	**110**	**244**	**333**	**0.45**
	(0.19, 32)	(0.23, 32)	(0.36, 32)	(0.27, 32)	(30, 26)	(58, 28)	(109, 28)	(94, 28)	(0.19, 32)
	0.12, 0.24	*0.41, 0.57*	*0.44, 0.68*	*0.07, 0.25*	*78, 100*	*88, 132*	*204, 284*	*298, 368*	*0.39, 0.51*

Table 4.13. Sensitivity analysis for the proportion of high severity fires at a site (PROPHIGH) variable. Two criteria are used for calculating this variable. Criterion 1 follows the fire severity key (Table 5.2) in considering the earliest fire recorded at a site as an age cohort to be of unknown severity. Criterion 2 deviates from the key and considers the earliest fire to always be of high severity. The difference variable summarizes the differences between the results of applying the two criteria for each site. For each cell, the first row (bold type) shows the mean; the second row (parentheses) shows first the standard deviation, then the number of sites sampled; and the third row (italics) shows the 95% confidence interval for the mean.

Frequency Class	Criterion 1	Criterion 2	Difference
High	**0.21** (0.28, 27) *0.11, 0.31*	**0.35** (0.25, 27) *0.25, 0.44*	**0.14** (0.11, 27) *0.10, 0.18*
Moderate	**0.09** (0.21, 31) *0.02, 0.16*	**0.28** (0.22, 31) *0.20, 0.36*	**0.19** (0.18, 31) *0.13, 0.25*
Low	**0.16** (0.27, 32) *0.07, 0.25*	**0.37** (0.24, 32) *0.28, 0.45*	**0.21** (0.13, 32) *0.16, 0.25*

Fig. 4.27. Number of shade-intolerant age cohorts and number of cohorts per century of stand age

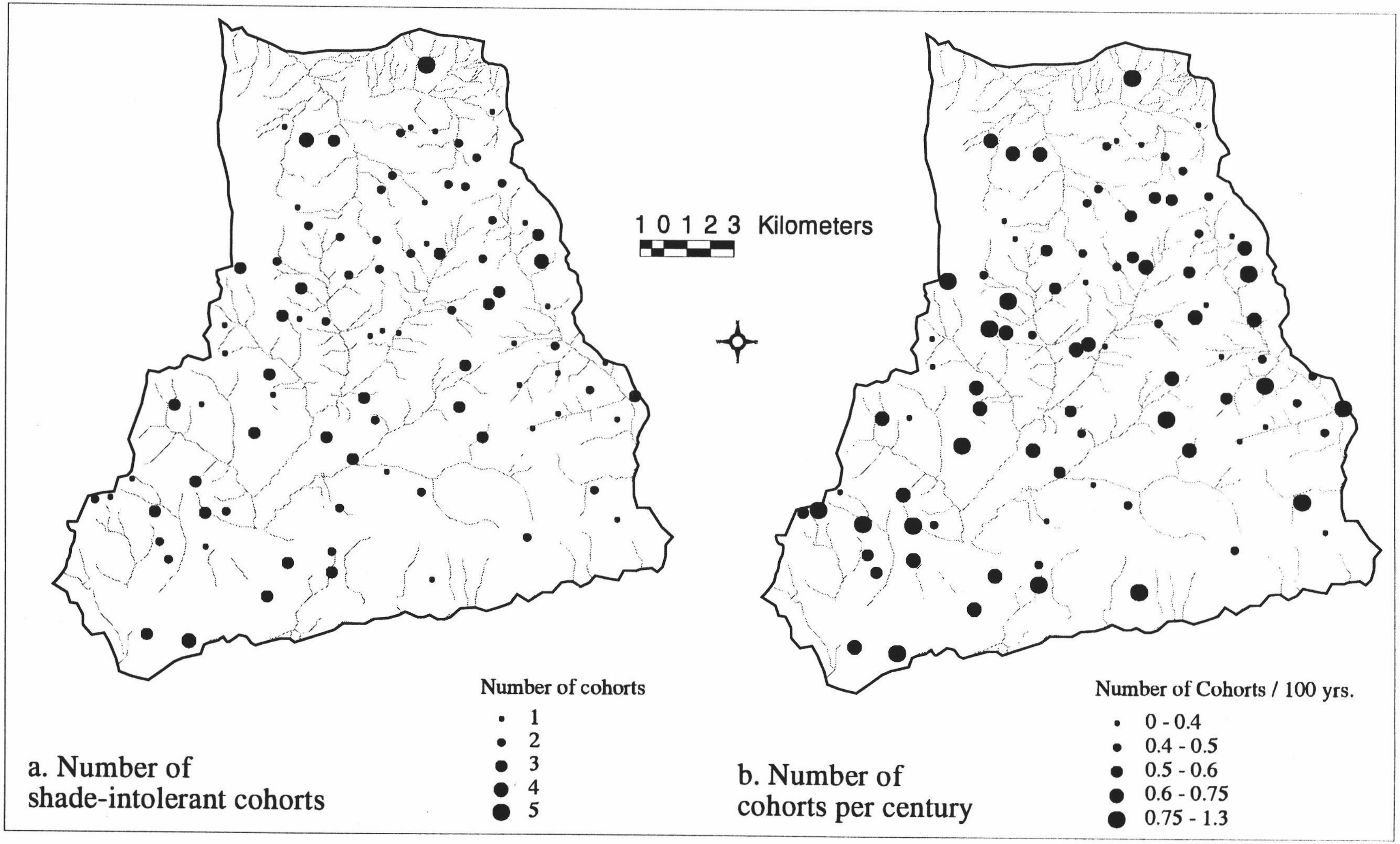
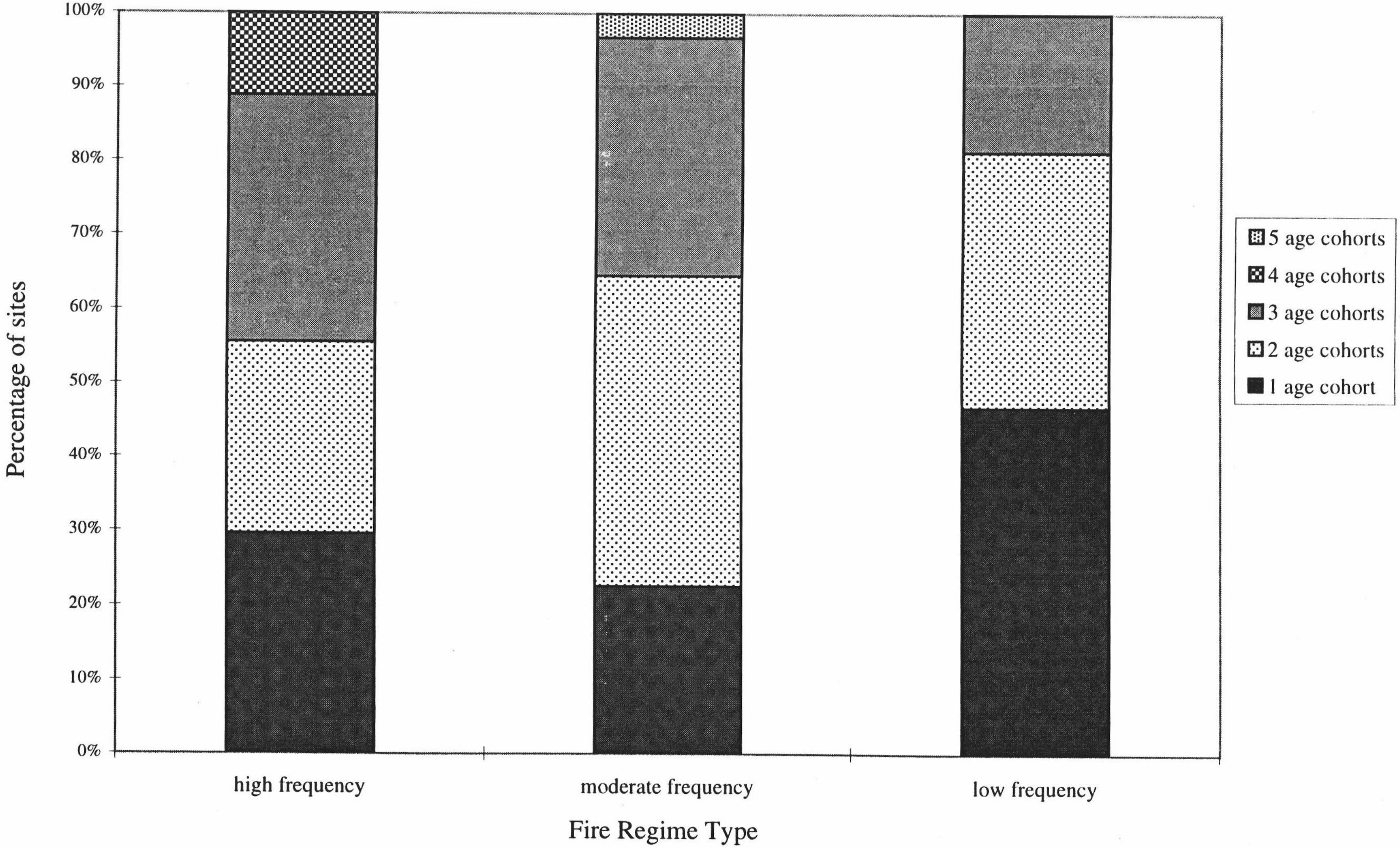


Fig. 4.28. Distribution of sites with different numbers of age cohorts over three fire regime classes



Spatial heterogeneity of fire regimes is often delineated using boundaries between forest vegetation types. I compared observed values for several frequency and severity measures between the western hemlock and Pacific silver fir series (Table 4.14). Confidence intervals overlap for every measure. Using forest series boundaries to characterize fire regime was not as effective as using topographically predicted fire frequency for this study area. However, this study may not have provided a good test of fire regime delineation using vegetation types because areas of western hemlock and Pacific silver fir forests were closely juxtaposed, and fires originating in one forest series may easily have spread to another.

4.5. Discussion

4.5.1. Fire Patterns over Time

Changing fire patterns over time may be related to: (a) climate variability, (b) changing anthropogenic influences, or (c) cyclic patterns of fuel accumulation related to stand development (Agee and Huff 1987). The degree of regional synchronicity in temporal fire regime changes may provide useful clues to understanding the relative importance of these factors. If climate variability is a major influence, temporal changes in fire regime should be synchronous over regional scales. Anthropogenic influences of Euro-American settlement should be roughly synchronous, but differ slightly according to different timing and rates of settlement, travel and land use. If changing fire patterns over time result solely from endogenous stand development processes, changes should occur at different times for different parts of the region. Interactions among these three factors

Table 4.14. Observed values for selected fire history variables for the western hemlock and Pacific silver fir series. For each variable, the first row (bold type) shows the mean; the second row (parentheses) shows first the standard deviation, then the number of sites sampled; and the third row (italics) shows the 95 % confidence interval for the mean. Douglas-fir scar density is the ratio of the number of Douglas-fir fire scars sampled to the number of Douglas-fir trees sampled. Low severity fires (including underburns) are reported as both the proportion of all fires at a site, and the frequency per century of stand age.

Forest Series	Douglas-fir Scar Density	Low Severity (prop.)	Low Severity (freq.)	High Severity (prop.)	WMPI (all fires)	MFI (all fires)	MFI (not low severity)	MaxFI (not low severity)	Age Cohorts per Century
western hemlock	**0.18**	**0.40**	**0.54**	**0.17**	**70**	**89**	**181**	**278**	**0.59**
	(0.15, 55)	(0.24, 55)	(0.36, 55)	(0.28, 55)	(30, 46)	(49, 48)	(103, 46)	(94, 46)	(0.21, 55)
	0.14, 0.22	*0.34, 0.46*	*0.45, 0.63*	*0.10, 0.24*	*61, 78*	*76, 103*	*152, 211*	*251, 305*	*0.54, 0.64*
Pacific silver fir	**0.19**	**0.47**	**0.59**	**0.12**	**81**	**108**	**232**	**319**	**0.48**
	(0.20, 32)	(0.24, 32)	(0.48, 32)	(0.21, 32)	(28, 26)	(69, 29)	(123, 27)	(99, 27)	(0.19, 32)
	0.12, 0.26	*0.39, 0.54*	*0.41, 0.76*	*0.04, 0.19*	*70, 92*	*82, 133*	*186, 278*	*281, 356*	*0.41, 0.55*

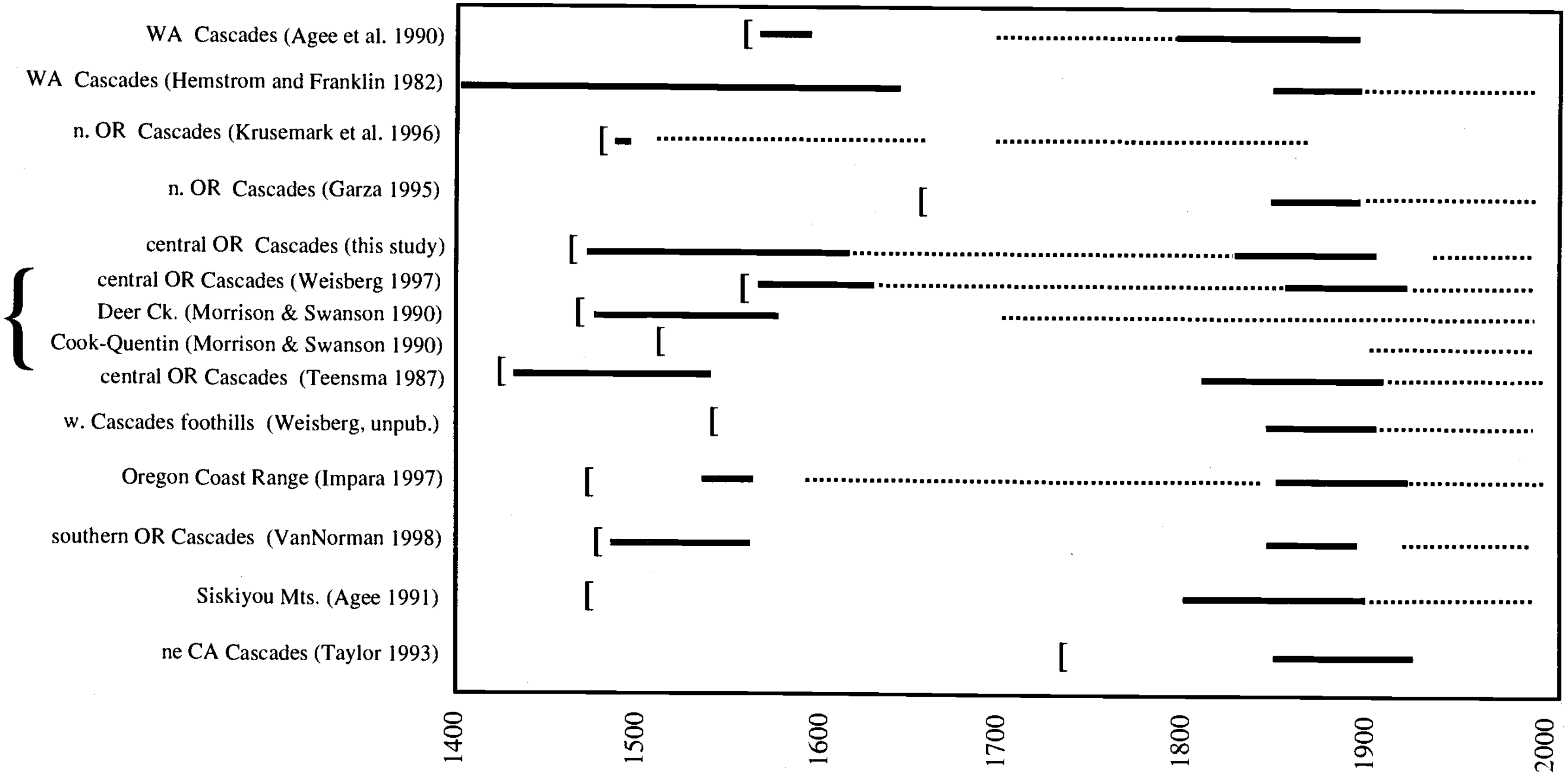
confound interpretation of the importance of any one factor. For example, a major drought might render a whole region prone to high-severity fire, causing the timing of stand development to coincide over a large area. Subsequent droughts might not lead to widespread fires due to lags in fuel accumulation, as stands develop following the earlier fire.

For the Blue River study area, the period from ca. 1475 to ca. 1620 was characterized by widespread, high-severity fire; the period from ca. 1620 to ca. 1830 by reduced fire frequency, burned area, and fire severity; the period from ca. 1830 to ca. 1910 by high fire frequency, burned area, fire severity, and reburn occurrence; the period from ca. 1910 to ca. 1940 by reduced fire extent and severity; and the period from ca. 1940 to the present by extremely low fire frequency, burned area, and fire severity. Low-severity fires that occurred during the earlier period may no longer be detectable, while intense prescribed fires associated with logging activities during the most recent period were not considered in this study.

Patterns of temporal variation in fire regime are stikingly similar among 13 tree-ring-based fire history studies from west of the Cascade Crest in Oregon and Washington (Fig. 4.29). The earlier period of widespread, high-severity fire (ca. 1475 to ca. 1620) roughly overlaps similar periods found for other areas throughout the western Cascades and Oregon Coast Range (Fig. 4.29). Most old growth forests in the western Cascades date from this general period (i.e., 1400s - early 1600s), making it difficult to use tree-ring-based methods to reconstruct forest history for earlier periods.

The period of reduced fire frequency, extent, and severity from ca. 1620 to ca. 1830 is also evident from other fire history studies in the western Cascades (Fig. 4.29).

Fig. 4.29. Comparison of periods of widespread fire with periods of limited fire, adapted from selected fire history studies west of the Cascades crest, listed from north to south. Periods of widespread or frequent fire are shown with a thick line, while periods of more limited fire are shown with a dashed line. Square brackets mark the beginning of reliable fire history records, while the curly bracket indicates five studies within the same general area.



Although the ending of the widespread fire period occurred at different times among different parts of the region, there was a complete absence of widespread fire from ca. 1640 to ca. 1800 among all studies summarized (Fig. 4.29). Also, there was remarkable synchronicity among sites in recording periods of widespread fire from ca. 1800 - 1850 to ca. 1900 - 1920. All study areas recorded limited fire occurrence since ca. 1900- 1920.

Cooler climate associated with the Little Ice Age (ca. 1690 - 1840) has been linked with reduced fire frequency and burned area in northwestern Minnesota (Clark 1990), the southern Canadian Rockies (Johnson and Larsen 1991), and in the western Cascades (Agee et al., 1990). Tree-ring chronologies from timberline trees in the Washington Cascades show: (1) a period of warm summers and low snow accumulation from 1650 to 1690; (2) a period of very cool temperatures from 1690 to 1760; (3) a transition period toward warmer temperatures from 1760 to 1840; (4) a period of warm summers, but cool, snowy winters from 1840 to 1900; and (5) a period of warm summers and low snow accumulation from 1920 to the present (Graumlich and Brubaker 1986). If wetter, cooler periods are associated with reduced fire frequency and extent, one would expect forests west of the Cascades to have experienced limited fire from ca. 1690 to ca. 1800. This closely approximates the period of limited fire observed in regional studies (Fig. 4.29), although these studies also show limited fire from 1650 to 1690, described by Graumlich and Brubaker (1986) as a warm period. Extensive, widespread fires during the 1500s and early 1600s would have resulted in young-mature stands with low fuel loadings (Agee and Huff 1987), limiting the possibility of an ignition becoming a widespread fire during the 1650 to 1690 period. It is interesting that this study found a transition toward high-severity fire, while the extent of burned area remained relatively low, from ca. 1750 to ca. 1789, during the climatic transition out of the Little Ice Age.

The most recent period of regional, widespread fire (Fig. 4.29) is associated with a warmer, drier climate beginning ca. 1840 (Graumlich and Brubaker 1986). However, dramatic changes in human influences on forest patterns and fire regimes were also underway. Were native burning an important influence on fire regime, one would expect fire frequency and burned area to have been reduced following the series of deadly epidemics from 1782 (smallpox) to 1833 (malaria), and the 1855 relocation of nearly all Kalapuya to the Grand Ronde reservation (Mackey 1974). Since the McKenzie and South Santiam river valleys were not utilized by Euro-Americans substantially until the mid-1850s (Burke 1979), the early 1800s should have experienced relatively few fires, if humans were an important ignition source. In the Blue River study area, the onset of the widespread fire period in the 1800s followed the decimation of native populations, but preceded significant Euro-American settlement. Similar results for Desolation Peak in the Washington Cascades (Agee et al. 1990), for the Siskiyou Mts. (Agee 1991), and for the Cook-Quentin and Deer Ck. studies within the Blue River study area (Morrison and Swanson 1990), suggest that climatic factors may have been more important than changing human influences in leading to a period of widespread fire in the mid-1800s. Also, I found little difference in the spatial distribution of fire frequency between pre-settlement (1588 - 1849) and post-settlement (1850 - 1996) periods (Fig. 4.7). Increased fire frequency in the mid-to-late 1800s may not have been solely caused by increased anthropogenic activities.

It is likely that both human and climatic change were causal factors for the shift to a period of widespread fire following ca. 1830. The relative importance of anthropogenic influences should be greater for study areas closer to the Willamette Valley, where both native people and Euro-American settlers were concentrated. Perhaps for this reason, the period of widespread fire in the middle 1800s was more pronounced in the Bear-Marten watershed (Weisberg 1997) and the Coburg Hills (Weisberg, unpublished m.s.) than in the Blue River study area.

Limited fire occurrence since ca. 1910 - 1920 coincides with warm, dry conditions (Graumlich and Brubaker 1986) and the onset of fire suppression activities. Clearly, the dramatic trend toward smaller, lower-severity fires during this recent period is due to anthropogenic influences. For the Blue River study area, fire frequency did not undergo a dramatic reduction until ca. 1940, suggesting relatively ineffective fire suppression for the 1910 to 1940 period, prior to development of an extensive road system and modern fire-fighting technology. Patterns of 20th century fire have been associated with proximity to the McKenzie Valley and South Santiam Valley travel corridors, with mining activities in the Gold Hill area, and with sheepherding activities in higher elevation areas and ridgetops (Fig. 4.8).

It is difficult to separate anthropogenic and climatic influences on the observed temporal patterns of fire regime, since they have varied at nearly the same times. Both clearly played a role. However, the presence of widespread fire during the decades following native American extirpation, and prior to significant Euro-American activities suggests that climatic influences may have been more important in the Blue River study area. Similarities in temporal trends in fire frequency and extent among different fire history studies in the region also suggest a strong climatic influence (Fig. 4.29). Endogenous patterns of fuel accumulation associated with post-fire stand development may help explain why the relatively warm period from 1650 to 1690 experienced limited fire over the region. Observed rates of post-fire fuel succession suggest that surface fire intensity is lowest for stands 110 to 181 years old (Agee and Huff 1987).

4.5.2. Environmental and Topographic Influences on Fire Regime Patterns

Fire frequency and severity patterns are associated with spatial variation in hillslope position, slope aspect, slope steepness, and elevation. Fire frequency was predicted more accurately by topographic variables than fire severity, reflecting in part the greater error associated with using tree-ring methods to reconstruct past fire severity. Coefficients of determination did not exceed 0.36 for any of the fire frequency regression models, suggesting that topographic influences on fire are highly variable (Tables 4.6, 4.7). Topographic and landform influences on spread patterns of individual fires may be less important for fires of higher intensity and severity, where the influence of weather may outweigh that of fuels (Swanson 1981, Turner and Romme 1994, Bessie and Johnson 1995).

Generalized fire frequency was lower for higher elevations, lower slope positions, and more mesic slope aspects (Table 4.10). These relationships are not surprising, given the climatic factors represented by these three topographic variables. Higher elevations in the study area are cooler, wetter in the summer, and have a deeper and longer duration snowpack in the winter. Decreased fire frequency with increasing elevation, or with forest community types associated with higher elevations, has also been observed in

Crater Lake National Park (McNeil and Zobel 1980), at Desolation Peak in the Washington Cascades (Agee et al. 1990), in the Little River watershed in the southern Oregon Cascades (VanNorman 1998), in the northern Oregon Cascades (Garza 1995), and for two small study areas within the Blue River study area (Morrison and Swanson 1990). The reverse trend of greater fire frequency at higher elevations has been observed previously for a study area including the Lookout Creek watershed, within the Blue River study area (Teensma 1987), and for the Bull Run watershed in the northern Oregon Cascades (Krusemark et al. 1996). Krusemark and others (1996) conjecture that the higher-elevation, Pacific silver fir forests of the Bull Run may have burned more because they occupy ridgetops bordering the watershed, and so were more vulnerable to fires spreading from surrounding drier, lower-elevation areas. The same hypothesis might explain the observed relationship between elevation and fire frequency for the Lookout Creek watershed. An alternative, or complementary, explanation might be that elevation is highly correlated with hillslope position for both studies, and ridgetops are more prone to frequent fire than valley bottoms.

Lower hillslope positions were expected to have experienced reduced fire frequency for multiple reasons having to do with fire behavior and microclimate. One reason involves a basic principle of fire science: fire burns uphill more rapidly, and with greater intensity, than downhill. Therefore, uphill locations are more likely to burn than downhill locations, assuming random distribution of ignition sources. Another mechanism associated with fire spread is the tendency for riparian areas to serve as fire-breaks. Riparian areas in the study area contain a relatively large component of hardwood species with lower foliage flammability than coniferous species. Also, periods of cold air drainage cause lower slope positions to remain cooler and moister for longer periods during the fire season. In the study area, cold air drainage patterns in summer and early fall are pronounced in lower slope positions along Lookout Creek (Rosentrater 1997). Finally, topographic shadowing helps keep lower slope positions cool and moist during the summer.

Numerous studies worldwide document the tendency for riparian forests, or other low-lying wet areas, to burn less frequently or with lower severity than upland forests (Quirk and Sykes 1971, Zackrisson 1977, Agee and Huff 1980, Romme and Knight 1981, Foster 1983, Engelmark 1987), although fire history studies quantifying the effects of different hillslope positions along a continuous gradient are few. Fewer fires at lower slope positions have been reconstructed for the Oregon Coast Range (Impara 1997), and for the southern Oregon Cascades (VanNorman 1998). This study found reduced fire frequency at lower slope positions both at the scale of different plots 200 m apart within a site, and for separate sites at least a kilometer apart.

More mesic slope aspects should have moister fuels, resulting in lower fire frequency, as observed for the Blue River study area. Reduced fire frequency for more mesic aspects, or for forest community types associated with more mesic aspects, has also been reported for study areas in the northern Washington Cascades (Agee et al. 1990), in the low-elevation central western Cascades along the McKenzie River (Weisberg 1997), and for the southern Oregon Cascades (VanNorman 1998). No relationship between fire frequency and aspect was found for study areas in the Oregon Coast Range (Impara 1997) and the northern Oregon Cascades (Garza 1995).

Few landscape fire history studies in the region have attempted to describe topographic influences on reconstructed fire severity. Steeper slopes are expected to have greater fire severity due to more intense burning from preheating of upslope fuels, convective winds, and greater exposure to solar radiation for drier aspects (Swanson 1981). Fire severity was greater for higher elevations in the northern Oregon Cascades (Garza 1995); greater for wetter slope aspects, steeper slopes, and lower elevations (associated with lower slope positions) in the low-elevation central Oregon Cascades (Weisberg 1997); and less for lower slope positions in the Oregon Coast Range (Impara 1997). In the Blue River study area, I found the proportion of low-severity fires to have been greater at higher elevations and lower slope positions. This result agrees with those of Impara (1997) and Weisberg (1997). Also, I found the number of fire scars relative to the number of Douglas-fir trees sampled to be greater, suggesting fire severity was less on more north-facing and more gradual slopes, a result that is in only partial agreement with Weisberg (1997), where fire severity was observed to be greater on more north-facing slopes. Both regression models show that topography explains only a small amount of the variance in reconstructed fire severity (Tables 4.8, 4.9).

Given that most descriptions of fire regime imply an inverse relationship between fire frequency and severity (Agee 1993), it is surprising that I found a positive association (Table 4.12). This result differs from that of previous fire regime characterization efforts in nearby areas (e.g, Weisberg 1997, Cissel et al., in review), and may be explained by both methodological and ecological considerations. The methodological considerations suggest that the observed relationship is an artifact of inappropriate fire severity interpretation methods, while the ecological considerations suggest that, despite possibly inappropriate methods, the observed relationship is true.

Both severity variables may be imprecise or misleading descriptors of actual fire severity. Since a given fire intensity will have different fire severity effects on different tree species (Agee 1993), both variables are calibrated with respect to fire effects on Douglas-fir. However, much of the study area lies within the Pacific silver fir forest series, where Douglas-fir is present but sometimes not the dominant species. Regeneration following moderate-or-high-severity fire in the Pacific silver fir series might consist solely of western hemlock, or even of silver fir. If a few old Douglas-fir trees survived to be scarred by several such fires, and if regeneration of shade-intolerant species (i.e., Douglas-fir, noble fir) following the most recent fire was minimal, I would have erroneously reconstructed multiple low-severity fires for the site. Also, the SCAR.ratio would be high since many scars would be present on few Douglas-fir trees, erroneously suggesting frequent, low-severity fire. My methods for estimating fire severity may be more appropriate for the lower and middle elevation parts of the study area, in the western hemlock forest series.

There are also ecological explanations for the positive association between fire frequency and severity in the Blue River study area. Mesic slopes and valley bottoms are closely juxtaposed with drier environments in landscapes of complex topography. It makes sense that the two environments should burn with similar frequency, since both would typically burn in the same widespread fire. However, the more mesic environment would be more conducive to lower severity fire since fuels would be moister. Also, high-elevation forests in the study area, dominated by true firs, are often directly upslope from western hemlock forests that tend to burn more frequently (Agee 1993). Fires starting in western hemlock forests would burn upslope to the silver fir forest where, except under conditions of extreme drought, they might be expected to burn with reduced intensity and eventually go out. Since fires are often of lower severity near their edges (Krusemark et al. 1996), the higher elevations of the study area may, in fact, experience a greater proportion of low-severity fires.

It may seem counter-intuitive that fire regime pattern should vary over such a fine grain as is created by the overlay of slope aspect, steepness, and hillslope position, when most fires recorded in fire history studies burn large areas encompassing many slope facets. However, variation in fire frequency or severity over such fine scales does not imply that individual fires burn at this spatial resolution. Where a site with a cooler, moister microclimate is adjacent to a site with a hotter, drier microclimate, as may occur on opposite sides of a stream or ridgetop, both sites are likely to be burned by a given fire. The moist site may burn with lower severity due to greater fuel moisture. If the fire goes out completely in the moist site, that site represents a "skip" and will have a lower fire frequency than the dry site. If the fire burns the moist site only as a low-intensity, surface fire that does little more than scar a few trees, it may be undetected by future fire history studies, and the moist site will again have a lower fire frequency. The probability of a future fire history study detecting occurrence of that fire at the moist site is closely associated with the level of sampling intensity employed. If the fire burns the moist site with lower severity than the dry site, but scars and kills enough trees so as to be detectable, the fire frequency of the two sites will be comparable, but the moist site will be reconstructed as having burned with lower severity. There is a multivariate gradient of fire severity and fire history detection capability where, over a narrow domain, fire regime may be described at the moist site as being either of low frequency and high severity (i.e., few of the low-severity fires are detected, or most are "skips"), or of comparable frequency and low severity (all fires are detected). At this fine scale of topographic resolution, reconstructed fire frequency and severity may not be clearly separable.

Certain environmental influences on fire regime may not be well represented by the proxy topographic variables. These include proximity to human land use (native and Euro-American), exposure to adiabatic east wind events, patterns of cold air drainage, valley and watershed orientation, and the degree of juxtaposition of mesic and dry environments on the landscape. Proximity to human land use has been greatest in the vicinity of the S. Santiam and McKenzie river valleys, both before and after Euro-American settlement (Burke 1979). East wind exposure is especially high for the lower Deer Creek watershed, the long northwest-facing slope over Blue River, and the two major river valleys. Cold air drainage is strongly associated with elevation in the Lookout Creek watershed, but likely varies also with slope aspect, hillslope position, and basin orientation (Rosentrater 1997). Masters (1990) suggested that valley orientation to prevailing wind direction may be more important for explaining spatial variation in fire frequency than topographic variables such as elevation and aspect. Watershed orientation was hypothesized to play a role in observed fire regime differences for a low-elevation study area in the central western Cascades (Weisberg 1997). In the Blue River study area, both major river valleys, which have burned frequently, are oriented parallel both to prevailing west winds and dessicating east winds. The Blue River drainage, which has burned frequently except at its higher elevations, is also exposed to both wind directions.

The Lookout Creek watershed, parts of which have burned infrequently, is oriented to the west, and so relatively protected from east winds. The Tidbits Creek watershed, parts of which have burned infrequently, is oriented to the southeast but protected from east winds by a long north-south trending ridge. The juxtaposition of mesic and dry fire environments is greatest in the topographically dissected southwestern part of the Blue River watershed.

4.5.3. The Spatial Context of Fire Regime

The fire regime of the Blue River study area may be summarized, as indicated by Teensma (1987) and Morrison and Swanson (1990), as a "variable regime: frequent, low-intensity surface fires and long return interval, stand-replacement fires (100- to 300-year intervals)" (Kilgore 1981). Many sites in the lower-elevation, drier areas would be better described as having, "Short return interval, crown fires (25- to- 100-year return intervals)" (Heinselman 1973), although surface fires of varying severity were also important for these sites. Such characterizations are perhaps too broad to be useful, except for comparing fire regimes of rather different forest types. Many forests of the westside Oregon Cascades and Oregon Coast Range have fire regimes that would be characterized similarly (Means 1982, Agee et al. 1990, Garza 1995, Impara 1997, Weisberg 1997, VanNorman 1998). Limited fire history information for the foothills of the Willamette Valley suggests that fire regimes for this drier environment consist of partial stand-replacing fires occurring at approximate mean intervals of 60 years (Cascades foothills) to 90 years (Coast Range foothills) (Weisberg, unpublished manuscript, Impara 1997). Forests in extremely wet environments of the Washington

Cascades have experienced very infrequent, mostly stand-replacing fires, with NFR's in excess of 300 years (Hemstrom and Franklin 1982, Krusemark et al. 1996).

Using topographic variables that represent patterns of climate and fire behavior to predict fire frequency, I defined three fire regime classes for the study area (Fig. 4.26). The high and low frequency classes represent areas with quite different fire regimes. The moderate frequency class is similar to the low frequency class with respect to some fire regime descriptors (e.g., WMPI, rate of Douglas-fir age cohort establishment), similar to the high frequency class with respect to others (e.g., PROPLOW, the frequency of low-severity fires, MFI.nlow, maxFI.nlow), and in some cases intermediate between the two extremes (e.g., MFI) (Table 4.12). Thus, I have mapped and defined two fire regime classes that qualitatively differ, and one that is intermediate. These seemingly discrete classes are delineated from a continuous, multidimensional fire regime gradient.

Other fire history studies have used forest series or plant community type as mapping units for fire regime (Engelmark 1987, Agee et al. 1990, Simon 1991). For the Blue River study area, the distinction between the Pacific silver fir and western hemlock forest series did not explain the spatial variability of fire regime descriptors very well (Table 4.14). This is because wet sites in the Western Hemlock zone generally burned less frequently, and often with lower severity, than drier sites in the Pacific Silver Fir zone. It is possible that fire regime variability might be more closely associated with vegetation at a finer scale (e.g., plant communities or plant association groups). Also, much of the Pacific silver fir zone in the Blue River study area occupies ridgetops above the western hemlock zone, and so is susceptible to fires spreading uphill from the drier, warmer vegetation below. Forest series might be more useful for distinguishing fire regimes where they are spatially discrete, so that juxtaposition of different vegetation types and fire environments is not important.

Spatial variation in fire regime occurs over multiple nested scales. At the within-site scale, plots 200 m upslope from other plots, and sites on upper hillslope positions, have experienced more frequent, higher severity fires. At the between-site scale, sites on different slope aspects and slope steepnesses have experienced different fire regimes. At the scale of the whole study area, fires were less frequent and possibly less severe at higher elevations. The statistical models used to characterize and map fire regime incorporated variables over each of these scales. Aggregation of fire regime information to larger scales would increase variability within fire regime classes, since much of the variation in fire regime is explained by within-slope and between-slope predictors. Interaction between environmental factors varying over different scales (e.g., slope steepness and elevation) complicates efforts to scale up from small scales to large ones.

The association between fire severity and frequency may also be scale-dependent. Established fire regime classification systems generally consider fire frequency and severity to be inversely associated (Heinselman 1973, Kilgore 1981). There are at least two, complementary explanations for this. Areas that burn infrequently occur in wet or cold climates unsuitable for fire ignitions and spread. Fires can only ignite and spread under extreme conditions. Under these weather conditions, fires are likely to become widespread and of high severity. The second explanation involves patterns of fuel consumption and subsequent accumulation. Frequent fires keep fuel loadings low by consuming fine, dry fuels and killing understory species. As a result, they are likely to be of low severity. With lengthened intervals between fires, more ground and ladder fuels can accumulate, and fires will be more intense and damaging to vegetation (Biswell et al. 1973).

These explanations for an inverse association between fire severity and frequency work well for comparing noncontiguous areas over large spatial extents. However, where the areas being compared are near enough to be burned by the same fire, the results of this study suggest that fire severity and frequency are positively associated. Wet, cool, snowy environments that burn less frequently tend to burn less severely when a fire does spread from adjacent, drier forests. The first explanation, given above for an inverse association, does not hold because fire frequency at such sites is highly dependent upon ignition and spread potential at neighboring sites, allowing fires to occur in the wetter sites even when climatic conditions are not extreme. The second explanation may not apply for the same reason, particularly when the fire regime comparison is between areas for which fires have occurred so infrequently that fuel loading limitations to fire spread have not been of great importance (e.g., Hemstrom and Franklin 1982). Due to uncertainty associated with the measures of fire severity employed in this study, I do not attach much importance to the finding of positive assocation between fire frequency and severity, other than to suggest that future studies of fire regime over similar spatial scales pursue the question further.

4.5.4. Fire Regime in the Temporal Context

The meaning and value of any fire regime characterization are dependent upon the temporal context of the period of record for which fire regime is measured, interpreted, and defined. Based on results from a paleoecological study of lake sediment charcoal accumulation at Little Lake in the Oregon Coast Range, Long (1996) concluded that fire frequency over the past 9000 years has varied in a non-stationary manner that is only partly associated with climate change. Therefore, reconstructed fire regimes are unique for, and meaningfully applied to, only those time periods for which sampled fire history information is representative. Fire frequency trends at Little Lake have been relatively homogeneous over the past 2000 years (MFRIs from 160 - 190 years), suggesting that tree-ring-based fire history results for the past 500 years (Impara 1997) may adequately describe fire regime over two millennia.

Pollen records from Gordon Lake, just outside the western boundary of the Blue River study area, show that climate had changed dramatically from ca. 16000 B.P. to ca. 10000 B.P (Grigg and Whitlock 1998). Over this period, climate was both warmer and colder than at present, with resulting dramatic shifts in dominant vegetation among *Picea*, *Pinus*, *Abies*, and *Pseudotsuga*. Unfortunately, charcoal data were not analyzed in this study, and the reported pollen record does not extend to the late Holocene, so I was unable to determine the temporal extent over which the Blue River fire regime interpretation is relevant.

What is the meaning of the fire regime concept in a fluctuating fire environment? In light of past and future change, is fire regime a moving target that can never be characterized as a spatio-temporal entity with meaning beyond the vagaries of a particular set of historical, climatic, and stochastic contingencies? Since fire regime is always varying in time, and in a way that is not cyclical and cannot be explained by concurrent climate alone, the fire regime derived for a particular period is unique to that period. However, the relationships of fire regime with spatial heterogeneity in topographic and climatic conditions over the landscape may not change greatly over time. Spatially distinct fire regimes described in this study are useful for distinguishing between different fire environments that differ, in a general and highly variable way, with regard to the frequency, severity, spatial pattern, and type of fire. As fire frequency in the Blue River study area changes over time with changing climate, sites at higher elevations, more northerly aspects, and in lower hillslope positions are likely to still experience less frequent fire than sites at lower elevation ridgetops. The actual values for fire regime descriptors, described for the 1475 to 1996 period, will become less relevant as descriptors of "natural fire regime" if climate warms significantly in coming decades, but may help us to understand forest structures and landscape patterns of yesterday and today.

Chapter 5. Influences of Fire History and Topography on Forest Stand Structure, Central Western Cascades, Oregon, U.S.A.

5.1. Introduction

Twentieth century fragmentation of old-growth forests, and concurrent declines in certain animal species associated with late-successional habitats, have generated much interest in the structure and function of old-growth forests throughout North America (Franklin et al. 1981, Spies and Franklin 1988, Mladenoff et al. 1993, Vora 1994, McCarthy and Bailey 1996, Timoney and Robinson 1996). To more rapidly create old-growth habitat structures and ecosystem functions in areas dominated by young, managed stands, some have suggested facilitating old-growth development through silvicultural manipulations such as longer rotations, snag creation, thinning, selection cutting, and leaving residual large trees following harvest (McComb et al. 1993, Vora 1994, Spies and Franklin 1996). Yet there is no single pathway for old-growth structural development, and the distribution of different structural pathways is likely related to variation in the physical environment, proximity to seed source, pre-disturbance forest composition and structure, history of fine-scale and low-severity disturbances, and many other factors. Just as for any aspect of forest succession, multiple temporal pathways are possible (West et al. 1981), and there is not a single "climax" structural type for any given area.

Forest vegetation patterns may not be predictable without an understanding of both environmental influences and disturbance history (White 1979). In the Douglas-fir (*Pseudotsuga menziesii*) forests of the Pacific Northwest region, fire has been prominent in shaping forest patterns at stand and landscape scales (Agee 1993). There is little empirical information about the long-term influences of fire history and fire regimes on forest stand structures in the Douglas-fir forests of the westside Cascades (but see Means 1982, Stewart 1986a, b, Agee and Huff 1987, Huff 1995), although there is much information concerning the influences of finer-scale, treefall gap disturbances (Spies and Franklin 1989, Alaback and Tappeiner 1991, Lertzmann 1992, Gray and Spies 1996a, b). Few studies have measured both stand structure and detailed fire history for forest stands in this region.

The purpose of this study was to determine the role of fire history in forming contemporary stand structures. The role of fire has been more complex than to simply reset the successional clock. Fire history prior to stand-initiating fire influences the species composition and size structure of the pre-fire stand, which in turn influence fire severity and propagule availability. The spatial variation in fire severity for stand-initiating fire is important in determining the landscape pattern of residual trees, advanced regeneration, and seed sources. The number of years since the stand-initiating event is of major importance, since forest structures change over time due to successional processes. In the absence of fire over centuries, Douglas-fir forests of the westside Cascades are likely to become dominated by western hemlock (*Tsuga heterophylla*) and other shade-tolerant species (Dale et al. 1986, DeBell and Franklin 1987, Huff 1995). The frequency and timing of low-and-moderate-severity fires which allow many overstory trees to survive are also expected to have played a role in shaping forest structure.

The influences of fire history on forest structure are dependent on spatial variation in features of the physical environment that influence vegetation response to fire. For example, white birch (*Betula papyrifera*) forest development following high-severity wildfire in southeast Labrador has been associated with moist, well-drained soils on south-facing slopes in topographically dissected areas, provided a seed source is available (Foster and King 1986). Further, fire history is itself influenced by features of the physical environment which influence fire patterns (Chapter 4).

In this study, multiple regression analysis was used to evaluate the influences of variables describing fire history and topography on forest structure. My general goals were to:

(1) Quantitatively examine the influence of fire history on forest stand structure, especially as stand structure relates to the development of old-growth characteristics; and,

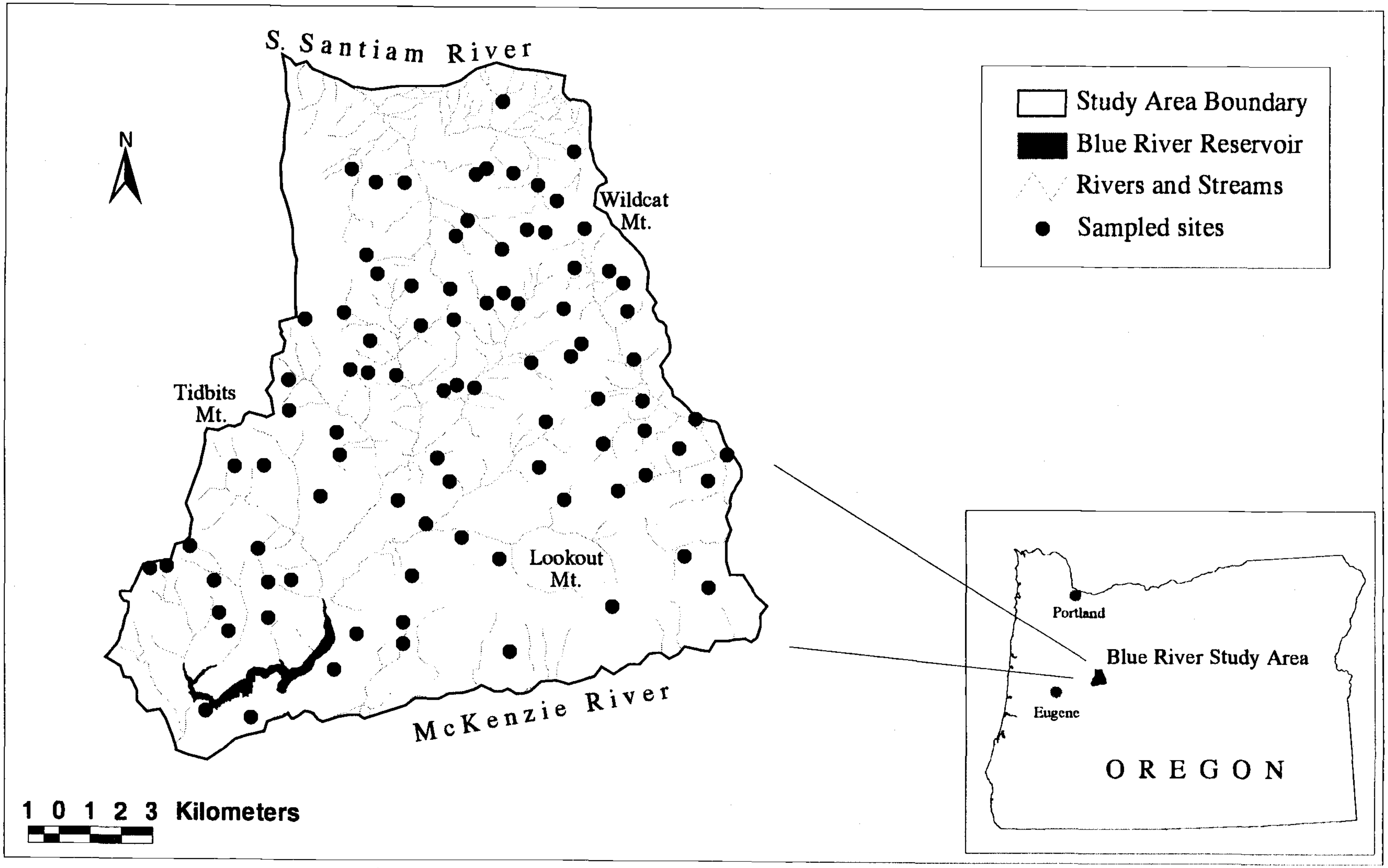
(2) Describe how fire history influences on stand structure vary for different environments, where topography is used as a proxy for features of the physical environment that relate to tree growth and population dynamics. Forest structure is limited to the diameter structure of trees and snags, at the scale of 4-ha sites.

5.2. Methods

5.2.1. Field Methods

The Blue River study area and methods for site selection are described in Chapter Four. Within this 450-km^2 area, I sampled tree diameters for 90 4-ha sites for which detailed fire history and environmental information were also collected (Fig. 5.1) (Chapter Four). Sites were located in clearcuts to facilitate collection of fire history data (Chapter Four). Each 4-ha square site was subsampled using four 0.1-ha circular plots located at the corners. Within each plot, I recorded diameters at stump height, by species,

Fig. 5.1. Map of the study area, showing sampled sites.



for all stumps of at least 5-cm diameter. I also recorded diameter at stump height or breast height, depending which was shorter, of snags of at least 1-m in height, by species. I measured diameter at breast height (d.b.h.), by species, for all standing trees; this information was aggregated with stump data to describe the diameter structure, by species, for each site.

5.2.2. Data Analysis

Diameter measurements for each site were aggregated over all plots to calculate tree density (per ha), basal area (m^2 per ha), and mean and standard deviation diameter, of each tree species present (including snags), for each site. Diameters were not corrected to breast height prior to calculating basal area, because not all stump heights were measured. Stump heights varied from 30 cm to 120 cm, but were usually between 60 and 90 cm. I believe errors in basal area calculations resulting from variable stump heights to be negligible. Size class histograms suggested that trees of less than 20-cm diameter were under-represented in the sample, perhaps due to being knocked down during harvest, faster decay rates of small stumps, or greater difficulty locating small stumps in brushy clearcuts. It is likely that trees of at least 20-cm diameter were completely sampled. Therefore, all calculations included only trees of at least 20-cm diameter. This should not significantly influence measurements of basal area, but greatly influences density measures.

Tree heights could not be recorded because stand structure was measured in clearcuts. Therefore, direct analysis of stand volume or vertical structure was impossible. However, tree height may be roughly correlated with tree diameter, and differences in vertical structure (e.g., number of canopy strata) should roughly parallel differences in horizontal structure (e.g., diversity of diameter classes).

Fire history and topographic variables (Table 5.1) were used to predict five variables describing stand structure: the proportion of shade-tolerant basal area (SHTOL.ba); total stand basal area (BA.tot); standard deviation of dbh (STD.tot); density of large ($\geq$ 100 cm dbh) Douglas-fir trees (BIGDF.dens); and density of large ($\geq$ 100 cm dbh) snags (BIGSNAGS) (Table 5.2). These variables are important for distinguishing stand structures of young, mature and old-growth forests throughout the Pacific Northwest (Spies and Franklin 1991, Acker et al. 1998). Multiple regression analysis was used to calculate statistical models for the five univariate responses. A stepwise method was used to help select the model with the smallest Akaike's Information Criterion (AIC) statistic, proceeding in both directions and stepping through all second-order interactions (Hastie and Pregibon 1993). All statistical analyses were conducted using Splus software (MathSoft, Inc. 1995, Version 3.3).

To describe the relative influences of topographic and fire history variables on the five simple descriptors of stand structure, I partitioned the variance explained by the two sets of variables. Partial R^2 coefficients were calculated as:

$$\text{Partial } R^2 \text{ (Topo | Fire)} = (SSR_{\text{Topo + Fire}} - SSR_{\text{Fire}}) / SST;$$

$$\text{Partial } R^2 \text{ (Fire | Topo)} = (SSR_{\text{Topo + Fire}} - SSR_{\text{Topo}}) / SST;$$

where: SSR = regression sum of squares, and

SST = total sum of squares = SSR + residual sum of squares.

Table 5.1. Predictor variables used in the analysis of fire history and environmental influences on stand structure. Abbrevations for these variables are italicized in parentheses.

Fire History Variables
Number of years since the last high-severity fire (*yrs.hisev*)
Number of fires since the last high-severity fire (*nf.hisev*)
Ratio: (nf.hisev / yrs.hisev) * 100 (*nfhisev.ratio*)
Number of years since the last fire with early seral regeneration (*yrs.regen*)
Proportion of fires that were underburns or of low severity (*prop.low*)
Maximum fire interval between moderate and high severity fires (*maxFI.nlow*)

Environmental Variables
Elevation
North-south transformed slope aspect (*cosasp.ns*)
Northeast-southwest transformed slope aspect (*cosasp.nesw*)
Slope steepness (gradual, moderate, steep)
Hillslope position (lower/valley bottom, middle, upper/ridgetop)
Forest series (Western Hemlock, Pacific Silver Fir, other)

Table 5.2. Stand structure variables used in this study, with their abbreviations. The first eight variables are simple descriptors of stand density and size structure. The last 5 variables are complex descriptors of stand structure derived from linear combinations of simple descriptors. Unless otherwise specified, variables refer to all tree species pooled.

Variable	**Abbreviation**
Proportion of shade-tolerant basal area	SHTOL.ba
Stand basal area (m^2ha^{-1})	BA.tot
Standard deviation of diameters at stump	STD.tot
Density of large (≥ 100 cm diameter)	BIGDF.dens
Density of large (≥ 100 cm diameter)	BIGSNAGS
Range of Douglas-fir diameters	DF.range
Maximum diameter	MAX.tot
Stand density	DENS.tot
Average diameter	MEAN.tot
Old-growth development	*og.dev*
Mature structure	*mature.stx*
Big snags without shade-tolerants	*snag.noshtol*
Big snags with shade-tolerants	*snag.shtol*
Dense, shade-tolerant dominated	*shtol*

The partial R^2 coefficients describe the proportion of variance explained by one set of predictor variables, taking into account the effects of the other set (Sokal and Rohlf 1981). Synergistic effects were also calculated as the difference between the R^2 of the full model, including topographic and fire history variables, and the sum of the two partial R^2 values.

Since many of the stand structure variables were highly correlated (Table 5.3), I conducted a second set of analyses to consider stand structure as a multivariate response. Four additional stand structure variables were included: the range of Douglas-fir diameters (DF.range); the maximum diameter of any species (MAX.tot); total stand density (DENS.tot); and the average diameter, including all species (MEAN.tot) (Table 5.2). Principal components analysis (PCA) was first used to simplify the set of nine correlated stand structure variables into a smaller set of uncorrelated variables which maximized the variance, by interpreting each of the first five principal components (PCs) as a linear combination of those variables with high loadings (i.e., ≥ 0.4 or ≤ -0.4). Prior to calculation of the linear combinations, stand structure variables were standardized to unit variance. The resulting linear combinations were modeled as a function of fire history and environmental variables using multiple regression analysis.

Fire history over a 500 year period was reconstructed for each site, and fire history variables calculated, as reported in Chapter Four. Because the number of years since the last fire of a given severity is probably a better predictor of forest structure than fire frequency descriptors, the approach to describing fire history differs from that of Chapter Four. Six fire history variables were used as predictor variables for regression analysis (Table 5.1). Either the *nf.hisev* or the *nfhisev.ratio* variable was used for a particular

Table 5.3. Pearson's correlations among nine stand structure variables. Correlations of greater than 0.5 are shown in bold, and only correlations significant at $\alpha = 0.05$ are shown.

Variable	SHTOL.ba	BA.tot	DF.range	MAX.tot	MEAN.tot	STD.tot	BIGDF.dens	DENS.tot	BIGSNAGS
SHTOL.ba	1								
BA.tot		1							
DF.range		0.2593	1						
MAX.tot		**0.5279**	**0.8058**	1					
MEAN.tot		**0.6362**	**0.6362**	0.3061	1				
STD.tot		**0.6918**	**0.5016**	**0.7917**	**0.5447**	1			
BIGDF.dens	-0.2882	**0.7827**	0.3252	**0.5472**	**0.6050**	**0.8033**	1		
DENS.tot					**-0.7024**	-0.4181	-0.2972	1	
BIGSNAGS									1

regression analysis, depending which had a stronger association with the response variable. The number of years since the last high-severity fire describes the position of a stand along "successional time". The *maxFI.nlow* and *prop.low* variables describe fires and fire intervals that may predate the stand-initiating fire, and so are important in describing more long-range effects than the other fire history variables. Also, the fire regime classification derived in Chapter Four was used to interpret the association between the five univariate stand structural variables and generalized fire frequency.

Topographic variables are identical to those described in Chapter Four for analysis of topographic effects on fire regime descriptors (Table 5.1). Second-order interactions between all possible combinations of fire history and topographic variables were examined in fitting each model, since it was expected that several of these factors would have interactive effects in influencing fire patterns. I considered polynomial terms for inclusion in the regression model where expected stand structure responses to predictor variables were nonlinear, or where observed trends or residual analysis suggested it was necessary. Prior to statistical analysis, all continuous variables (i.e., elevation, northness, northeastness, hillslope position) were aggregated to an approximately 4-ha scale using a rectangular moving window averaging filter.

5.2.3. Extrapolation of Stand Structure Variables to the Landscape

Using the predictive algorithms, I extrapolated the five stand structure descriptors to the study area. Since statistical models included both fire history and topographic predictors, fire history variables were held constant for each extrapolation, and assumed to be homogeneous for the study area. This is an unrealistic assumption that allows spatially explicit visualization of how the development of stand structure in different environments might have responded differently to the same fire history. Four maps, representing four points along a successional sequence, were created for each stand structure variable using the GIS. Topographic variables at the filtered 4-ha scale were used to extrapolate stand structure across the spatial heterogeneity of the study area. Study area averages for predicted values of each of the five variables were used to illustrate average conditions for successional trends in stand structure.

The parameterization of fire variables requires further explanation (Table 5.4). For all variables except total basal area, values for *yrs.hisev* represented points along the successional sequence, and the first 400 years were extrapolated. For total basal area, where *yrs.hisev* was not significant in the final regression model, the first 200 years of *yrs.regen* were used, since most stands experienced a fire causing some regeneration of early-seral species within that time period. For the standard deviation of diameters and total basal area, the frequency of non-high-severity fires was kept at 1 fire per 100 years (Table 5.4), which is representative for the study area (Chapter Four). For the density of large Douglas-fir trees, the maximum interval between moderate and high severity fires was assumed to have been 200 years prior to the high-severity fire used to reference *yrs.hisev*, so that maxFI.nlow was 200 years for the first 200 years, after which it was identical to *yrs.hisev*, since the most recent fire interval was now the longest.

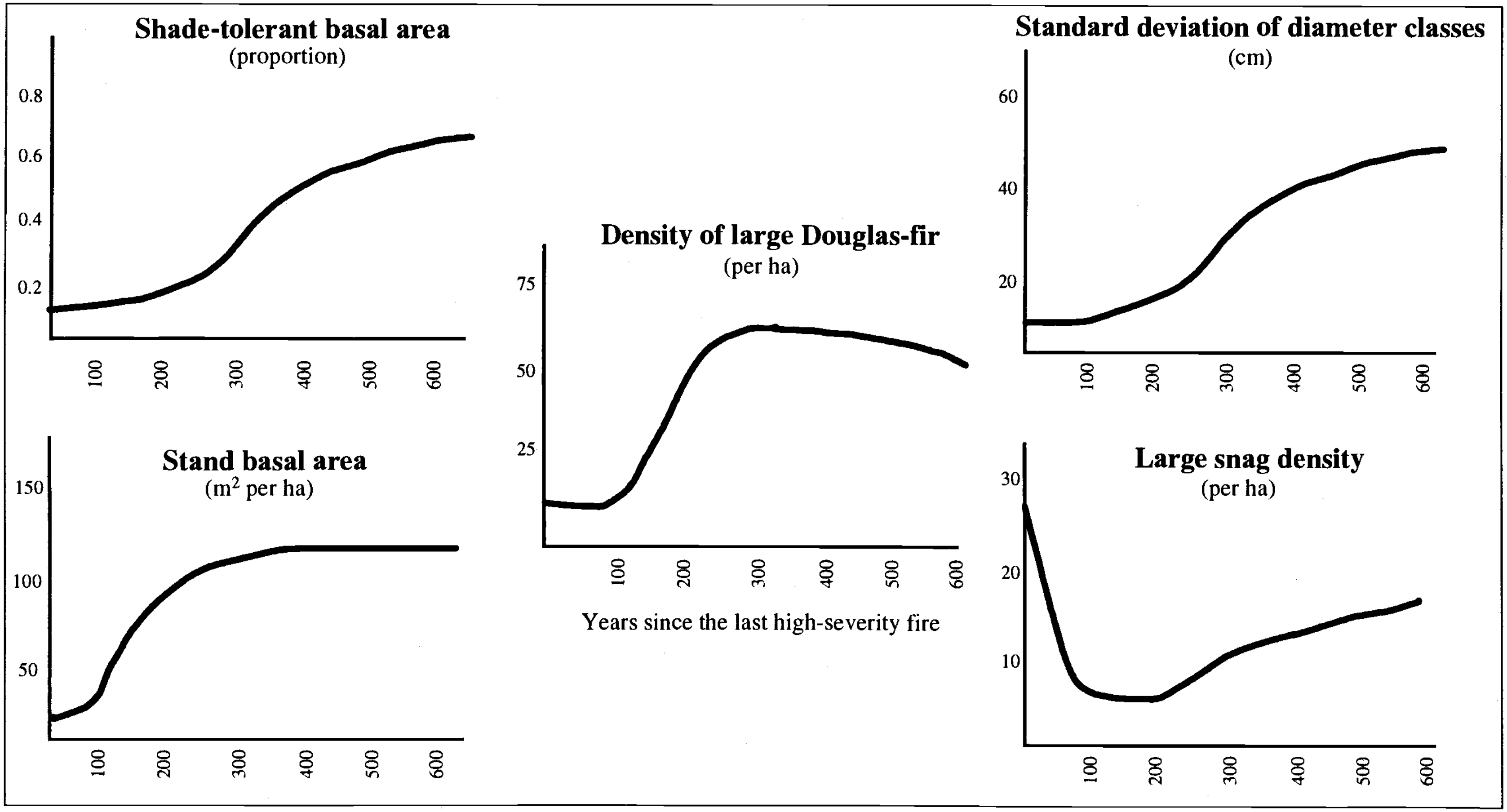
5.2.4. Expected Relationships between Stand Structure and Successional Time

I hypothesized that the five univariate descriptors of stand structure would follow different trends over successional time (*yrs.hisev*) (Fig. 5.2). Spies and Franklin (1988)

Table 5.4. Parameterization of fire history variables for landscape extrapolation of predictive algorithms. See Table 5.2 for abbreviations.

Variable	yrs.hisev	yrs.regen	nf.hisev	nfhisev.ratio	maxFI.nlow
SHTOL.ba	100				
	200				
	300				
	400				
BA.tot		50		0.01	
		100		0.01	
		150		0.01	
		200		0.01	
STD.tot	100	100	1		
	200	100	2		
	300	100	3		
	400	100	4		
BIGDF.dens	100			0.01	200
	200			0.01	200
	300			0.01	300
	400			0.01	400
BIGSNAGS	100				
	200				
	300				
	400				

Fig. 5.2. Hypothesized relationships between selected descriptors of stand structure and successional time. Successional time is represented by the number of years since the last high-severity fire.



suggested that ecosystem characteristics associated with the growth and development of live trees follow an "S-shaped curve" over successional time, while ecosystem characteristics associated with snags or coarse woody debris follow a "U-shaped curve". My hypothesized trends generally followed one or the other of these theoretical patterns. Shade-tolerant basal area, and standard deviation of diameters, were expected to follow an S-shaped trend. For the first century or two, early seral species dominate and shade-tolerant species do not attain large sizes. As gap dynamics begin to play a greater role in providing gaps for patchy recruitment of shade-tolerant trees, at the expense of overstory shade-intolerant trees, both relative shade-tolerant basal area and the standard deviation of diameters increase at a faster rate. That rate of increase slows as the growth of old trees slows, and as a "steady state" of gap formation and colonization is approximated.

I hypothesized that total basal area would also follow a sigmoidal curve, but that the period of rapid increase would begin earlier as Douglas-fir trees grew large, and would end earlier as increases in diameter growth became balanced by formation of canopy gaps due to mortality of big trees (Fig. 5.2). The sigmoidal curve describing the density of large Douglas-fir differs in that the period of rapid increase occurs over a short time, as many trees grow into the 100 cm diameter class. Also, BIGDF.dens should decrease over time in undisturbed old-growth stands as Douglas-fir trees die and are replaced by late-seral tree species. I hypothesized that large snag density would follow the U-shaped curve suggested by Spies and Franklin (1988) and observed by Agee and Huff (1987), where many large snags early in succession are created by fire or are residual from the previous stand, few large snags remain in the mature forest, but large snags begin to be created during the understory reinitiation phase of stand development (Oliver and Larson 1990).

These hypothesized relationships neither include the effects of non-stand-replacing disturbances nor consider environmental variability in post-fire successional trajectories. Analysis of both of these sources of variation is an important contribution of this research.

5.3. Results and Discussion

5.3.1. Influences of Fire History and Topography on Simple Stand Structural Descriptors

Simple univariate descriptors of stand structure varied according to fire history and topography, where successional time, measured as *yrs.hisev*, was considered a fire history variable. Relative shade-tolerant basal area increased linearly with increasing time since the last high-severity fire, for a given slope aspect and elevation (Table 5.5, Fig. 5.3). For a given *yrs.hisev*, SHTOL.ba was greatest at higher elevations and for more northerly aspects. The influence of slope aspect was especially important (Figs. 5.4, 5.5). Dry, south-facing slopes had low SHTOL.ba, even after 400 years of succession. The frequency of non-stand-replacing fires was not a signicant predictor of SHTOL.ba given the effects of these three variables. The influence of slope aspect on SHTOL.ba may be caused by differences in the tree species composition of post-fire regeneration, and different rates of establishment and canopy accession for shade-tolerant tree species during stand development.

Table 5.5. Regression model for the proportion of shade-tolerant basal area as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	0.0481	0.0915	0.7253	(-0.1312, 0.2274)
Yrs.hisev	0.0007	0.0001	0.0000	(0.0005, 0.0009)
Northness	0.1297	0.0237	0.0000	(0.0832,0.1762)
Elevation	0.0002	0.0001	0.0085	0.0000, 0.0004)

$R^2 = 0.51$, $F(3, 84) = 28.67$, $p = 0.0000$

Fig. 5.3. Study area averages, predicted from multiple regression analysis, for five simple stand structure variables at different times along a successional sequence, assuming the entire study area to have experienced a common fire history (Table 5.4).

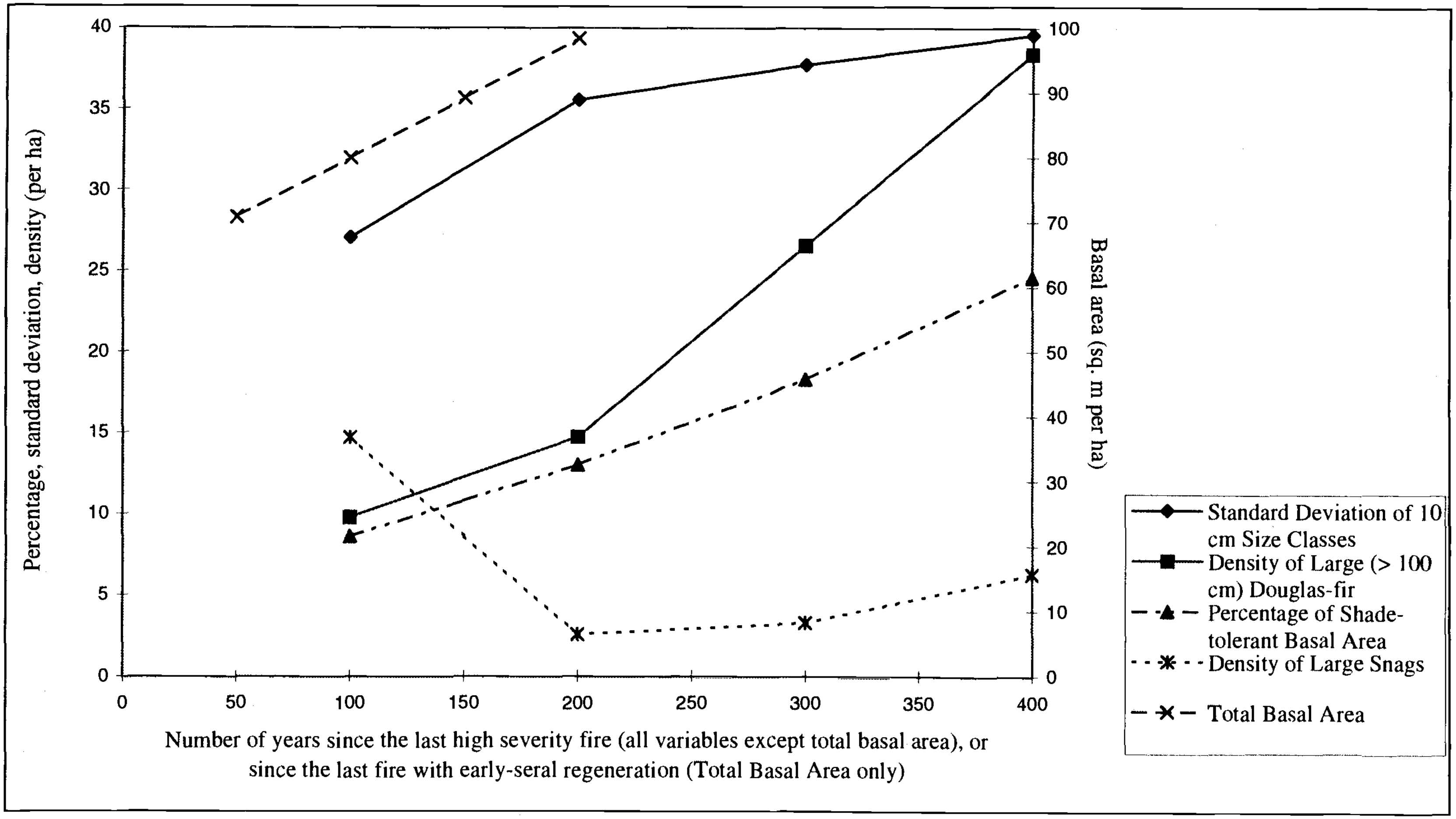


Fig. 5.4. Proportion of shade-tolerant basal area over successional time, for different slope aspects.

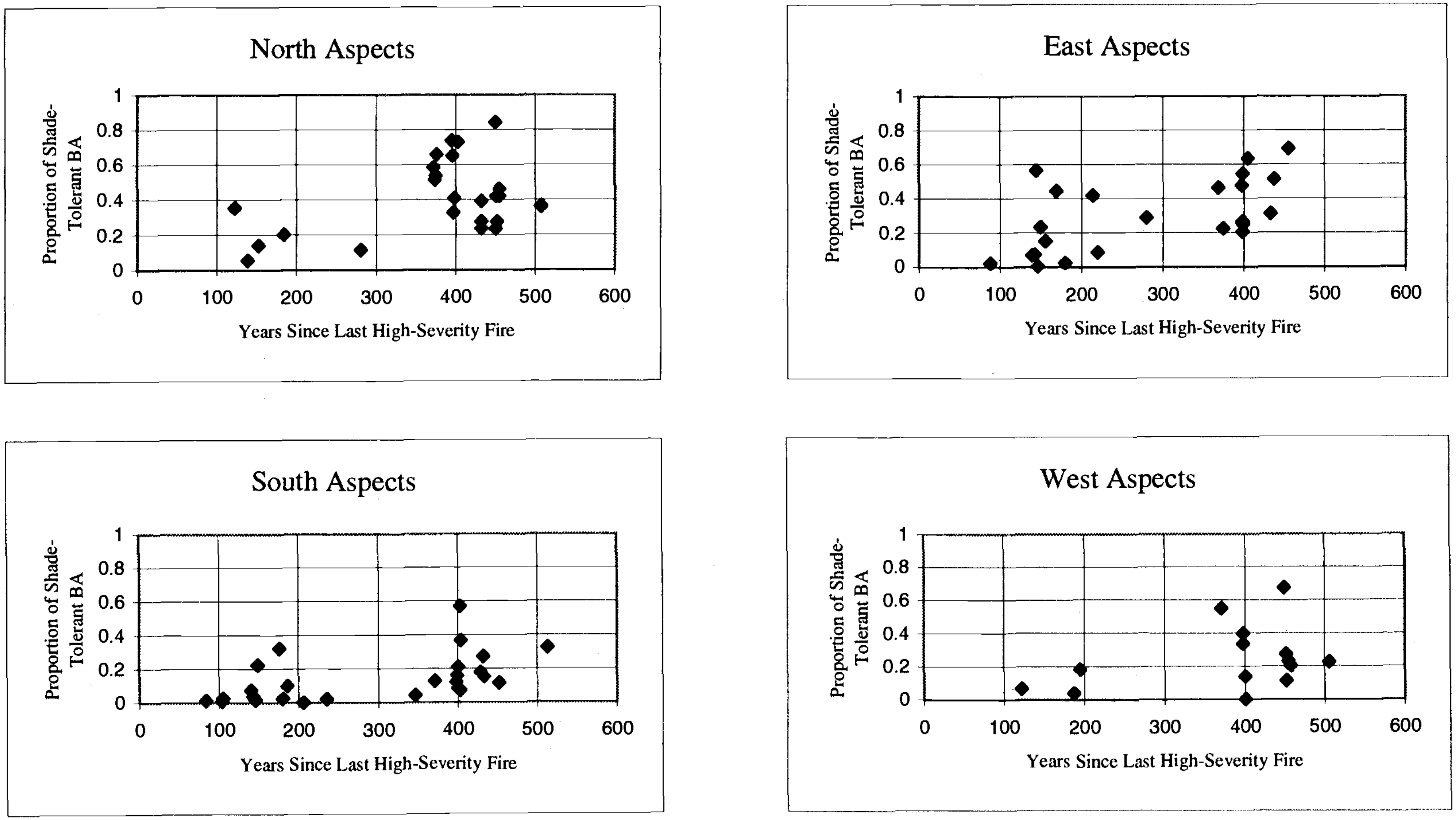
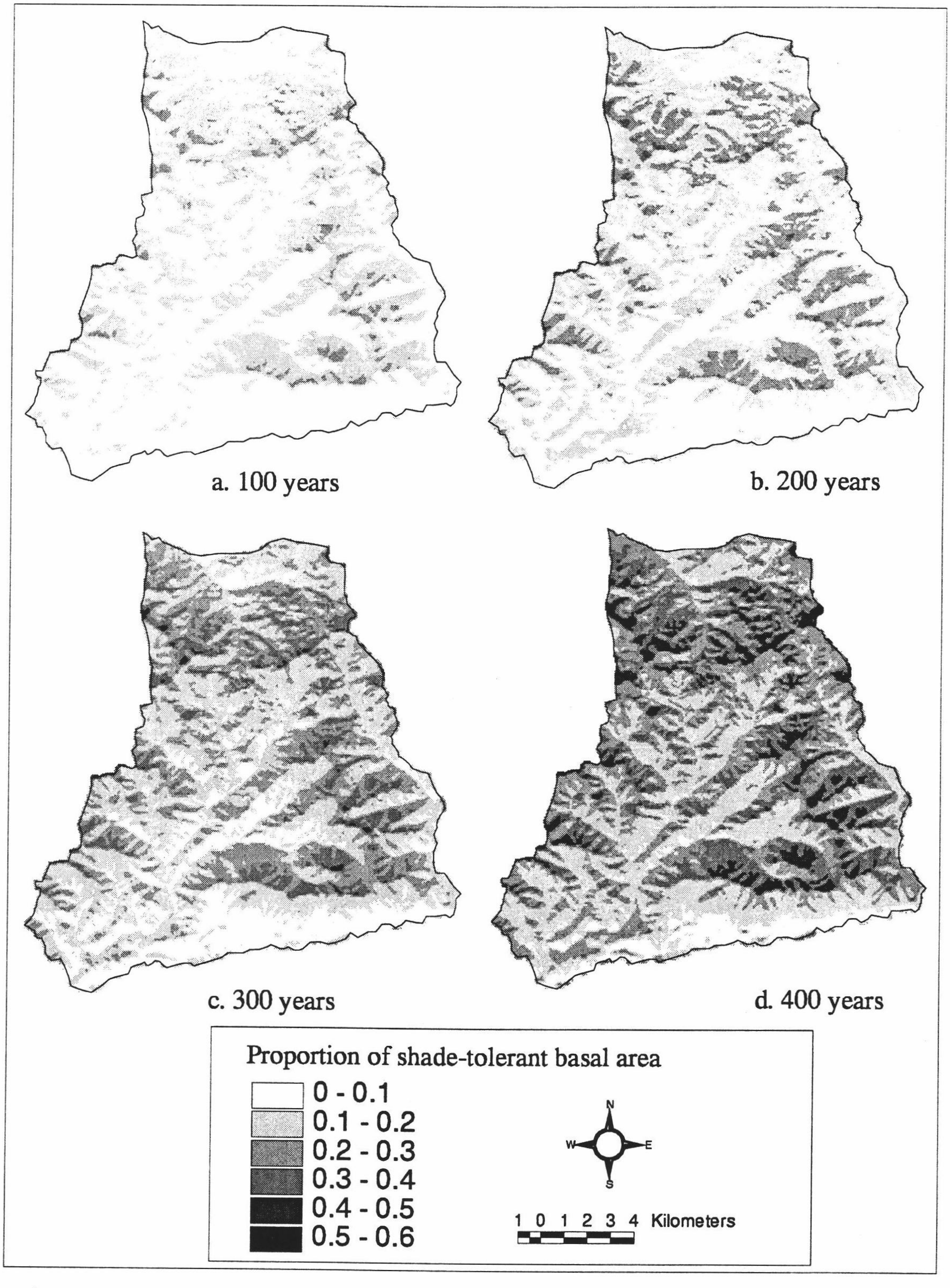


Fig. 5.5. Predicted proportion of shade-tolerant basal area over cumulative 100-year increments since the last high-severity fire, assuming the study area to have experienced a common fire history (Table 5.4). This figure represents the potential development of shade-tolerant basal area in the absence of disturbance.



Stand basal area increased linearly with *yrs.regen*, was greater for stands having had a greater frequency of non-stand-replacing fires since the last high-severity fire, and was greatest on drier slope aspects and more gradual slopes (Table 5.6, Figs. 5.3, 5.6). These results suggest that basal area was increased by the "thinning effect" of non-stand-replacing fires which allowed surviving trees to increase rapidly in diameter growth. Drier slope aspects and more gradual slopes in the study area are more likely to have more favorable growing conditions for Douglas-fir (Zenner 1995). In addition to having thin soils, steep northerly and easterly slopes are often shaded, resulting in less sunlight available for photosynthesis. The greater overstory component of shade-tolerant species on more northerly slopes might compete with Douglas-fir, inhibiting the diameter growth of this species, that can make the greatest contribution to total basal area. A modeled interaction between elevation and *yrs.regen* predicted that the increase in total basal area over time was greatest for lower elevations (Fig. 5.7). Shortly after the last fire with regeneration of early seral tree species, stands at higher elevations had greater basal area; by 200 years, stands at lower elevations had greater basal area (Figs. 5.6, 5.7). This interaction might have resulted from post-fire regeneration at higher including a large component of noble fir (*Abies procera*) and shade-tolerant western hemlock, that can establish at high densities and so maintain a high basal area early in succession. However, the greater proportion of Douglas-fir establishing at lower elevations is capable of more rapid, sustained diameter growth over subsequent decades than the shade-tolerant species establishing at higher elevations. Also, high-elevation sites that are especially cold or snowy are more likely to stagnate than low-elevation sites with superior growing conditions.

Table 5.6. Regression model for total stand basal area as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect. Slope steepness is treated as an indicator variable where gradual slopes represent the reference condition. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	3.38	30.93	0.9134	(-57.24, 64.00)
Nfhisev.ratio	9.25	4.63	0.0492	(0.18, 18.32)
Yrs.regen	0.5642	0.1798	0.0024	(0.2118, 0.9166)
Elevation	0.0621	0.0260	0.0194	(0.0111, 0.1131)
Northness	-8.02	3.38	0.0201	(-14.64, -1.40)
Moderately Steep	-11.13	5.95	0.0649	(-22.79, 0.53)
Very Steep	-24.33	6.71	0.0005	(-37.48, -11.18)
Elevation:Yrs.regen	-0.0004	0.0002	0.0090	(-0.0006, -0.0002)

$R^2 = 0.37$, $F(7, 80) = 6.67$, $p = 0.0000$

Fig. 5.6. Predicted stand total basal area (square meters per ha) over four cumulative 50-year increments since the last fire to have caused early seral regeneration, assuming the study area to have experienced a common fire history. (Table 5.4)

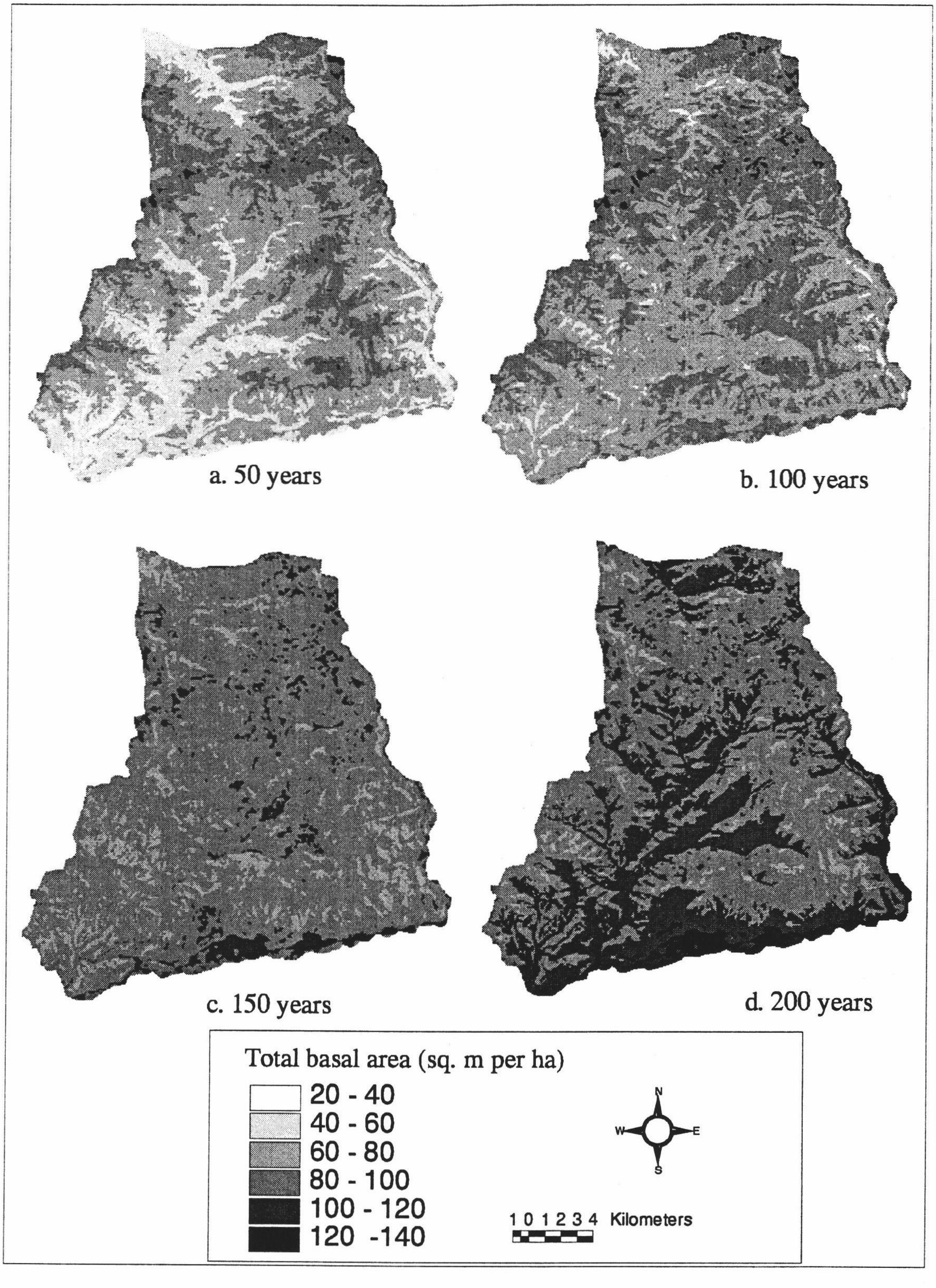
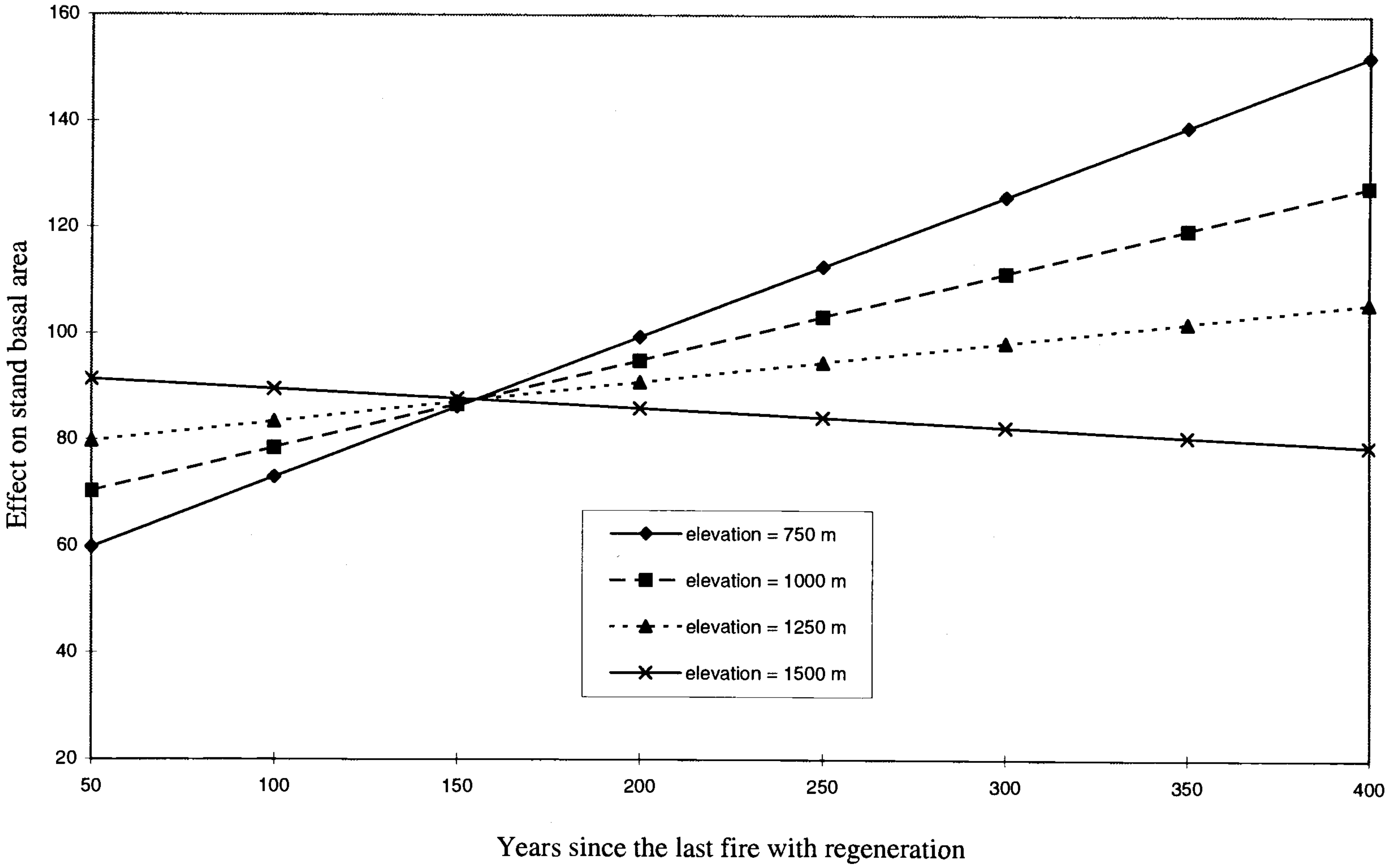


Fig. 5.7. Interaction plot showing the predicted effects of elevation and number of years since the last fire with regeneration on stand basal area (sq. m per ha.)



Variability in tree diameters increased asymptotically with *yrs.hisev* and linearly with *yrs.regen*, and was greater for sites that had experienced more non-stand-replacing fires (Table 5.7, Fig. 5.3). Stands with greater *yrs.hisev* have progressed further into the understory reinitiation stage, and so have experienced more chronic non-fire disturbances that result in recruitment of a variety of size-classes. Higher *nf.hisev* also leads to greater opportunities for recruitment of new size-classes, increasing variability in tree diameters. Each low-severity fire is likely to initiate a patchy cohort of Douglas-fir, noble fir, or western hemlock, and so increase the variability of tree diameter. Also, the patchy overstory mortality produced by such fires creates localized areas where height and diameter growth of surviving trees might be stimulated by release from competition. For a given *yrs.hisev* and *nf.hisev*, increasing time since the last fire with early seral regeneration would lead to greater variability in tree diameters because enough time would have elapsed for understory and subcanopy trees establishing after the disturbance to have reached the 20 cm diameter limit used in these calculations.

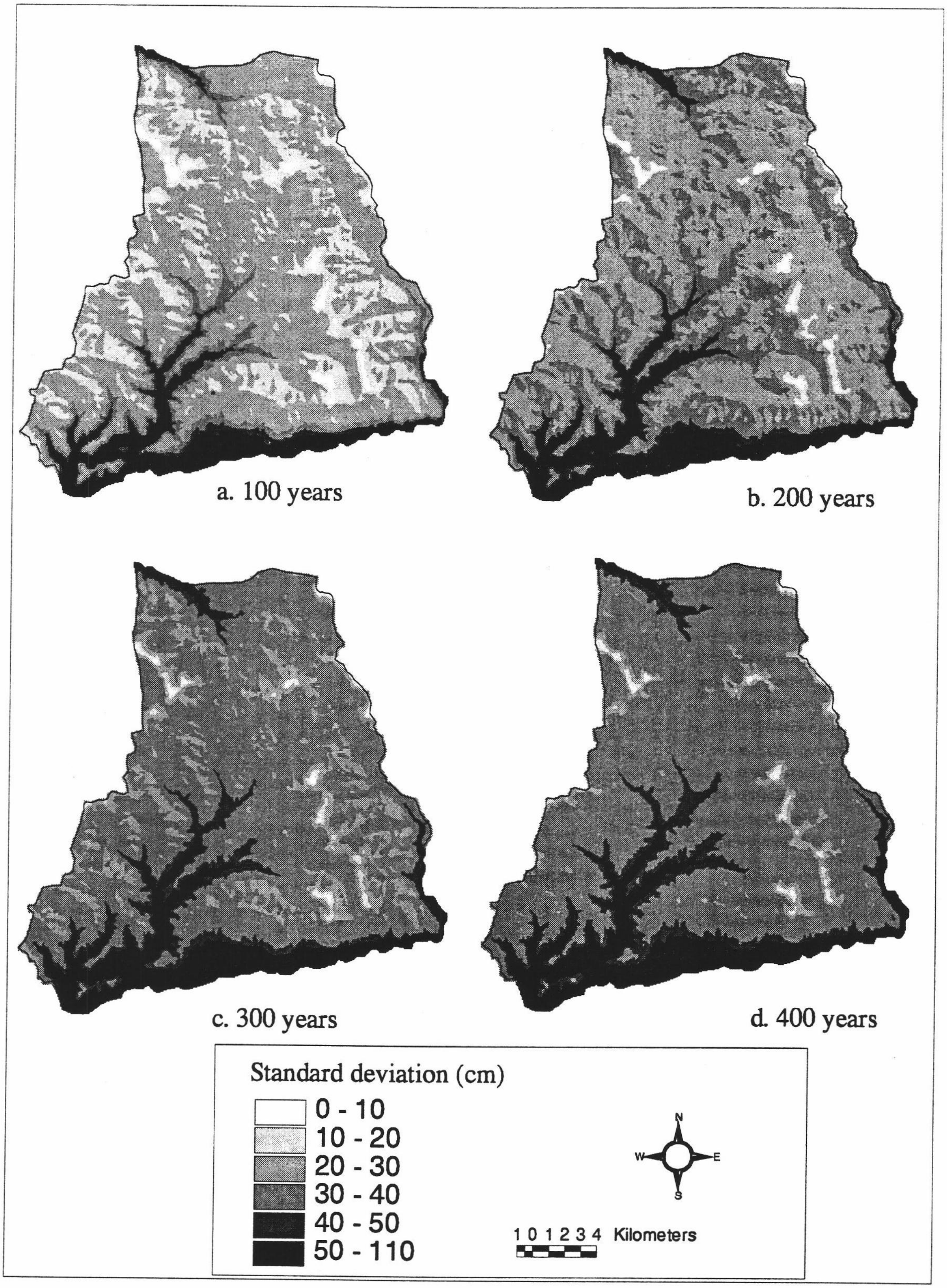
There was less variability in size structure for wetter aspects and higher elevations (Fig. 5.8), where relative shade-tolerant basal area was greater (Figs. 5.4, 5.5) and total basal area was less (Fig. 5.6). Stands in such environments are more likely to have a significant component of hemlock and true fir in the upper canopy, inhibiting development of lower canopy strata and so resulting in more homogeneous stand structures. Douglas-fir trees in such stands may also be less likely to attain very large sizes due to competition with more shade-tolerant species, further reducing variability in tree diameters. The influence of slope aspect on STD.tot was minor, and most evident early in succession (Fig. 5.8). The association between elevation and STD.tot was

Table 5.7. Regression model for the standard deviation of 10 cm size-classes, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northeasterly aspect.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	236.80	79.96	0.0040	(80.08, 393.52)
Yrs.hisev	0.0828	0.0488	0.0937	(-0.0128, 0.1784)
Yrs.hisev^2	-0.0001	0.0001	0.1394	(-0.0003, 0.0001)
Nf.hisev	1.73	0.68	0.0133	(0.39, 3.07)
Yrs.regen	0.0314	0.0116	0.0086	(0.0087, 0.0541)
Elevation	-0.6729	0.2535	0.0096	(-1.1698, -0.1760)
Elevation^2	0.0007	0.0003	0.0148	(0.0001, 0.0013)
Elevation^3	-2.09e-07	NA	0.0206	NA
Northeastness	-3.68	1.16	0.0021	(-5.94, -1.41)

$R^2 = 0.50$, $F(8, 79) = 9.96$, $p = 0.0000$

Fig. 5.8. Predicted standard deviation of tree diameters at stump height, over 100-year increments and assuming the study area to have experienced a common fire history (Table 5.4).



nonlinear, such that variability in tree diameters declined rapidly with increasing elevation for low elevations (to about 800 m), was fairly constant from 800 m to 1300 m, and then declined rapidly with elevation again for elevations above 1300 m. Douglas-fir, the species that can attain the largest sizes and so greatly increase STD.tot, is less likely to be an important stand component at the highest elevations. The presence of abundant western redcedar (*Thuja plicata*) may lead to greater variability in tree diameters at moist, lower elevation sites because this potentially fast-growing, extremely shade-tolerant species may exhibit a wide range of diameter classes for stands of a given age.

The density of large Douglas-fir trees increased linearly with number of years since the last high-severity fire, and was greatest for sites that had experienced longer maximum intervals between moderate- and- high-severity fires, a higher frequency of non-stand-replacing fires since the last high-severity fire, and that were on drier slope aspects (Table 5.8, Fig. 5.3). Stands with higher *maxFI.nlow* have experienced a long interval without stand-replacing disturbance where trees were able to attain large diameters. Such trees may have become large enough to have had a greater probability of surviving subsequent high-severity fires, as suggested by the significance of the *maxFI.nlow* variable, even when *yrs.hisev* was included in the regression model (Table 5.8). The relationship with *nfhisev.ratio*, consistent with that for total basal area, suggests that non-stand-replacing fires have had an important "thinning effect" by causing growth releases for surviving trees. Lower densities of large Douglas-fir trees for wetter slope aspects probably resulted from the greater density of large trees of shade-tolerant species in these environments, where overstory competition between Douglas-fir and species

Table 5.8. Regression model for the density of large (d.b.h. > 100 cm) Douglas-fir trees, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-18.25	7.46	0.0169	(-32.87, -3.63)
MaxFI.nlow	0.0686	0.0201	0.0011	(0.0292, 0.1080)
Yrs.hisev	0.0496	0.0169	0.0046	(0.0165, 0.0827)
Nfhisev.ratio	8.03	3.69	0.0329	(0.80, 15.27)
Northness	-10.87	2.30	0.0000	(-15.38, -6.36)

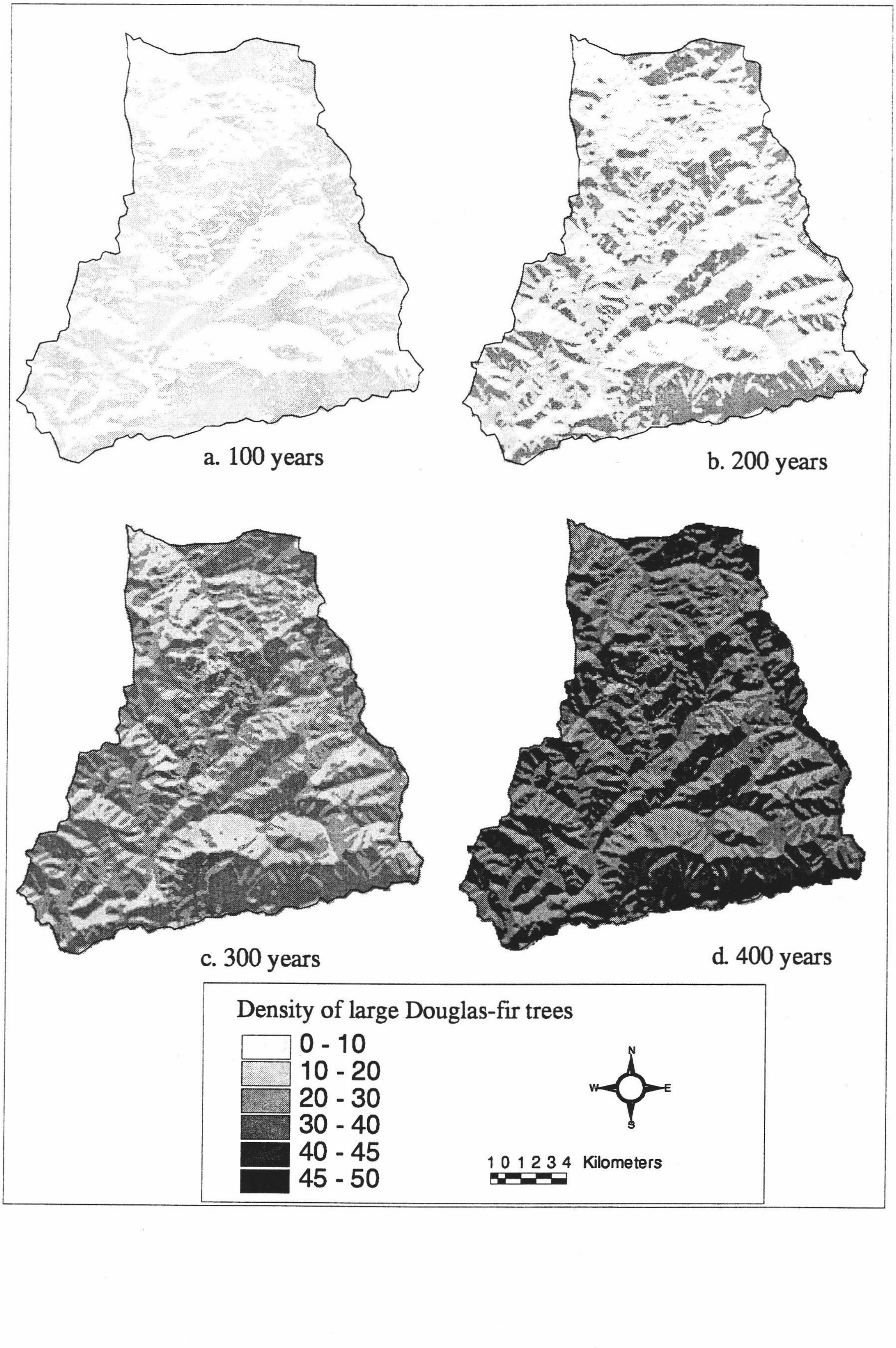
$R^2 = 0.43$, $F(4, 69) = 12.75$, $p = 0.0000$

such as western hemlock, western redcedar, and noble fir is greatest. The influence of slope aspect was minor compared to that of *yrs.hisev* (Fig. 5.9).

Large snag density followed the hypothesized "U-shaped trend" over successional time (Fig. 5.2). It was highest soon after the last high-severity fire, decreased to a low point at about 200 years, and increased gradually thereafter (Table 5.9, Figs. 5.3, 5.10). Large snag densities were predicted to be still relatively high 100 years after the fire. For a given number of years since the last high-severity fire, large snag density was greatest for drier (i.e., more southwesterly) slope aspects, likely due to the previously described trend toward fewer large, living Douglas-fir trees on wetter slopes. Also, wetter slopes have higher wood decomposition rates (Harmon et al. 1986), causing snags to persist for shorter times.

The relative contributions of topographic and fire history variables toward explaining stand structure differed for the five stand structure descriptors (Fig. 5.11). Topographic variables explained far more of the variance than fire history variables for relative shade-tolerant basal area and total basal area, suggesting that these measures of stand structure were greatly influenced by the environmental heterogeneity of vegetation response to fire. For measures of stand compositional complexity, such as relative shade-tolerant basal area, this was a reasonable result. Since the highest values of total basal area were usually associated with stands dominated by Douglas-fir, the species capable of attaining the greatest diameters, total basal area was also influenced by stand compositional complexity. Both relative shade-tolerant basal area and total basal area should be strongly influenced by the tree species composition of the post-fire regeneration cohort.

Fig. 5.9. Predicted density of large Douglas-fir (number of trees per ha with dbh > 100 cm) over cumulative 100-year increments since the last high severity fire, assuming the study area to have experienced a common fire history (Table 5.4).



a. 100 years

b. 200 years

c. 300 years

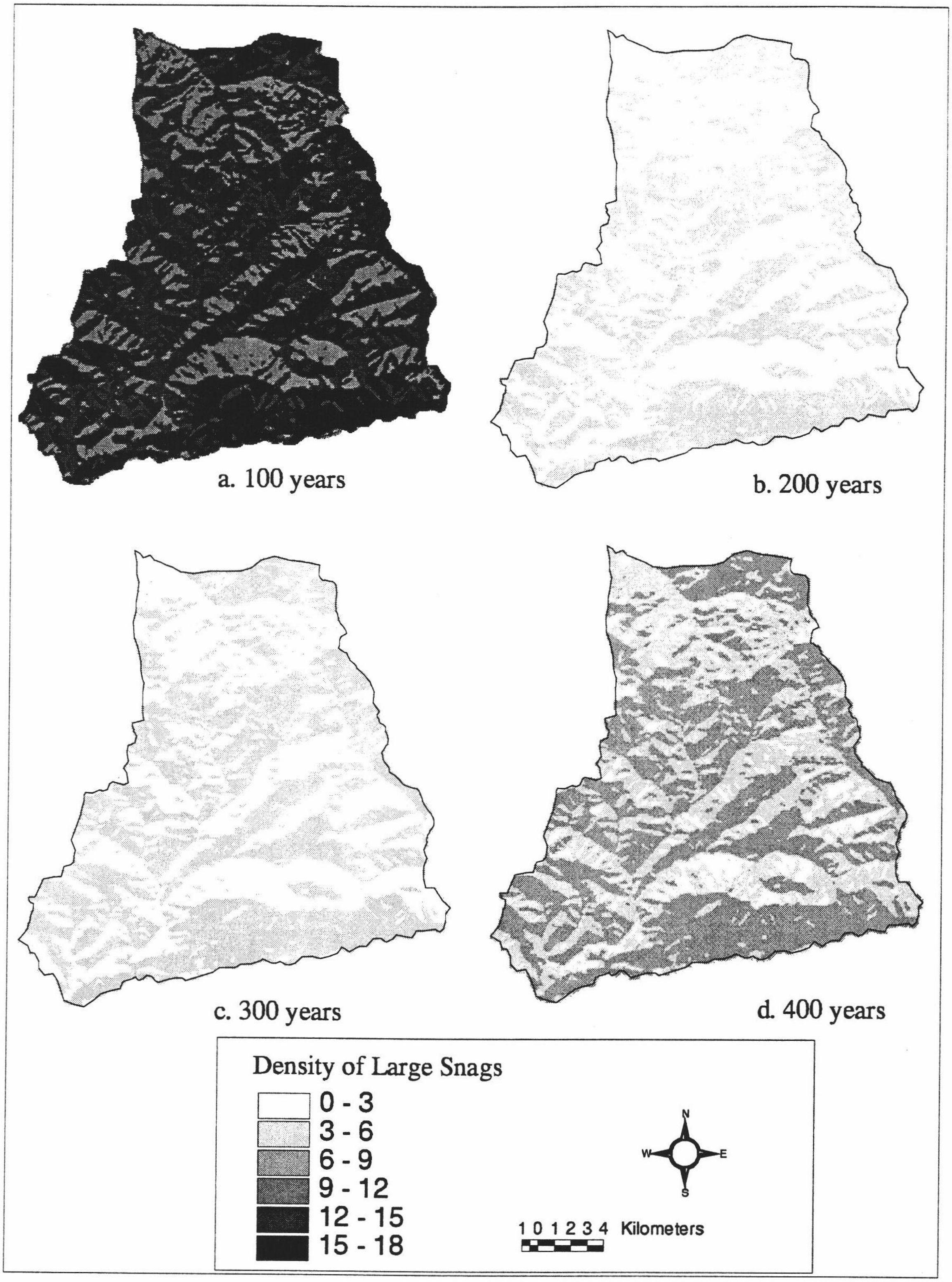
d. 400 years

Table 5.9. Regression model for the density (per ha) of large (> 100 cm) snags, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northeasterly aspect.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	49.87	12.32	0.0001	(25.73, 74.01)
Yrs.hisev	-0.5078	0.1452	0.0008	(-0.7923, -0.2232)
Yrs.hisev^2	0.0017	0.0005	0.0008	(0.0007, 0.0027)
Yrs.hisev^3	1.763e-06	NA	0.0013	NA
Northeastness	-3.02	1.08	0.0064	(-5.14, -0.90)

$R^2 = 0.24$, $F(4, 83) = 6.59$, $p = 0.0001$

Fig. 5.10. Predicted large snag density (snags > 100 cm dbh per ha) over cumulative 100-year increments since the last high severity fire, assuming the study area to have experienced a common fire history (Table 5.4).



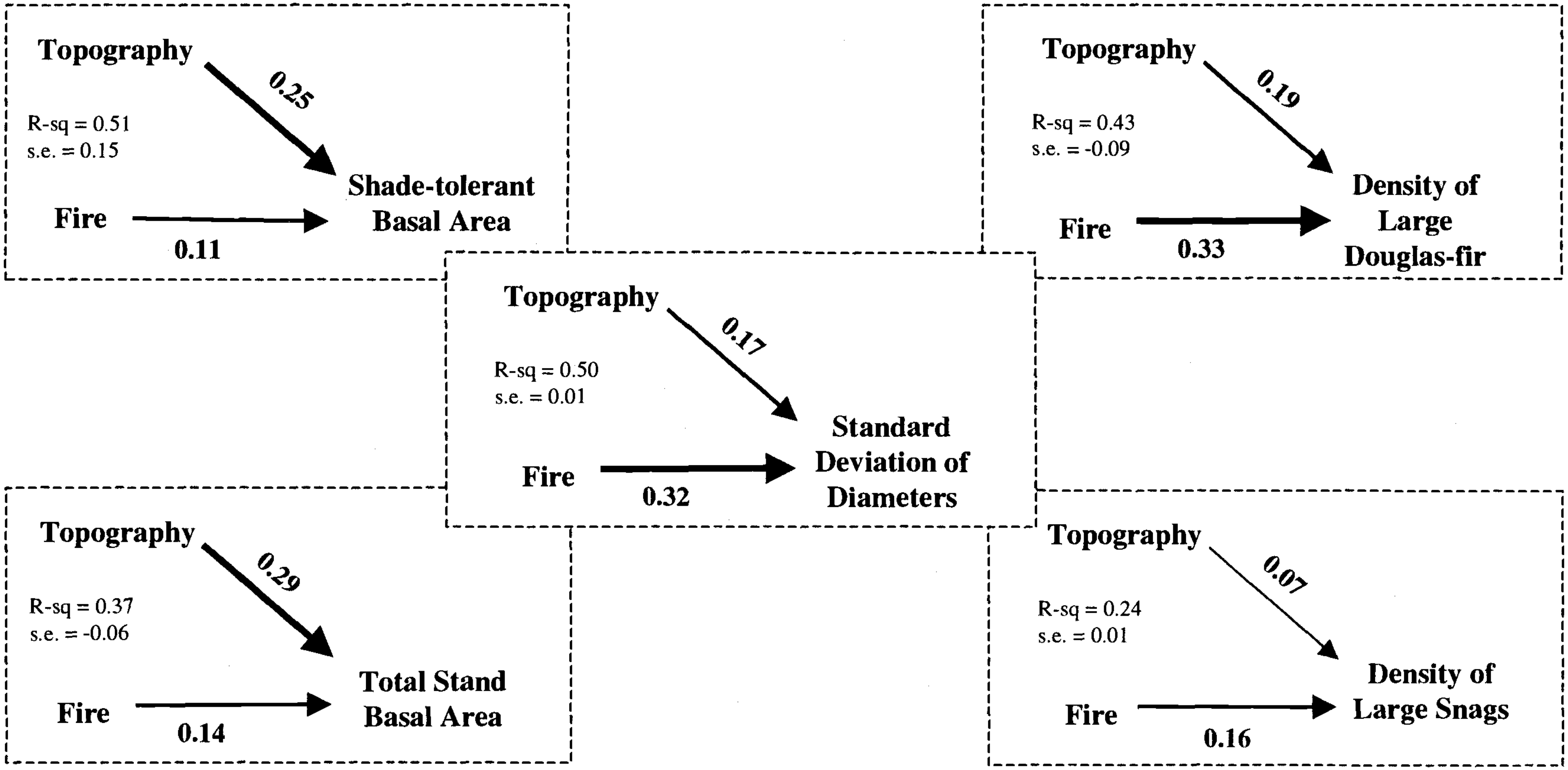
a. 100 years

b. 200 years

c. 300 years

d. 400 years

Fig. 5.11. Relative contributions of topographic and fire history variables to regression models for each of five variables describing some aspect of stand structure. Partial R-sq coefficients were used to partition the variance between the two sets of predictor variables, such that the effects of each set are shown after accounting for the effects of the other. Synergistic effects (s.e.) are the differences between the coefficient of determination for the full model and the sum of the two partial R-sq values.



The importance of fire history variables exceeded that of topographic variables for standard deviation of tree diameters, density of large Douglas-fir trees, and density of large snags (Fig. 5.11). Tree diameter variability was influenced primarily by the frequency of non-stand-replacing, cohort-initiating disturbances, as measured in this study by *nf.hisev* (for fires) and *yrs.hisev* (for non-fire disturbances, the frequency of which is a function of time). Environment influenced tree diameter variability relatively little because this measure was not affected by the species composition of post-disturbance regeneration. The density of large Douglas-fir trees was likely influenced more by fire history variables because the overriding factor was *yrs.hisev*; the post-fire Douglas-fir cohort grew in diameter as a function of stand age. It makes sense that the density of large snags should have been influenced mainly by the number of years since the last high-severity fire, since in the first two centuries of stand development, large snag accumulation comes from residual snags and fire-killed trees from the prefire stand, and later from the gradual accumulation of snags from non-fire and low-severity fire causes of mortality.

All five stand structure measures were influenced by both topographic and fire history variables (Fig. 5.11). The most important fire history variable was *yrs.hisev*, which can be interpreted simply as "stand age". An understanding of overstory forest structure at the stand level requires knowledge of: stand age; the history of low and moderate severity fires since the stand-initiating event (for BA.tot, STD.tot, and BIGDF.dens); the longest interval between high-severity fires prior to the most recent stand-initiating event (for BIGDF.dens), stand environment, the relationships between stand environment, fire effects, and post-fire regeneration responses; and the relationships between stand environment and stand development processes, including growth, regeneration, mortality, and response to fine-scale or low-severity disturbances.

5.3.2. Fire Regime Influences on Stand Structure

Spatial variability in fire regime, as characterized using fire frequency descriptors (Chapter 4), was not strongly associated with most descriptors of forest structure (Table 5.10). Stands with a lower fire frequency had a greater proportion of shade-tolerant basal area than stands with a higher fire frequency. Stands with a lower fire frequency were also more likely to occur at higher elevations, lower slope positions, or more mesic aspects (Chapter 4). Since these environments were more likely to have a higher proportion of shade-tolerant basal area regardless of fire history (Table 5.5), it is difficult to ascribe the observed pattern solely to fire regime differences. Total basal area, density of large Douglas-fir trees, standard deviation of diameter classes, and large snag density, did not differ significantly among the three fire frequency classes. The overall fire regime of a site was not as good a predictor of current stand structure as the number of years since the last fire of a given severity, since stand structure is a direct result of time-dependent stand development processes.

5.3.3. Relationships among Stand Structural Descriptors

Correlation analysis showed strong associations between many of the stand structure variables (Table 5.3). Strong positive associations between descriptors of size variability (STD.tot, DF.range) and size (BA.tot, MEAN.tot, BIGDF.dens) represent the tendency for larger tree sizes to be associated with a greater diversity of tree sizes, and

Table 5.10. Observed values for five variables describing stand structure, for different fire frequency classes in the Blue River study area. For each variable, the first row (bold type) shows the mean; the second row (parentheses) shows the standard deviation; and the third row (italics) shows the 95 % confidence interval for the mean.

Frequency Class	Shade-tolerant Basal Area (prop.)	Total Basal Area ($m^2\ ha^{-1}$)	Density of Large Douglas-fir trees (ha^{-1})	Standard Deviation of Diameter Classes (cm)	Density of Large Snags (ha^{-1})
High	**0.18**	**75**	**25**	**33**	**8**
(27 sites)	(0.18)	(25)	(19)	(10)	(6)
	0.11, 0.25	*66, 84*	*18, 32*	*29, 37*	*6, 10*
Moderate	**0.29**	**79**	**25**	**33**	**12**
(31 sites)	(0.19)	(25)	(18)	(10)	(10)
	0.22, 0.36	*70, 88*	*18, 31*	*30, 37*	*8, 16*
Low	**0.35**	**87**	**25**	**33**	**10**
(32 sites)	(0.22)	(27)	(19)	(10)	(7)
	0.27, 0.44	*77, 96*	*19, 32*	*30, 37*	*7, 12*

with more complex stand structures, over the course of stand development. Neither the proportion of shade-tolerant basal area nor the density of large snags was strongly associated with any other stand structure descriptor.

Principal components analysis was used to simplify the set of nine stand structural descriptors into a subset of linear combinations representing uncorrelated principal components (Table 5.2). The first five principal components combined to represent 94% of the measured variation in stand structure (Table 5.11). PC 1 represents the successional pathway where large trees and high stand basal area develop concurrently with the establishment of smaller trees through fine-scale disturbances, such that the variability of tree sizes is increased. As mature forests go through stand differentiation during the stem exclusion developmental stage (Oliver and Larson 1990), size variability is caused primarily by differences in overstory tree sizes as some trees increase in diameter, while others are suppressed and grow very little. Later in stand development, the establishment of multiple canopy strata, from creation of canopy gaps and accession of shade-tolerant trees into the subcanopy, is the main contributor to size variability. The linear combination suggested by PC 1, or the average of total basal area, maximum tree diameter, standard deviation of tree diameters, and density of large Douglas-fir trees, was considered to be a measure of stand development towards heterogeneous late-successional structures, and therefore was labelled, "Old-Growth Development" (*og.dev*).

The second principal component was high for sites that had large trees on average, low density, and a low range of diameter sizes. Low values for PC 2 describe sites with many small trees, but a few very large ones. The linear combination suggested by PC 2, labelled "Mature Structure" (*mature.stx*), is the algorithm: MEAN.tot - average(DF.range,

Table 5.11. Loadings of stand structural variables on the first five principal components. Shown in parentheses is the amount of variance explained by each principal component. The loadings represent the linear combinations of each variable comprising the component. Loadings less than 0.2 are not shown; loadings greater than 0.4 are shown in bold.

Variable	**PC 1** (0.44)	**PC 2** (0.19)	**PC 3** (0.12)	**PC 4** (0.10)	**PC 5** (0.09)
SHTOL.ba			**-0.752**	**0.447**	**0.404**
BA.tot	**0.408**				**0.566**
DF.range	0.257	**-0.557**			-0.320
MAX.tot	**0.402**	-0.307	-0.320		
MEAN.tot	0.351	**0.485**			
STD.tot	**0.468**				
BIGDF.dens	**0.446**				
DENS.tot	-0.215	**-0.520**			**0.581**
BIGSNAGS		-0.287	**0.464**	**0.830**	

SHTOL.ba	the proportion of shade-tolerant basal area
BA.tot	total stand basal area
DF.range	the range of Douglas-fir diameters
MAX.tot	the diameter of the largest tree
MEAN.tot	the average tree diameter
STD.tot	the standard deviation of tree diameters
BIGDF.dens	the density of Douglas-fir trees of at least 100 cm diameter
BIGSNAGS	the density of snags of at least 100 cm diameter

DENS.tot). PC 3 ("Big Snags without Shade-Tolerants", or *snag.noshtol*) was described by the linear combination: BIGSNAGS - SHTOL.ba. PC 4 ("Big Snags with Shade-Tolerants", or *snag.shtol*), was described by the average of SHTOL.ba and BIGSNAGS. PC5 ("Dense, Shade-Tolerant Dominated", or *shtol*) was described using the average of SHTOL.ba, BA.tot, and DENS.tot. Examples of stand structures representative of *og.dev*, *mature.stx*, and *shtol* are shown in Figure 5.12.

Linear combinations of variables suggested by PCA were not identical to the principal components themselves, and so were likely to be correlated. No two pairs of the five combination variables described above were highly correlated, although weak but significant correlations existed between *og.dev* and *mature.stx*, *og.dev* and *shtol*, *mature.stx* and *shtol*, and *snag.noshtol* and *shtol* (Table 5.12).

5.3.4. Relationships between Fire History, Topography and Complex Stand Structural Descriptors

The "Old-Growth Development" variable (i.e., a combination of stand basal area, maximum diameter, standard deviation of diameters, and density of large Douglas-fir trees) was greatest where more years had passed since the last high-severity fire, and since the last fire with early seral regeneration (Table 5.13). For a given *yrs.hisev* and *yrs.regen*, old-growth development was greater for lower elevations and drier slopes. Old-growth development was also greater for stands where a greater proportion of fires were of low severity. However, there was an interaction betwen slope steepness and the proportion of low-severity fires such that the effect of *prop.low* was very influential for gradual slopes, but minimal for moderate and steep slopes (Fig. 5.13). Old-growth

Fig. 5.12. Size class histograms for sites representing different complex descriptors of stand structure.

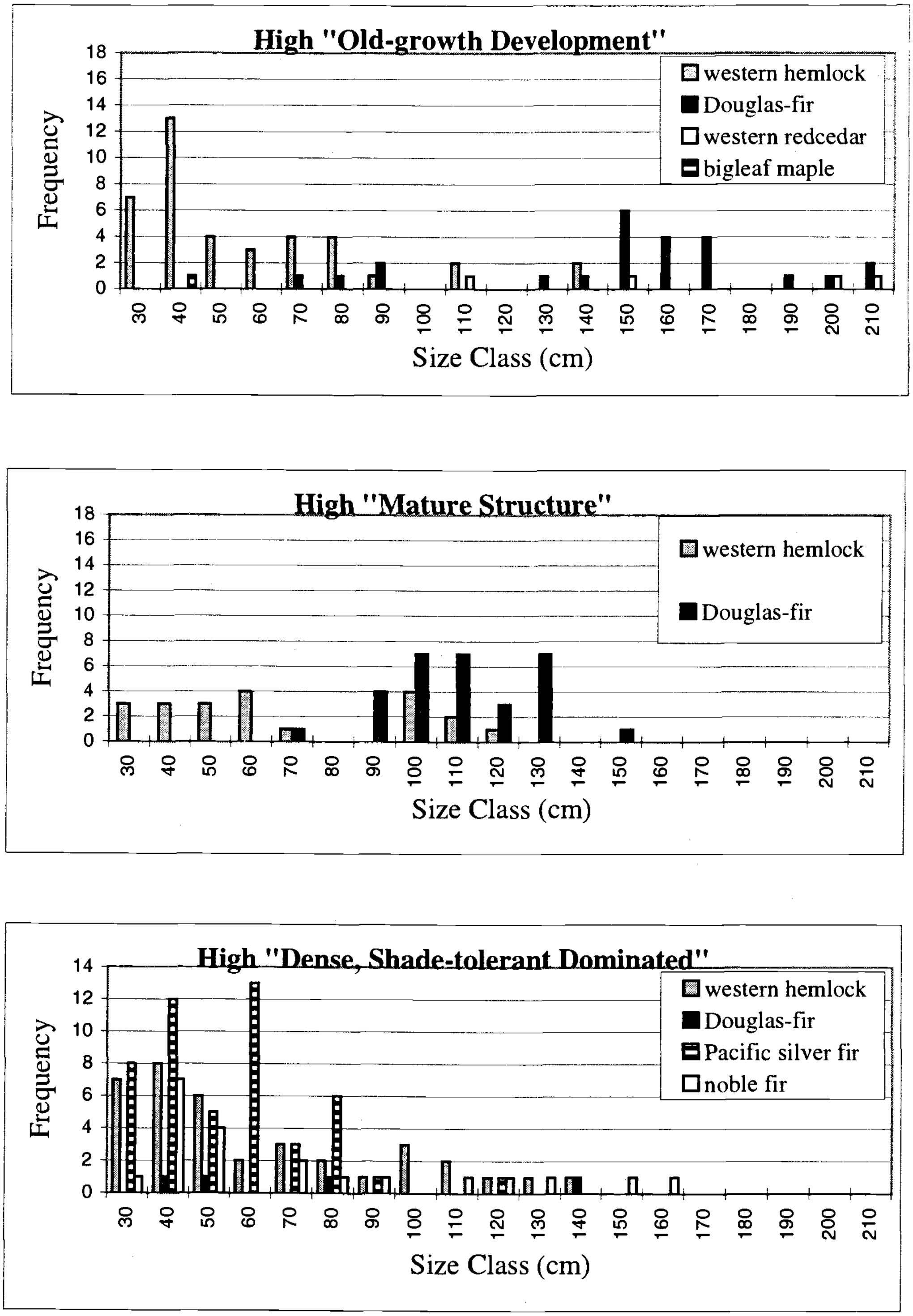


Table 5.12. Pearson's correlations among the five complex stand structural variables. Correlations significant at $\alpha = 0.05$ are shown in bold.

Variable	*og.dev*	*mature.stx*	*snag.noshtol*	*snag.shtol*	*shtol*
og.dev	1				
mature.stx	**0.3542**	1			
snag.noshtol	-0.1639	-0.0255	1		
snag.shtol	-0.0406	-0.1122	**0.2322**	1	
shtol	**-0.2896**	**0.3502**	-0.0440	0.1986	1

Explanation of Abbreviations

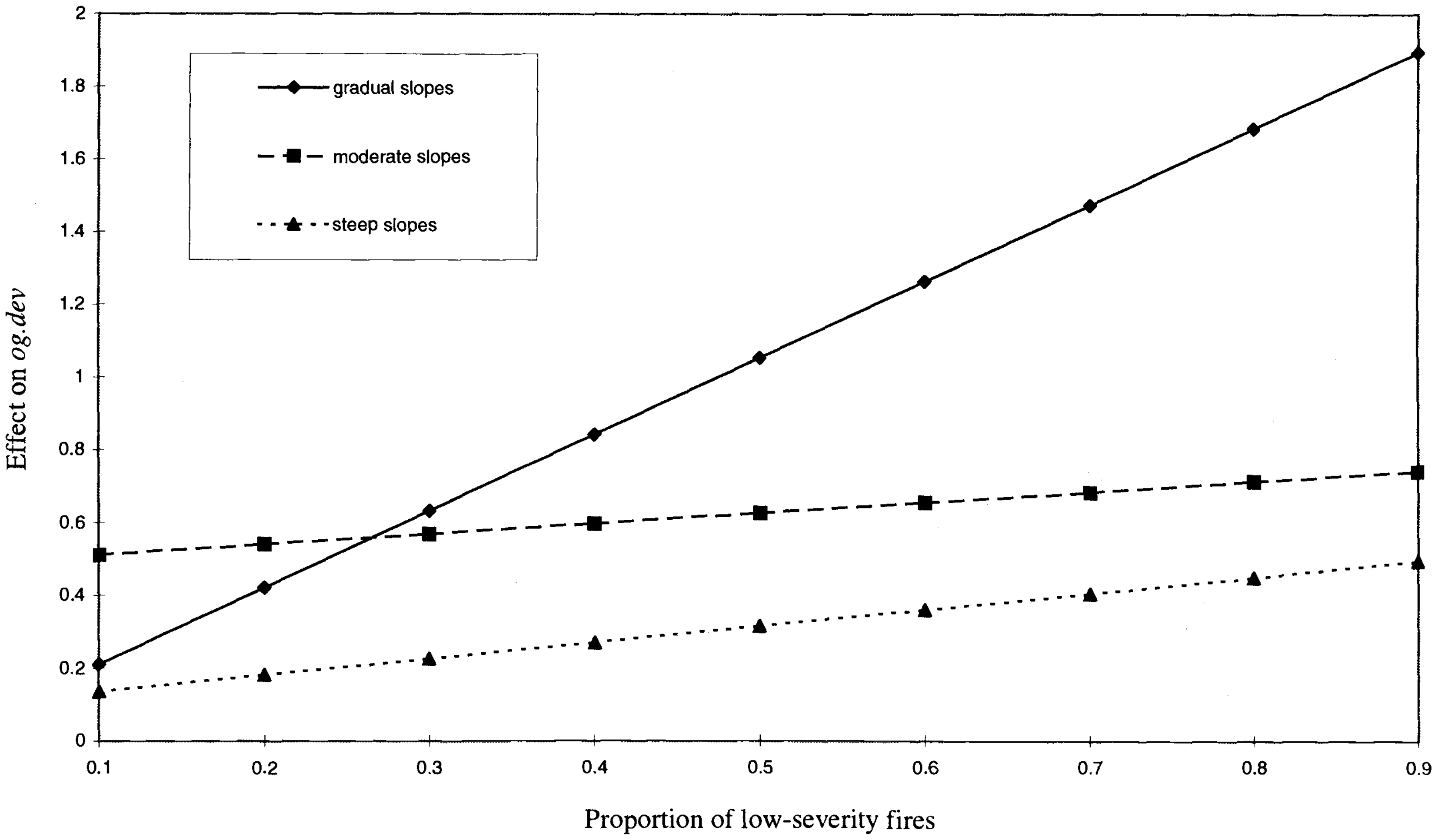
og.dev	Old-growth development
mature.stx	Mature structure
snag.noshtol	Big snags without shade-tolerants
snag.shtol	Big snags with shade-tolerants
shtol	Dense, shade-tolerant dominated

Table 5.13. Regression model for the "Old Growth Development" variable, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northeasterly aspect. Slope steepness is treated as an indicator variable where gradual slopes represent the reference condition. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-0.6572	0.4477	0.1460	(-1.5347, 0.2203)
Prop.low	2.1047	0.4393	0.0000	(1.2437, 2.9657)
Yrs.hisev	0.0016	0.0006	0.0059	(0.0004, 0.0028)
Yrs.regen	0.0022	0.0008	0.0079	(0.0006, 0.0038)
Elevation	-0.0007	0.0003	0.0296	(-0.0013, -0.0001)
Northeastness	-0.2269	0.0960	0.0206	-0.4151, -0.0387)
Moderately Steep	0.4823	0.3115	0.1255	(-0.1282, 1.0928)
Very Steep	0.0915	0.3433	0.7436	(-0.5814, 0.7644)
Prop.low:Moderately Steep	-1.8176	0.6095	0.0038	(-3.0122, -0.6230)
Prop.low: Very Steep	-1.6578	0.7436	0.0286	(-3.1153, -0.2003)

$R^2 = 0.52$, $F(9, 80) = 9.80$, $p = 0.0000$

Fig. 5.13. Interaction plot of the predicted effects of slope steepness and the proportion of low-severity fires on the "Old Growth Development" variable.



development was generally more rapid on more gradual slopes. Stands at lower elevations, and on warmer, more gradual slopes experience better growing conditions in the study area, and so development of stand basal area and complexity might be expected to be more rapid.

Stands with high values for "Mature Structure", where mean diameter was high but the range of Douglas-fir sizes and overall tree density were low, were negatively associated with *yrs.hisev* but positively associated with *yrs.regen* (Table 5.14). Such stands, likely in the transition between stem exclusion and understory reinitiation phases of stand development (Oliver and Larson 1990), had not experienced a fire with Douglas-fir regeneration recently enough to have higher density and lower mean diameter. However, the period of stand development (i.e., *yrs.hisev*) had not been long enough for non-fire disturbance and mortality processes to have caused much establishment of smaller diameter classes. Stands with the lowest values for *mature.stx* had experienced a cohort-initiating fire recently, but had not experienced a stand-replacing fire for a very long time, such that they consisted of both small and large diameter classes. Since smaller diameter cohorts are generally present in greater abundance, this resulted in low mean diameter and high Douglas-fir diameter range and total density. Topographic variables were not significantly associated with the Mature Structure variable (Table 5.14).

The stand structure complex variable, "Big Snags Without Shade-tolerant Trees" (*snag.noshtol*), was high for stands with a low proportion of basal area attributed to shade-tolerant species, and a high density of large snags. High values of *snag.noshtol* were found in stands that had experienced a cohort-initiating fire recently (Table 5.15).

Table 5.14. Regression model for the “Mature Structure” variable, as a function of fire history and topographic variables.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-0.9270	0.3234	0.0052	(-1.5609, -0.2931)
Yrs.hisev	-0.0019	0.0009	0.0407	(-0.0037, -0.0001)
Yrs.regen	0.0104	0.0013	0.0000	(0.0079, 0.0129)

$R^2 = 0.41$, $F(2, 87) = 29.64$, $p = 0.0000$

Table 5.15. Regression model for the "Big Snags Without Shade-Tolerant Trees" variable, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northeasterly aspect. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	1.6945	0.1518	0.0000	(1.3970, 1.9920)
Prop.low	-0.4620	0.3403	0.1783	(-1.1290, 0.2050)
Nfhisev.ratio	-0.4175	0.1421	0.0043	(-0.6960, -0.1390)
Yrs.regen	-0.0011	0.0006	0.0837	(-0.0023, 0.0001)
Prop.low:Nfhisev. ratio	-0.7472	0.3178	0.0211	(-1.3701, -0.1243)
Northeastness	-0.2074	0.0659	0.0023	(-0.3366, -0.0782)

$R^2 = 0.42$, $F(5, 83) = 4.83$, $p = 0.0006$

Such fires were likely to kill some overstory trees, creating large snags, and may have killed shade-tolerant trees preferentially over Douglas-fir. In the study area, shade-tolerant species (e.g., western hemlock, western redcedar, Pacific silver fir (*Abies amabilis*)) are the least fire-resistant due to thin bark and shallow root systems (Minore 1979). High values of *snag.noshtol* were also found in stands that had experienced either many low-severity fires or few moderate-severity fires, as suggested by the interaction between *prop.low* and *nfhisev.ratio* (Table 5.15, Fig. 5.14). Too few fires would not have created many large snags, unless the fires were of moderate severity. Too many moderate severity fires would not have allowed many trees to become large enough to form large snags. Topographic variables were less important influences, with the exception of northeastness (Table 5.15). *Snag.noshtol* was higher for sites on drier slope aspects, for reasons discussed for the SHTOL.ba and BIGSNAGS regression models.

Stands with both a high density of large snags and a large proportion of shade-tolerant basal area (i.e., *snag.shtol*) occurred where there had been low fire frequency since the last high-severity fire (Table 5.16), probably because low and moderate severity fires in such stands kill a relatively high proportion of shade-tolerant species. It is likely that stands with high values for *snag.shtol* had many large snags resulting from non-fire disturbance processes. Such stands were also likely to have experienced a cohort-initiating fire recently if fire severity was generally low, or to have experienced the most recent cohort-initiating fire a long time ago if fire severity was generally moderate or high (Table 5.16, Fig. 5.15). This interaction suggests that, in the short term, low-severity, early-seral-cohort-initiating fires may enhance large snag density and shade-tolerant basal area, while moderate- and- high-severity, early-seral-cohort-initiating fires reduce the

Fig. 5.14. Interaction plot showing the predicted effects of the proportion of low-severity fires and fire frequency on the *snag.noshtol* variable.

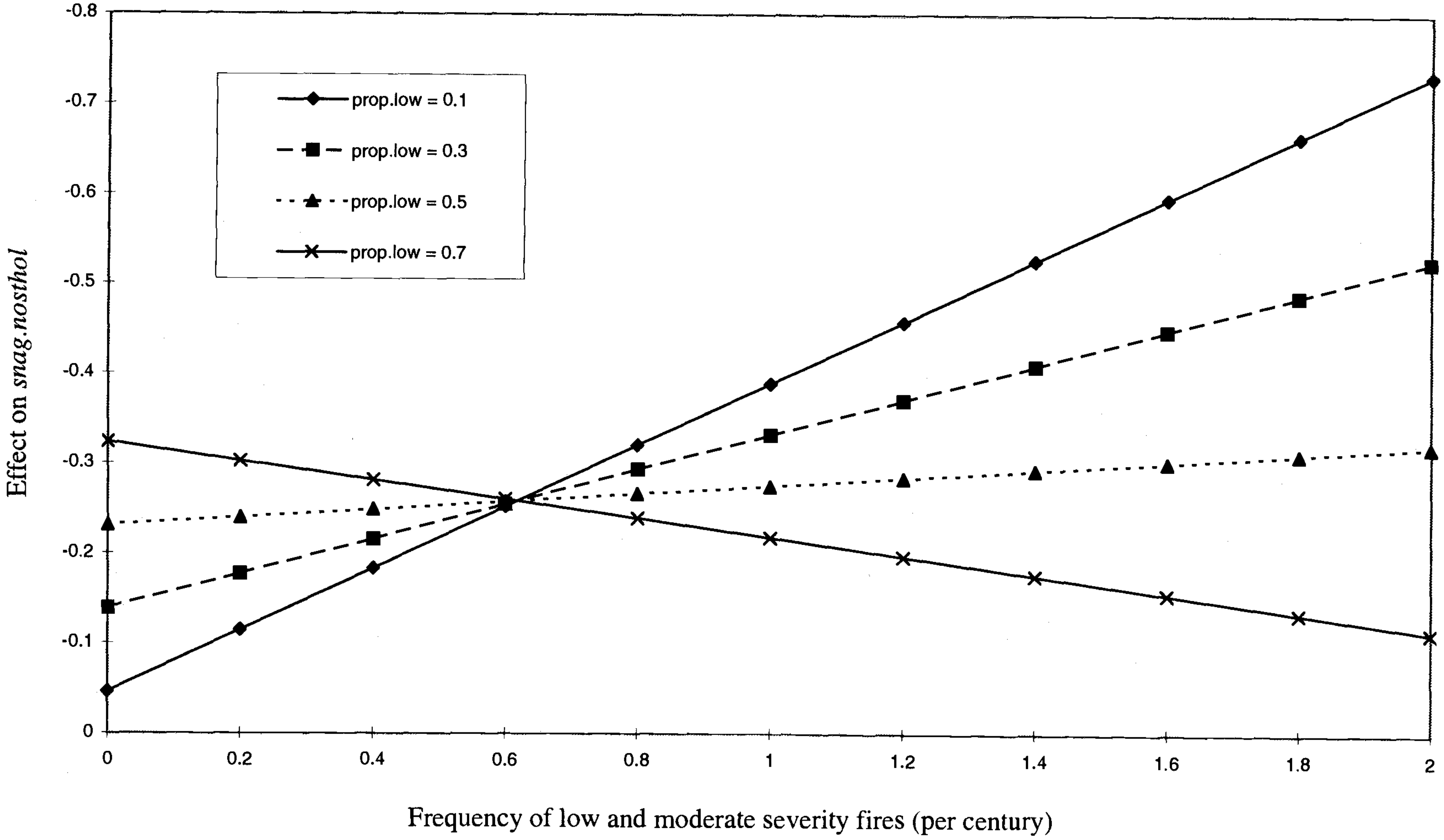
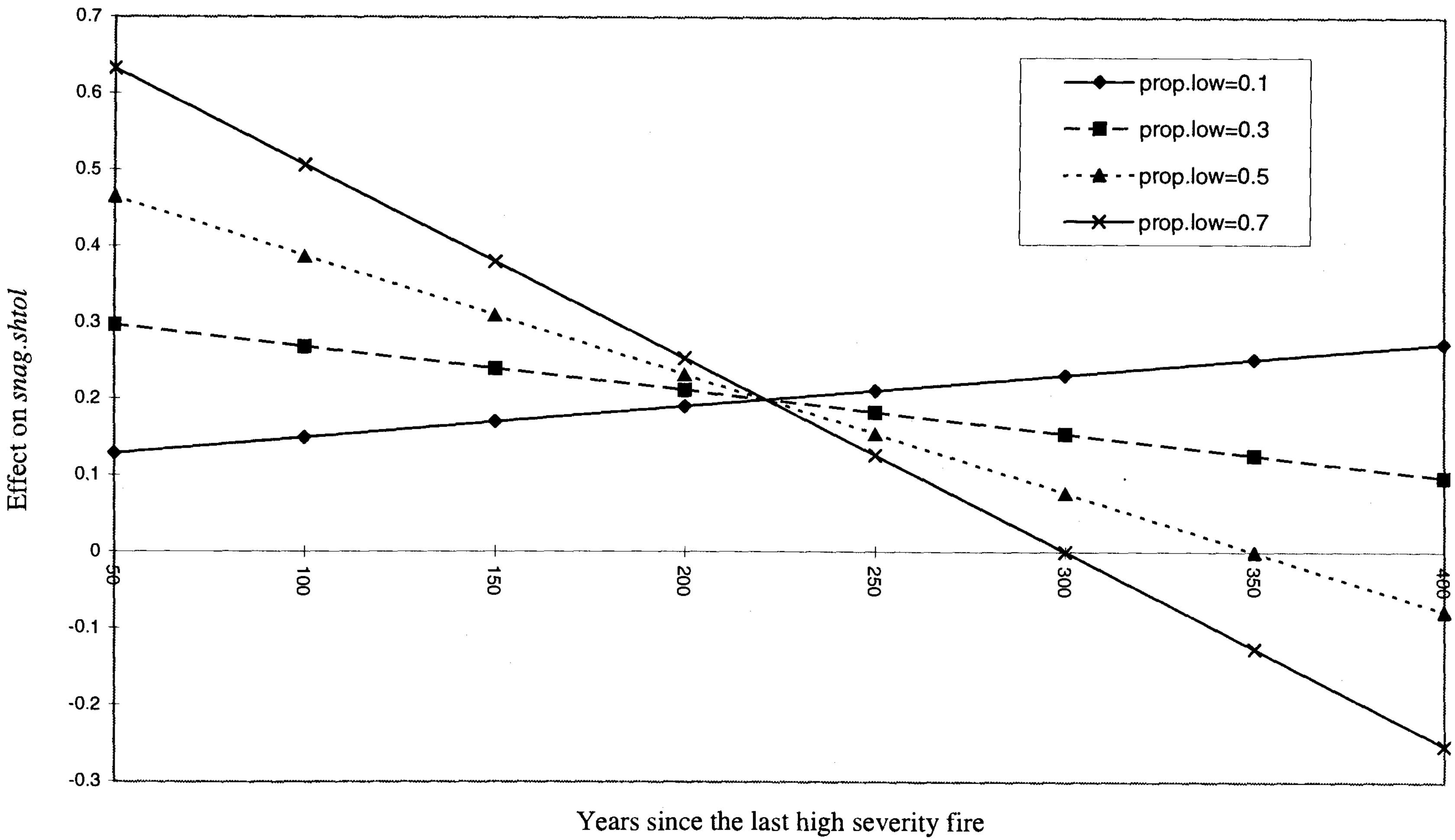


Table 5.16. Regression model for the "Big Snags With Shade-Tolerant Trees" variable, as a function of fire history and topographic variables. A colon between variables indicates an interaction term.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-0.4406	0.7963	0.5685	(-2.0013, 1.1201)
Prop.low	1.0845	0.5193	0.0399	(0.0667, 2.102)
Yrs.hisev	-0.0007	0.0021	0.7475	(-0.0048, 0.0034)
Yrs.regen	-0.0009	0.0016	0.5853	(-0.0040, 0.0022).
Nfhisev.ratio	-0.3132	0.1390	0.0270	(-0.5856, -0.0408)
Prop.low: Yrs.hisev	-0.0049	0.0027	0.0752	(-0.0102, 0.0004)
Elevation	-0.0005	0.0008	0.5343	(-0.0021, 0.0011)
Elevation: Yrs.hisev	3.44e-06	NA	0.0982	NA

$R^2 = 0.42$, $F(7, 80) = 8.14$, $p = 0.0000$

Fig. 5.15. Interaction plot showing the predicted effects of the proportion of low-severity fires and number of years since the last fire with regeneration on the *snag.shtol* variable



potential for stands to have both many large snags and an important overstory component of shade-tolerant species. *Snag.shtol* was positively associated with the number of years since the last high-severity fire because older stands were more likely to have developed large snags from gap formation processes that, in turn, liberated "growing space" for regeneration of shade-tolerant species. The association between *snag.shtol* and *yrs.hisev* was strongest for sites at higher elevations, where the potential for canopy dominance by western hemlock and Pacific silver fir was greatest. For this reason, *snag.shtol* increased with increasing elevation for stands at least 150 years old (Fig. 5.16). This relationship was reversed for young stands.

The variable describing stands that were "Dense, Shade-Tolerant Dominated" (i.e., *shtol*) was negatively associated with *yrs.hisev*, but positively associated with *yrs.regen* (Table 5.17). This relationship is similar to that for the *mature.stx* complex variable, and describes a similar stage of successional development, in transition between stem exclusion and understory reinitiation phases. However, sites with high values for *shtol* were also associated with more mesic, snowy environments at higher elevations and on more north-facing slopes. In such environments, shade-tolerant tree species may dominate the post-fire regeneration cohort, forming dense, shaded stands with high basal area resulting from a large number of moderately large trees.

Fig. 5.16. Interaction plot showing the predicted effects of elevation and number of years since the last high severity fire on the *snag.shtol* variable

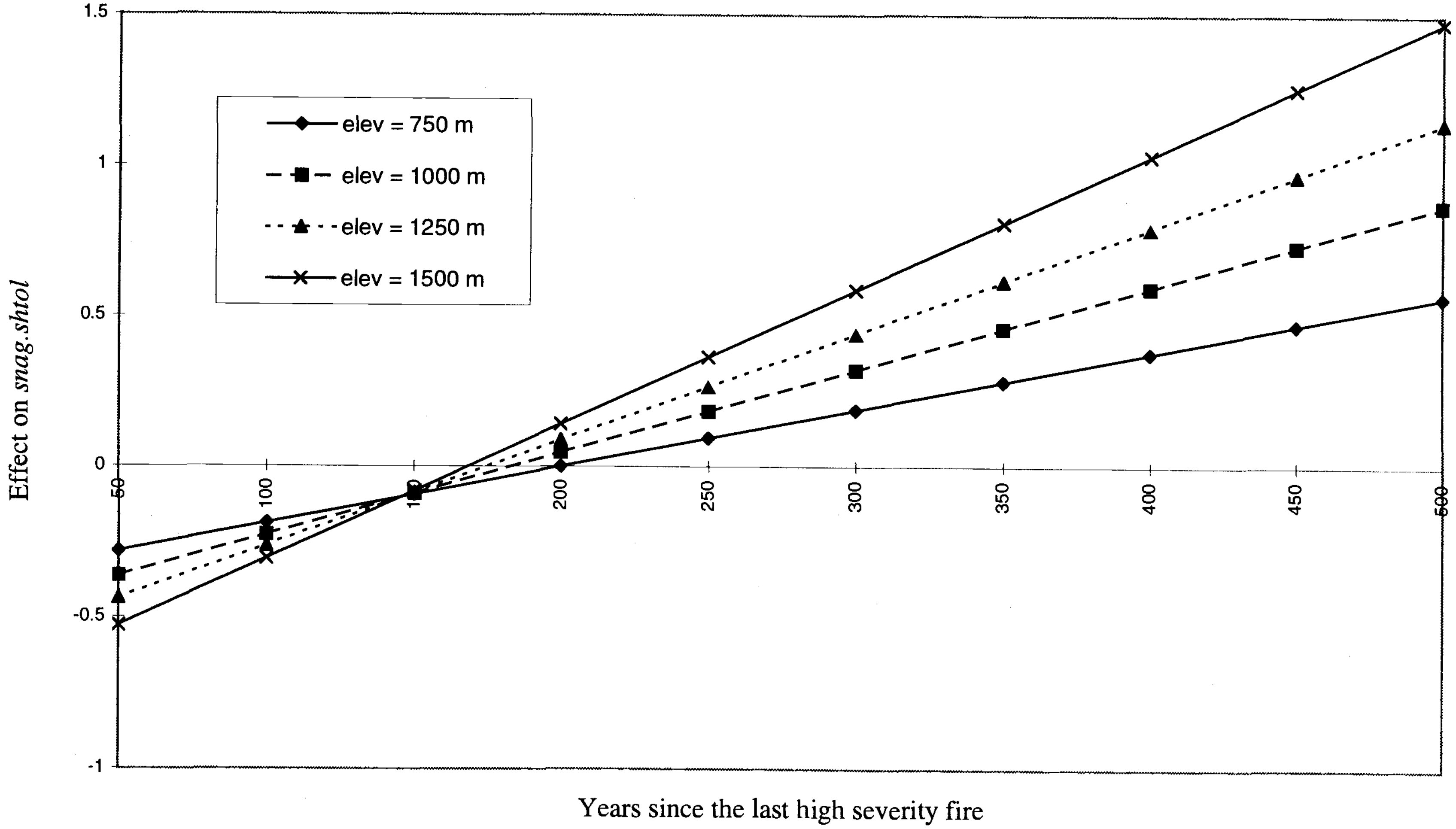


Table 5.17. Regression model for the "Dense, Shade-Tolerant Dominated" variable, as a function of fire history and topographic variables. Slope aspect has been linearized using a cosine transformation to a variable where high values indicate a northerly aspect.

Variable	Coefficient	Std. Error	P-Value	95% C.I.
Intercept	-1.1818	0.5123	0.0235	(-2.1859, -0.1777)
Yrs.hisev	-0.0022	0.0008	0.0082	(-0.0038, -0.0006)
Yrs.regen	0.0040	0.0012	0.0011	(0.0016, 0.0064)
Elevation	0.0013	0.0005	0.0071	(0.0003, 0.0023)
Northness	0.4493	0.1356	0.0014	(0.1835, 0.7151)

$R^2 = 0.30$, $F(4, 83) = 4.83$, $p = 0.0000$

5.4. General Discussion

5.4.1. Development of Stand Structure over Successional Time

The number of years since the last high-severity fire was an important predictor for nearly all descriptors of stand structure. For the two stand structure descriptors where *yrs.hisev* was not a significant predictor (i.e., BA.tot, *snag.noshtol*), *yrs.regen* was important. Clearly, the temporal position of a stand along its successional trajectory is a major influence.

Some of the observed relationships between stand structure and successional time (i.e., *yrs.hisev*) differed from what I had anticipated (Fig. 5.2). I observed SHTOL.ba and BIGDF.dens to increase linearly with *yrs.hisev*, although I had hypothesized an S-shaped curve. This relationship was complex for BIGDF.dens, where *maxFI.nlow* was found to be a significant predictor, since stands with a low *yrs.hisev* tended to have a high *maxFI.nlow*, while for stands with a high *yrs.hisev*, *maxFI.nlow* often equals *yrs.hisev* since the maximum interval is the most recent one (Table 5.4). Including this relationship, the response of BIGDF.dens to *yrs.hisev* was nonlinear such that the rate of BIGDF.dens increase was greater after 200 years, which still did not match the hypothesized relationship (Fig. 5.2). The regression model for BA.tot, which was expected to exhibit an S-shaped response to *yrs.hisev*, included a positive linear response to *yrs.regen* and no relationship with *yrs.hisev*.

The standard deviation of diameters was fitted with a second-order polynomial response to *yrs.hisev* that approximates the hypothesized S-shaped curve (Figs. 5.2, 5.3). The U-shaped response of BIGSNAGS, fit with a third-order polynomial, also approximated the hypothesized relationship, although large snag density did not increase nearly as rapidly after 200 years as I had expected. Forests may not regain the large snag component of young, post-fire stands through non-fire disturbance processes for several centuries, or until another high-severity fire occurs.

These interpretations should be viewed with caution, due to inherent limitations of the chronosequence approach and the low number of sites with *yrs.hisev* less than 100 years, between 200 and 350 years, or over 500 years. These are time periods when widespread, high-severity fires have been regionally very infrequent (Chapter Four). Although some differences in site history and physical environment have been controlled in this study by including representative variables in regression models, many differences between sites were likely not controlled for (e.g., climate-driven differences in post-fire regeneration that may have been mediated at some sites by local environmental conditions), and the main assumption of the chronosequence approach, that differences in stand environment and history are controlled for, violated (Spies and Franklin 1991).

More serious problems are presented by the poor representation of stand ages along the chronosequence. Only two sites had *yrs.hisev* of less than 100 years. A long-term study of 20 natural young and mature stands in the Washington and Oregon western Cascades showed that old-growth structural development is most rapid for the first 60 to 80 years, followed by a period of gradual increase (Acker et al. 1998). Also, the low number of sites with *yrs.hisev* between 200 and 350 years is problematic because all of the upper inflection points in hypothesized S-shaped curves occurred during this period (Fig. 5.2). If stand structure variables did follow S-shaped trends over successional time, these may well not have been detected.

5.4.2. Relationships between the Physical Environment and Stand Development Pathways

Stands of the same age, and of the same general fire history, were observed to have different structures. Much of this variation was explained by differences in simple topographic variables. Differences in elevation, slope aspect, slope position, and slope steepness reflect underlying spatial patterning of factors influencing tree growth, regeneration, mortality, and decomposition. Such factors include: sunlight availability, temperature, snowpack, length of the growing season, precipitation, soil moisture, relative humidity, soil depth, and nutrient availability.

The strong influence of wet aspects and high elevations on the relative dominance of shade-tolerant tree species is profoundly important for shaping the structure of forest stands. Detailed study of two sites within the study area, at the transition between the Western Hemlock and Pacific Silver Fir forest series, found little tree regeneration of any species beneath canopies where western hemlock was a major component (Stewart 1986a). For hemlock-dominated stands, regeneration was limited to canopy gaps that did not form in large numbers for 300 - 400 years. Lower tree regeneration and forest forb cover were also observed under hemlock canopies in southeast Alaska (Alaback 1982). Shade-tolerant tree species can occupy a stand at higher densities and continue to grow larger, shading out the understory and resulting in high density (for their age) stands with high basal area, little structural heterogeneity, and few very big or very small trees. Where shade-tolerant species occupy the overstory, they may inhibit the development of a subcanopy layer by forming a dense upper canopy, and so reduce vertical heterogeneity. Understory composition might be limited to the most shade-tolerant herbaceous species. Higher basal areas of shade-tolerant species on wetter sites were also observed in a regional study of 196 Douglas-fir stands in Washington and Oregon (Spies and Franklin 1991).

Wet aspects also had lower stand basal area, density of large Douglas-fir trees, large snag density, standard deviation of diameters, *snag.noshtol*, and *og.dev*. The development of large tree sizes, multiple hortizontal and vertical strata, and large snags and logs, characterizing typical old-growth structure for a variety of ecosystems (Franklin et al. 1981, Vora 1994, McCarthy and Bailey 1996), appears to occur at a slower rate on moist, snowy sites. However, the tendency for these environments to experience less frequent fires (Chapter Four) may counteract this effect, and help to explain why "classic" old-growth is often found in such locations. Spies and Franklin (1991) observed that the density of large Douglas-fir decreased with increasing moisture in the Oregon Coast Range, perhaps because they included sites at the eastern margin of the Sitka Spruce Zone, but did not find this effect for the Cascades. In contrast to this study, they found tree diameter variation to be highest in moister stands.

Old-growth development has generally been slowest on steeper slopes, wetter aspects, and higher elevations. Such sites represent the harshest conditions for Douglas-fir establishment and growth in the study area, due to cold temperatures, persistent snowpack, less sunlight for photosynthesis, and shallow, unstable soils. Higher Douglas-fir diameter growth, basal area, and volume were found for southern aspects on 14 stands from 55 to 121 years old in the general region encompassing the study area, after accounting for understory and residual tree density (Zenner 1995). These results imply that sites with better growing conditions for Douglas-fir are capable of achieving old-growth structures more rapidly. For montane forests of the Colorado Front Range, Douglas-fir growth and regeneration are favored on north aspects, and so similarly aged stands on north slopes have greater tree densities and basal areas than south aspects (Hadley 1994). Caution must be exercised in extrapolating the results of this study to other regions with tree species in common, where relationships between topography and climatic factors suitable for tree growth and regeneration may differ.

It is unexpected that slope position played no significant role in influencing stand structure, as measured in this study. Slope position has greatly influenced fire frequency and severity for the same study area (Chapter Four). A finer-scale look at stand structure that included understory species composition, or the relative dominance of riparian tree species, such as red alder or western redcedar, would likely find slope position to have been an important influence.

I have shown that, for the Blue River study area, some pathways of stand structure development are associated more with certain topographic environments than with others. The most important distinction may be for post-fire stands where early dominance or co-dominance is achieved by hemlock or noble fir. Such stands differ greatly from stands where Douglas-fir dominates the overstory. At mature stages of development in hemlock or true-fir-dominated stands, there is more basal area and a greater density of trees, but individual tree sizes are not as large. Such stands are shadier, with less horizontal and vertical structure (Stewart 1986a). These differences can extend to the old-growth stage. With a lower Douglas-fir component, there are fewer extremely large trees that contribute to stand complexity, and ultimately become large snags and logs.

5.4.3. Importance of Low and Moderate Severity Fires for Defining Stand Structure

Overwhelming evidence that many old-growth stands of the western Oregon Cascades have survived multiple low-to-moderate intensity fires (Means 1982, Stewart 1986a,b, Teensma 1987, Morrison and Swanson 1990, Chapter Four) has led to the hypothesis that such fires added structural complexity by initiating new cohorts of shade-tolerant or shade-intolerant tree species, and may have been responsible for maintaining characteristic old-growth structures now present on the landscape (Morrison and Swanson 1990, Spies and Franklin 1991). Spies and Franklin (1988) propose that when such fires burned in young stands, many Douglas-fir trees were killed and new cohorts of Douglas-fir established, but that these same fires caused less overstory mortality in old-growth stands, initiating an understory cohort of shade-tolerant species.

I observed the frequency of low- and- moderate-severity fires to significantly influence forest structure, as measured in several ways. Low-severity fires were important for creating variability in tree diameter sizes, reducing tree density and allowing larger trees to grow in a shorter time (i.e., a "thinning effect"), and creating stand structures with many large snags and few overstory shade-tolerant trees. Since higher variability in tree size, lower tree density, larger trees, higher basal area, and higher large snag density are all important features of old-growth stands in the Pacific Northwest (Franklin et al. 1981, Spies and Franklin 1988, Spies and Franklin 1991) and elsewhere (McCarthy and Bailey 1996, Timoney and Robinson 1996), it is arguable that the occurrence of non-stand-replacing fires has fostered old-growth development in the study area. Interestingly, suggested and experimental efforts at accelerating the development of old-growth characteristics in highly stocked plantations often involve thinning strategies that may have effects on residual tree growth and subsequent tree regeneration similar to low-severity wildfires (McComb et al. 1993, Vora 1994, Spies and Franklin 1996, Barbour et al. 1997).

Abrams and Scott (1989) have proposed that disturbances may accelerate succession by killing pioneer tree species and creating conditions favorable for growth and/or regeneration of late-successional species. They demonstrated such "disturbance-mediated accelerated succession" for two forest types in Michigan. Logging hastened the conversion of sugar maple forest to a northern white cedar community, and clearcutting followed by burning changed a jack pine forest to one dominated by hardwoods. The hypothesis that low-severity fires in old-growth forests of the Pacific Northwest might increase the shade-tolerant component of some forest stands by causing patchy overstory mortality (Spies and Franklin 1988) is another example of disturbance-mediated accelerated succession.

If the total basal area variable is considered a proxy for successional development, the results of this study for testing the above hypothesis are mixed. Low-severity fires have not generally resulted in higher shade-tolerant basal area. Since shade-tolerant tree species in the study area have relatively low fire resistance and occupy mainly the understory, which is most susceptible to damage from surface fires, one would expect a higher frequency of low-severity fires to have decreased total basal area for many stands. That they have not resulted in significantly lower basal area on average suggests that, in at least some stands, total basal area might be positively associated with the frequency of low- and- moderate- severity fires. The regression model for snag.shtol shows that, for some sites, fires which did not initiate enough Douglas-fir regeneration to be considered moderate severity might have contributed to higher shade-tolerant basal area. In mature and old-growth forests of the western Cascades, Douglas-fir seedlings do not often establish in canopy gaps with diameters less than 0.4 times the canopy tree height, while western hemlock seedlings survive and grow in gaps with diameters of 0.2 times the canopy tree height (Gray and Spies 1996). Patchy, low-severity fires creating small overstory gaps may facilitate the eventual establishment of shade-tolerant canopy trees, particularly if they reduce competition from surface vegetation (Gray and Spies 1997). Fires probably do not accelerate succession towards a shade-tolerant dominated canopy as often or as rapidly as non-fire disturbances which cause canopy gaps but allow advanced regeneration to survive, such as windthrow, catastrophic windstorms, or insect epidemics (Spies and Franklin 1988).

Alternatively, low- and- moderate-severity fires may slow succession towards shade-tolerant overstory tree species by killing hemlock, cedar, and true fir regeneration in the understory, and killing a high proportion of overstory trees of these species compared to Douglas-fir (Morrison and Swanson 1990, Spies 1997). Such fires would maintain a Douglas-fir-dominated, old-growth forest for a longer period of time. This would be analogous to the role of periodic fires in maintaining *Pinus* - *Quercus* forest by eliminating shade-tolerant species, such as *Acer rubrum*, *Fagus grandifolia*, and *Tsuga canadensis*, in Appalachian and northeastern U.S. forests (Little 1974, Abrams et al. 1995).

It is likely that low-severity underburns and fires that initiate patchy regeneration within old-growth forests play dual roles, in some cases accelerating succession by facilitating shade-tolerant regeneration and canopy accession, and in other cases retarding succession by killing shade-tolerant regeneration. Future studies might be able to identify which features of vegetation, environment, and disturbance regime make either of these alternatives more likely.

5.4.4. Conclusions

Forest structure is highly associated with stand age, but stand age is an insufficient predictor. Stands of a given age differ structurally according to landscape heterogeneity in environment and topography, and with the relative occurrence of low- and- moderate-severity fires. Stand structure is likely also influenced by many factors not measured in this study, including variation in: (1) legacy effects from the previous stand, including residual overstory trees, snags, surviving understory plants, seedbed, distribution of serotinous cones; (2) adjacent seed sources; (3) weather patterns following the stand-initiating fire; (4) variation in intensity and severity of the stand-initiating fire; (5) the history of non-fire disturbances, such as windthrow, *Phellinus* infections, and insect epidemics; (6) chance; and (7) climatic influences that may not be explained well by topography at the site level, such as cold air drainage, exposure to adiabatic east wind events, and precipitation. The first six of these factors have been used to explain multiple successional pathways in jack pine forest, where young stands of the same age had species assemblages more dissimilar than the same stand at different ages (Abrams et al. 1985). Many studies over diverse ecosystem types have found a range of plant communities for a given time since disturbance, suggesting multiple successional pathways (e.g., Abrams et al. 1985, Halpern 1989, Tausch et al. 1993, Fastie 1995, Myster and Walker 1997). Development of forest size structure at the stand scale may be analogous to the succession of plant species composition, in that multiple and diverse pathways occur over the landscape.

The interactions among forest structure, fire history, successional processes, and physical environment are complex. This study just scratches the surface. Future studies might include: a greater range of pertinent environmental predictors; description of the vertical component of stand structure; description of understory plant composition and structure; description of coarse woody debris; a more representative sample of stand ages for analysis of temporal stand development patterns; analysis of the influence of non-fire disturbances; gradient analysis of how variance in stand structure is partitioned among gradients of fire history and the physical environment in a multivariate sense; experimental analyses of physiological processes to determine causes for observed associations; and simulation modeling of disturbance processes and forest recovery over landscape scales. After such studies are completed, we will perhaps be able to understand how Douglas-fir forests of the recent past and present were formed.

Chapter 6. Conclusions

6.1. Fire History Methodology

1. Tree-ring-based fire history reconstructions are affected by error and uncertainty introduced over four sequential steps: (1) erasure of fire evidence by mortality, decomposition, and subsequent fires; (2) fire history sampling; (3) use of evidence collected from the sampled record to detect and date fires; and, (4) analysis of fire history data to describe fire regimes. It is important for fire history researchers to understand and be explicit about limitations of their ability to accurately reconstruct and describe fire history.

2. Fire history researchers should adapt their methods to the fire regime they seek to describe. To assert that study protocols for one regime type pertain to all others is misguided.

3. It is possible to use cross-dating for fire history studies of Douglas-fir forests in the western Oregon Cascades, although in my test sample it required 22 times the effort of a non-cross-dated, field-counted study. I was able to cross-date 87% of fire-scarred slab sections.

4. Field-counted fire history studies may underestimate the ages of fire scar and tree origin years. In my study, field-counted scar years on Douglas-fir were within 10 years of their true values for about 75%, and within 20 years for about 87%, of the observed cases.

Fires were estimated as having occurred from 1 to 16 years later than they actually did, and, for one of four sites, a "fire" that never occurred was erroneously reconstructed. However, errors in fire dating and fire frequency estimation were small unless an incorrect number of fires was reconstructed.

5. Results from my test study suggest that most errors associated with field-counted studies in Douglas-fir forests of the western Cascades arise from counting errors on insufficiently prepared stump surfaces. Relatively few errors were found using non-cross-dated counts on well-prepared slabs. The average error in scar and origin year estimation was 1.47 and 1.24 years, respectively. Errors on prepared slab surfaces were equally likely to be over-estimates or under-estimates. Missing and double rings were uncommon among Douglas-fir trees of the study area.

6. I recommend that future fire history studies in the western Oregon Cascades employ cross-dating, or at least begin with a cross-dated pilot study to quantify error associated with not cross-dating, and to establish a master tree-ring chronology that might later be used to calibrate tree-ring counts in the field. However, fire history reconstruction is fraught with much subjectivity, error, and uncertainty, even when cross-dating is employed. Errors associated with failure to adequately prepare slab surfaces and/or cross-date, while significant, may not be as great as errors from other sources, such as an inability to consistently distinguish fire scars from other types of scars, or to detect many low-severity fires.

6.2. Fire History and Fire Regimes of the Blue River Study Area

7. I reconstructed 94 fire episodes for the 521-year period from 1475 to 1996. The average mean fire interval, Weibull median probability interval, and maximum fire interval of 4-ha sites over that period were 97 years, 73 years, and 179 years, respectively. Excluding low-severity fires, these values were 197 years, 91 years, and 291 years, respectively. The NFR for this period was 78 years for all fires, and 102 years excluding low-severity fires.

8. Fire frequency and pattern have changed over time as a result of: (a) climatic variability, (b) changing anthropogenic influences (e.g., Euro-American ignition sources, fire suppression), and (c) temporal patterns of fuel accumulation related to stand development. The period from ca. 1475 to ca. 1620 was characterized by widespread, high-severity fire; the period from ca. 1620 to ca. 1830 by reduced fire frequency, burned area, and fire severity; the period from ca. 1830 to ca. 1910 by higher fire frequency, burned area, fire severity, and reburn occurrence; the period from ca. 1910 to ca. 1940 by reduced fire extent and severity; and the period from ca. 1940 to the present by extremely low fire frequency, burned area, and fire severity (with the exception of prescribed fires in clearcuts). Patterns of temporal variation in fire regime were stikingly similar among 13 tree-ring-based fire history studies from west of the Cascade Crest, suggesting a strong climatic influence.

9. Fire frequency and severity patterns were associated with spatial variation in hillslope position, slope aspect, slope steepness, and elevation. Relationships between fire regime

and topographic variables were weakly significant, and consistent for different descriptors of fire frequency. Fire frequency was lower for higher elevations, lower slope positions, and more mesic slope aspects. Fire severity was lower for higher elevations, lower slope positions, more north-facing slopes, and more gradual slopes. The meaning of the variables used to describe fire severity, and their connection with variables used to describe fire frequency, is complex and scale-dependent.

10. Using topographic variables that represented patterns of climate and fire behavior to predict fire frequency, I defined and mapped three fire regime classes for the study area. These seemingly discrete classes were delineated within a continuous, multidimensional fire regime gradient. Spatial variation in fire regime occurred over multiple, nested scales. At the within-site scale, plots 200 m upslope from other plots, and sites on upper hillslope positions, experienced more frequent, higher severity fires. At the between-site scale, sites on different slope aspects and slope steepnesses experienced different fire regimes. More slope aspects were associated with less frequent, lower severity fires. At the study area scale, fires were less frequent and possibly less severe at higher elevations.

6.3. Influences of Fire History and Topography on Forest Stand Structure

11. The number of years since the last high-severity fire was an important predictor for nearly all descriptors of stand structure. Clearly, the temporal position of a stand along its successional trajectory was a major influence. Most measured aspects of stand size structure increased over successional time, although this increase was not always linear. The density of large snags followed a U-shaped curve with increasing number of years

since the last high-severity fire. Forests may not regain the large snag component of young, post-fire stands through non-fire disturbance processes for several centuries, or until another high-severity fire occurs.

12. Stands of the same age, and of the same general fire history, were observed to have different structures. Much of this variation was explained by differences in elevation, slope aspect, slope position, and slope steepness. The strongly positive influence of wet aspects and high elevations on the relative dominance of shade-tolerant tree species has been profoundly important for shaping the structure of forest stands.

13. Development of old-growth stand attributes (i.e., high stand basal area, maximum tree diameter, variability of tree diameters, and density of large Douglas-fir trees) appears to have been slowest on steeper slopes, wetter aspects, and higher elevations. These results imply that sites with better growing conditions for Douglas-fir are capable of achieving old-growth stand structures more rapidly.

14. Low-severity fires were important for creating variability in tree diameter distriubtions, reducing tree density and allowing trees to grow to large size in a shorter time (i.e., a "thinning effect"), and creating stand structures with many large snags and few overstory, shade-tolerant trees. Low-severity underburns and fires that initiated patchy regeneration within old-growth forests likely played dual roles in stand development, in some cases accelerating succession by facilitating regeneration and

canopy accession of shade-tolerant species, and in other cases retarding succession by killing shade-tolerant regeneration.

15. The interactions among forest structure, fire history, successional processes, and physical environment are complex. Development of forest size structure at the stand scale has likely included multiple and diverse pathways occurring over the landscape. Further studies will be necessary to understand how Douglas-fir forests of the recent past and present were formed.

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