AN ABSTRACT OF THE THESIS OF

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Title: Temporal and Spatial Variability of Historic Fire Frequency in the Southern Willamette Valley Foothills of Oregon.

Abstract approved: ______________________________

John C. Tappeiner II

A crossdated fire history was reconstructed for a 1562 km^2 area in the southern Willamette foothills of Oregon, using fire scars and tree origin years from twelve sites. The purpose of this study was to determine fire frequency for each site and to quantify temporal and spatial variability of fire frequency. Fire frequency distributions were related to climate history and the patterns of human settlement, and compared with other regional fire histories.

Dendrochronological methods were used to assign calendar years to fire scars and pith dates. General Land Office maps and surveyor notes were used to determine site and study area level changes in vegetation and Euro-American land use patterns. Climatic influence on fire over time was determined using superposed epoch analysis.

Forty-three fire dates were reconstructed for the 290 year period from 1700 to 1990. The minimum and maximum fire intervals were two years and 191 years; the study area mean fire return interval was 49 years. Over two-thirds of all site level fire intervals were less than 40 years, and less than one-fifth were longer than 80 years.

Fire frequency differed between the east and west sides of the Willamette Valley. West side sites experienced more frequent fires on average than the east side sites: 57% of all west side site fire intervals were less than 20 years, while 68% of all east side site fire intervals were less than 40 years. Both human and vegetative factors were potentially influencing the fire regimes of each side of the valley. West side sites were within, or adjacent to, woodland forest cover types and were closer to earlier and more intensive Euro-American settlement.

Fire frequency throughout the study area did not change substantially over time. Fire occurred every decade or so, with occasional longer fire intervals, until after 1905, at which time fire occurred roughly every 15 to 20 years until 1979. Unlike other regional fire history studies, this study found no statistically significant differences in the number of fires by time periods of varying land use and climate. When the rule set for defining fire events was modified, fire frequency could be shown to be weakly significantly associated with these time periods. This indicates that methodology can appreciably influence the results of fire history reconstruction. Moreover, the sample size of trees dating from the 1700s was small, so the estimate of fire frequency for the 1700s is uncertain.

Fire frequency was not related to drought over the whole study period (1700-1990), but fire was more likely to occur three years following a drought year over the period from 1700 to 1849, whereas after 1850, fire was significantly associated with drought years. Fire occurrence was as expected (but not significantly so) during the period 1700 to 1800, slightly higher than expected (but not significantly) for the period 1800 to 1850, higher than expected (but not significantly) after 1850, and lower than expected (but not significantly) after 1925. Several hypotheses could explain these findings: (1) the relationship between wildfire and drought is different during cooler, wetter periods than warm, dry periods; (2) Native Americans influenced fire during the 1700-1849 period, obscuring the relationship between fire and drought; (3) European settlement of the Willamette Valley in the mid to late 1800s increased the occurrence of fire and enhanced the effects of a warming climate, and (4) fire suppression after 1920 resulted in a decrease in fire occurrence.

More sampling of older stumps in the Willamette Valley foothills would likely lend credibility to the record of fire frequency before 1800 and would increase the sample depth for use in the Superposed Epoch Analysis of the fire-drought relationship. Sampling along transects extending from the foothills into the Cascades and Coast Ranges would foster a better understanding of the spatial scope to which Native American burning influenced forests adjacent to the valley floor.

Temporal and Spatial Variability of Historic Fire Frequency in the Southern Willamette Valley Foothills of Oregon

by
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APPROVED:

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Dean of the Graduate School

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

Danielle Robbins, Author

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Temporal and Spatial Variability of Historic Fire Frequency in the Southern Willamette Valley Foothills of Oregon.

1. Introduction

Forest fires were historically important in the forests of the Pacific Northwest (Agee 1993). Fire affects the composition and structure of forests, in turn affecting wildlife habitat and watershed processes (Morrison and Swanson 1990). However, in the Willamette Valley of western Oregon, fire suppression coupled with intensive timber management during most of the 20^{th} century, has significantly altered these forests from the "scattered timber" that general land office surveyors reported in the mid 1850s (prior to substantial settlement of the valley) to the closed canopy Douglas-fir forests of today. It is clear that the structure (and potentially the composition) of forests has changed over the last 150 years, although the disturbance regime that created such structure has been minimally quantified for the Willamette Valley foothills.

The role of humans in the historic fire regime(s) of the Willamette Valley is debated. Many studies have examined the extent of Native American influence over the landscape (Johannessen 1971, Boyd 1986, Knox 2000, Whitlock and Knox 2002, and Zybach 2003), yet different stories have emerged from these studies. Native Americans may have burned only in the prairies of the valley floor but may have participated in landscape-level burning of the forests too.

Several fire histories have been done in the Oregon Cascades and Coast Ranges (including Morris 1934, Morrison and Swanson 1990, Connelly and Kertis 1991, VanNorman 1998, Weisberg 1998, and Agee and Krusemark 2001), although only two studies specifically evaluated fire in the Willamette Valley foothills (Weisberg unpub. 1996 and Impara 1997). Weisberg (unpub. 1996) and Impara (1997) did not use dendrochronological methods however, as were used in this study, thus results vary somewhat.

Today, much of the southern Willamette Valley foothills are in the wildland urban interface. The checkerboard pattern of Bureau of Land Management (BLM) and private ownership has produced a very patchy landscape, prompting forest management that involves multiple stakeholders with varying objectives. Increased tree stocking can contribute to increased fuel loads, which *may* make these altered forests more susceptible to stand-replacing fire. Therefore, forest management and fire are key issues in the valley foothills.

Fire history provides baseline information to governing agencies for implementation of local and national fire management plans. Fire regime information is also important because it is used for management objectives such as determining type and timing of restoration and fuels reduction projects and for the prioritizing of these projects. However, continued alteration of the valley foothills landscape by logging, agriculture, urbanization, and fire suppression is making it increasingly difficult to ascertain the historical conditions (stand composition and structure) of the foothills forests.

The fire regime for the foothills could be different from that of the adjacent mountain ranges due to topographic and vegetative dissimilarities, local weather, and patterns of human influence. Fire regimes are controlled by moisture and temperature gradients, ignition patterns, and vegetation attributes (fuel characteristics and fire adaptations) (Agee 1990); fire behavior is controlled by the above components as well as topography. I expected to find a low to moderate severity fire regime, which is different than the moderate to high severity fire regime of higher elevations.

Additionally, due to changes in climate, specifically drought, and land use over time, I expected fire occurrence to have changed accordingly if climate or land use (or both) were influencing fire. Since humans have been a factor on the landscape for many centuries, I expected that fire occurrence was particularly related to land use change.

This thesis describes and evaluates historic vegetation and land use patterns, fire history reconstructed from tree rings, and climatic influence on fire. The objectives of this study were:

1. to determine the fire frequency of each site and the study area,
2. to quantify temporal and spatial variability of fire frequency,
3. to examine and infer possible causes of variability in fire frequency, and
4. to compare these findings with other regional fire histories.

In order to accomplish the objectives, I used historic vegetation and timber maps, General Land Office (GLO) surveyor's notes and maps, and constructed a crossdated fire history for the study area.

2. Methods

2.1 Description of Study Area—Current

The study area occupies 1562 km^2 of the southern Willamette Valley (SWV) in western Oregon (Figure 1). Western Oregon has a maritime climate with mild, wet winters and warm, dry summers. The average annual temperature and precipitation for the SWV (compiled from 1971-2000 at the Cottage Grove Dam climate station) are 11°C and 1270 mm respectively (obtained from Oregon Climate Service, Oregon State University in 2004).

The SWV foothills have an intermediate environment between the valley floor and the mountain ranges they flank. BLM-administered lands of these lower elevation forests have warmer, drier plant associations than typical higher elevation U.S. Forest Service-administered forests of western Oregon (McCain and Diaz 2002a). Plant associations allow a means to track and predict vegetation composition, structure, and response to disturbance (McCain and Diaz 2002). Association classification provides ecosystem managers knowledge of the plant and animal communities across the landscape. Plant associations in the study site locations were dry Douglas-fir, grand fir, and dry western hemlock. The major tree species in the Douglas-fir zone include Douglas-fir (*Psuedotsuga menziesii*), grand fir (*Abies grandis*), incense cedar (*Calocedrus decurrens*), and western hemlock (*Tsuga heterophylla*). All sites were located on silty clay loam soils (based on a GIS overlay of the sites with the Lane County soils survey map, 1987 (USDA Natural Resources Conservation Service 2004).

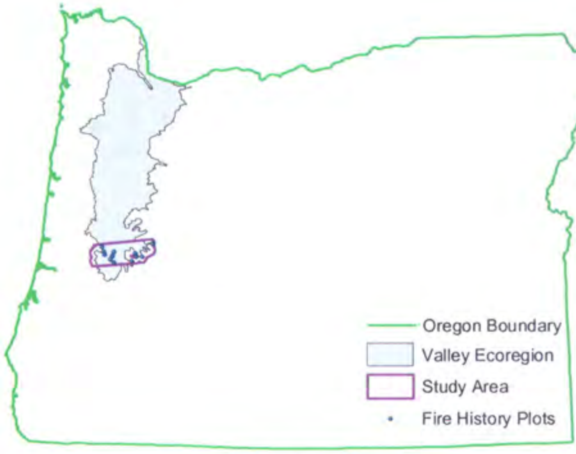

Figure 1. Location of fire history sites and Willamette Valley ecoregion.

The study was conducted using twelve 40 x 50m plots (hereafter called "sites") located on BLM forest land from site selection criteria detailed below. Seven plots were located on the Coast (west) side of the valley (Sites 1-7) and five plots were located on the Cascades (east) side (Sites 8-12). The study area was constructed in a geographic information system (GIS) by buffering the Willamette Valley ecoregion boundary line with one quarter township length (4828 meters) outward (away from the valley floor); this forms the east and west boundaries. The ecoregion buffer was bounded to the north and south by drawing in lines located within one quarter township length from sites (Figure 2). The Willamette Valley ecoregion represents one of several level III ecoregions defined for the state of Oregon by the U.S. Environmental Protection Agency. Ecoregions are "regions…identified through the analysis of the patterns and the composition of biotic and abiotic phenomena that affect or reflect differences in ecosystem quality and integrity" (Environmental Protection Agency 2003).

A quarter-township grid cell size was used for site selection (i.e. no sites were located within the same quarter-township). All sites were chosen based on inclusion within or proximity to the ecoregion boundary line and potential for older age classes (>100 years). Potential sites were chosen from a list, provided by the Eugene BLM office, of older-aged stands that had been clearcut within the last 15 years.

Each unit was visited and evaluated for feasibility of installing a site. Criteria included stump quality (the decomposition status of the majority of stumps), post harvest vegetation growth, and presence of an age class at least 100 years old. If there were multiple qualifying sites located within the same quarter-township, one site was chosen at random for plot-installation.

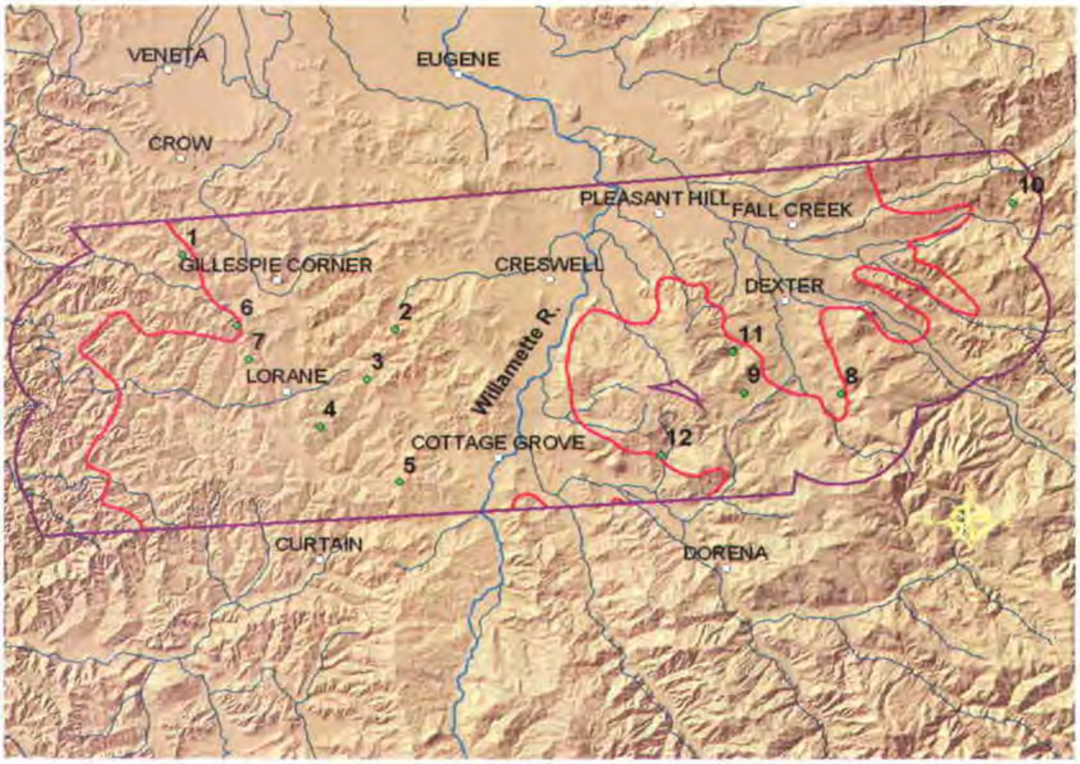

Figure 2. Location of fire history sites. Sites 1-7 are on the west side and Sites 8-12 are on the east side of the Valley (sites are green). The pink line represents the Valley Ecoregion boundary and the purple line in the study area, which a quarter-township buffer of the Ecoregion boundary. A hillshaded DEM shows the more-subdued topography of the west side as compared to the east side and shows the location of Willamette and Lorane Valleys (Lorane Valley is the small N-S oriented valley to the west of the Willamette Valley).

The west side has a more subdued topography than does the east side (Figure 2). West side sites, most of which are located within the ecoregion boundary, are in low-lying foothills somewhat separate from the adjacent Coast Range; east side plots are located in more-dissected, generally higher elevation foothills. The elevation range for all sites is 320 m (1050 ft) to 555 m (1820 ft) (Table 1). The average elevation is 420 m (1377 ft); 385 m (1262 ft) for the west side and 469 m (1539 ft) for the east side. In the Willamette Valley, elevation is strongly related to precipitation (Taylor 1993). Elevation also governs temperature. The mean growing season for the valley is 150-180 days/year, while in the foothills (>244 m, >800 ft) it is only 110-130 days/year.

All cardinal-direction aspects are represented by at least one site, although most sites face NW or SW (Table 1). Sixty-seven percent (67%) of sites (8 plots) are located on a west-facing slope, and half of these are on northwest and half on southwest slopes (33% of all sites are on NW and 33% are on SW slopes). More sites are on south-facing (58%, 7 plots) than on north-facing (42%, 5 plots) slopes. Four of the five east side sites are south-facing, while four of the seven west side sites are north-facing. Slope percent ranged, for all sites, from 7% to 60% with an average slope of 26%.

Average annual precipitation for all sites was derived by overlaying sites with a PRISM model precipitation layer from Spatial Climate Analysis Service, OSU (1998). Average annual precipitation ranges from 127 cm to 147 cm (50 to 58 in); the west side averages 127 cm (50 in) and the east side averages 139 cm (55 in) (Table 1).

Three vegetation series are present in the SWV study area: *Tsuga heterophylla* (TSHE), *Pseudotsuga menziesii* (PSME), and *Abies grandis* (ABGR) (Table 1). TSHE series are the most common plant associations for the fire history sites (6 sites). The PSME series forests are dry and warm compared to the more moist TSHE associations, and have the highest plant diversity of all the associations. ABGR series forests are characteristically dry associations and have the second highest plant diversity on average (McCain and Diaz 2002a).

2.2 Determination of Environmental Characteristics

Site level elevation, aspect, slope (%), and vegetation association were determined in the field upon plot installation. A handheld global positioning system (GPS) unit was used to determine elevation. By evaluating remnant plants and surrounding stands, vegetation association was established using the local plant association guides for the area (McCain and Diaz, 2002 a/b). Cardinal-direction aspect was determined as follows: NE = 1-90°, SE = 91-180°, SW = 181-270°, and NW = 271-360°.

Average annual precipitation (cm) was determined by integrating the fire history sites GIS layer with a PRISM data GIS layer of precipitation from the Oregon Climate Service (Spatial Climate Analysis Service, Oregon State University). The precipitation data has a 2 km precision; therefore, any one precipitation data point value may have an error of up to 10 cm (4 in).

A 10m digital elevation model (DEM) was used to estimate elevation range at the study area scale. A DEM-derived shaded relief map was also useful in describing the overall topography of the area and for analyzing possible fire behavior.

The limited number of sites used in this study precluded statistical analysis of fire and environmental variables. Instead, these characteristics were used to interpret fire history qualitatively.

Table 1. Site-level attributes. See Section 2.1 text for the source of each attribute.

SITE #	LOCATION	ASPECT	ELEVATION (m)	SLOPE (%)	AVE. ANNUAL PRECIP. (cm)	PLANT ASSOCIATION
1	Coast	140 (SE)	411	20	127	*Tsuga heterophylla/Mahonia nervosa-Gaultheria shallon*-DRY
2	Coast	330 (NW)	320	30	127	*Abies grandis/Holodiscus discolor/Polystichum munitum*
3	Coast	240 (SW)	419	10	127	*Pseudotsuga menziesii/Corylus cornuta-Symphoricarpos mollis/Polystichum munitum*
4	Coast	280 (NW)	360	30	127	*Pseudotsuga menziesii/Holodiscus discolor-Symphoricarpos sp.*
5	Coast	297 (NW)	457	25	127	*Abies grandis/Holodiscus discolor/Polystichum munitum*
6	Coast	300 (NW)	375	60	127	*Pseudotsuga menziesii/Mahonia nervosa/Gaultheria shallon*
7	Coast	180 (SE)	351	7	127	*Tsuga heterophylla/Gaultheria shallon*
8	Cascades	192 (SW)	463	20	137	*Tsuga heterophylla/Gaultheria shallon*
9	Cascades	76 (NE)	555	8	137	*Tsuga heterophylla/Gaultheria shallon*
10	Cascades	194 (SW)	488	22	137	*Tsuga heterophylla/Mahonia nervosa-Gaultheria shallon*
11	Cascades	202 (SW)	375	55	137	*Pseudotsuga menziesii/Mahonia nervosa*
12	Cascades	130 (SE)	464	22	147	*Tsuga heterophylla/Mahonia nervosa-Gaultheria shallon*-DRY
		AVERAGES:	420	26	131	

2.3 Background

Dry Douglas-fir forests dominate the southern Willamette Valley study area. Dry Douglas-fir forests of the Pacific Northwest have fire frequency intervals ranging from 50 to 100 years (Agee 1993). Morrison and Swanson (1990) found a natural fire rotation (NFR), which is the time it takes for an area the size of the study area to burn, of 95 years with low to moderate severity in their drier, lower elevation site in the central western Cascades. Weisberg (unpub. 1996) reconstructed fire history in the Coburg foothills (central western Cascades); he found a mean fire return interval (MFRI) of 53 years, with generally low fire severity. Impara (1997) established a MFRI of 75 years for the valley margin zone of the central Coast Range. Based on fire regimes for northwestern Oregon (USDA Forest Service 2000) the expected fire regimes for this study include Fire Regime I (<35 years MFRI with low severity) and IIIA (< 50 years MFRI with low to moderate severity). These fire regimes were assigned using plant association groups, geographic fire zones (in this case, the valley and foothills zone), and aspect.

Regional climate has fluctuated over both long and relatively short time spans in the region. Using lake sediment cores from Little Lake (located in the central Coast Range foothills), Long (1995) found that fire intervals changed dramatically over several millennia. From 9000 to 6200 years ago, fire intervals were approximately 100-175 years. From 6200 to 3500 years ago, fire intervals were 275-300 years. In the past 2000 years, fire intervals returned to ca. 175 years.

Based on tree-ring chronologies for the Pacific Northwest, Weisberg and Swanson (2003) concluded that temperatures were cooler from 1690 to 1760; a transition toward warmer periods occurred from 1760 to 1840; and a warmer period occurred from the mid 1800s to the present. Compiling several fire history studies from the Coast and Cascade Ranges, Weisberg and Swanson (2003) found widespread fire from the 1400s to about 1650 and reduced burning from 1650 to around 1800. They attribute this to possible climatic cooling. From 1800 to 1925, prior to effective fire suppression, fires were again widespread, possibly due to warmer conditions and/or burning by Euro-American settlers. Impara (1997) found extensive burning of the western Coast Range in the 1500s and the 1800s. Coastal sitka spruce (*Picea sitchensis*) forests burn only during extreme (very dry) conditions (Agee 1993), supporting the evidence for climatic change (i.e. warmer conditions during these times).

2.4 History of Study Area – Native Americans and Fire

Humans have had a substantial impact on fire frequency in the foothills. The three relevant historical periods, within the fire history length of record for this study, include Native American burning, and its cessation, European settlement, and fire suppression.

In pre-European settlement times, the Kalapuya Indians were the sole inhabitants of the Willamette Valley (Boyd 1986). They used fire for a variety of tasks including hunting (particularly for deer) and tarweed collection. For hunting, fire was used by burning relatively large areas to divert large game animals to smaller unburned areas (Johannessen et al. 1971), driving game into "entrapments", for example narrow chutes or over cliffs, and surrounding smaller animals (including rabbits and insects) with fire where they could be easily killed (Williams 2001). Tarweed (*Madia* spp.) was a main staple of the Kalapuya diet and was "very abundant on the benchlands of the Valley" (quote from Jesse Applegate, 1844; Boyd 1986). To harvest tarweed Indians would burn off the grass (the pitchy substance, or "tar", of tarweed was also burned off in the process) resulting in easily spotted, well-dried and bursting pods, ripe for collection. Women and children would use bats and beat the grain out of the pods and into baskets. The grain was typically ground and used for a variety of foods.

Additional Kalapuya fire-use activities include insect and acorn gathering, sunflower seed collection, tobacco sowing, and for warfare (Johannessen et al. 1971; Pyne 1981; Boyd 1986; Williams 1994). Kalapuya burned the prairies in order to harvest grasshoppers; the grasshoppers' wings would burn off and with the grass gone, harvest was facilitated. Another practice was burning under oaks to remove the grass for finding acorns (it is currently believed that removing undergrowth in oak groves also increased acorn production). There were reports of an annual September burning in order to procure sunflower seeds (burning was to such an extent that sunflower seeds were considered a staple). The Kalapuya likely burned prior to broadcasting tobacco seed as well and there are many accounts of Indian burning during warfare, usually to enable a clear view of any approaching enemy.

Through interpretation of early settler journals, Zybach (2003) suggests that Native Americans burned extensively over the landscape with little concern for the consequences. This argument is based on the large tracts of the coast range that are of a certain age. In contrast, Burke (1979) and Knox (2000) wrote that Indians did in fact burn the Valley, but it is unlikely that they also deliberately set fire to the forests. Knox (2000) states that journal entries *before* 1826 (the beginning of extensive Indian die out from disease) do not frequently mention native use of fire. Knox (2000) suggests that fewer entries reflect a more accurate description of use of fire (less widespread Indian use of fire) as opposed to a common contemporary assumption of widespread Indian fire use based on the frequent fire-use entries *after* 1826. Use of more fire after 1826 would have been doubtful in tandem with Indian numbers steadily dwindling. Instead, Knox points to the numerous accounts of settler-started fires burning over the land in early settlement days (post 1826).

Native American burning is possibly the reason that oak woodlands and extensive prairies were more abundant before European settlement. Johannessen et al. (1971) assert that a map of the "Prairies of the Willamette Valley, 1853" shows the pattern of intentional burning by Indians, which is directly related to fire frequency in pre-settlement times. Open prairie lands still exist today, although most are cultivated fields. Agricultural practices in the Willamette Valley using fire began in settler times to keep the fields clear (Pyne 1981). The extent of Oregon white oak (*Quercus garryana*) in the valley foothills may have been kept at its historical high by Native American burning practices. Most early explorers in Oregon noted burning each year in oak woodlands (Agee 1993).

There is much uncertainty concerning the role of aboriginal burning both in and surrounding the valley. There is no way to determine the difference between human caused and natural forest fires. Consequently, there is no distinction in this study between wild fires and aboriginal/settler fires either started in the foothill or that could have escaped the valley and entered foothill forests.

2.5 History of Study Area – European Colonization and the Fire Suppression Era

European settlement in the valley had begun in earnest by the 1850s and by the 1890s settlement had extended into the surrounding foothills (according to General Land Office maps). Early settlers used fire for clearing land, travel routes, agriculture (Johannessen et. al. 1971, Pyne 1981, Gibson 1985, Boyd 1986, and Whitlock and Knox 2002) and entertainment (Morris 1934, Zybach 2003). Numerous records tell of settler fire-use to clear land for and maintain agricultural fields (Johannessen et. al. 1971, Pyne 1981) and of using fire to hide illegal timber cutting (pers. comm. Mike Southard, Eugene BLM, 2-9-2004). Settlers realized early on that burning is useful in agriculture. Phillip Edwards (settler from the 1830s) wrote, "the ashes deposited from the burning of stubble or other remains of the previous year's produce, effect a marked improvement in the crops" (Gibson 1985). Additionally, GLO surveyors made note of settler burning such as the following passage from an 1889 GLO survey description: "none of the settlers on said Township [18S 1E] appears to have taken their claims for the sake of the timber or for any speculative purpose, indeed most of them have ruthlessly burned and destroyed the finest and most accessible timber on their claims".

At the turn of the 20^{th} century, fires were abundant in western Oregon at which time volunteer fire control organizations began to emerge (Agee 1990). Large regional fires in 1902 (as well as the infamous fires of 1910 in Idaho) spurred forest fire management in the Douglas-fir region (Morris 1934). By 1910, forest industries began to realize the importance of preserving timber; as a result, slash-burning permits were initiated (Agee 1993). Since circa 1920 fire suppression has been very effective. However, during the past few years, large-scale fires in the West have prompted a review of fire policy.

2.6 Reconstruction of Land Use and Disturbance History

To better understand what may have caused fire frequency changes over time it is important to reconstruct the land use and disturbance history for each site and for the study area. To accomplish this objective, I used General Land Office (GLO) maps and surveyor's notes as well as historic timber and vegetation maps to determine the historic condition of the area, particularly the forest. The distance between sampling sites and adjacent early settlement also was determined from these maps. Change in percent cover of vegetation and timber types for the study area (from 1850 to present) was quantified using GIS layers of historic and current vegetation and of 1914 and 1936 timber maps.

GLO maps (downloaded from the University of Oregon library) and the accompanying surveyor notes (attained from Mike Southard of the Eugene BLM) were acquired for each township within the study area. For each site, proximity of settlements, roads, trails, and openings (including agricultural fields and other human clearings) was determined. Also noted were any Indian-related surveyor remarks, such as notes of trails or camps.

GLO maps from the 1850s and 1890s capture the earliest detailed accounts of Indian and European land uses. The maps were created when the Township and Range federal system of land surveying was implemented. The primary reason for surveying in the 1850s was to document land suitable for settlement, which was restricted to cultivatable land. Consequently, parts of some townships were not surveyed until the late 1880s or early 1890s; these townships include Sites 8, 9, 10, and 12. Therefore GLO information was available for these four sites only in the late 1800s while all other sites were surveyed in the mid 1800s.

Surveyors identified bearing (or witness) trees at the corners of each section and these can be used as indicators of historic vegetation (Cogbill et al 2002 and Christy et al 2003). The distance between bearing trees and each section corner can be interpreted to estimate tree cover; tree species and diameter provides forest type and age information. In addition, surveyors made detailed notes about the characteristics of the land and forest that the section line transversed; this too provides valuable insight as to the presence of or lack of forest cover as well as the pre-settlement forest structure and composition.

Surveyors typically wrote general descriptions of the townships as well, which can serve to describe the overall condition of the township (i.e. settlement density, forest condition, soil condition, and suitability for future settlement). For some townships, surveyors noted why an area was or was not settled (e.g. a large railroad land claim on the east side of the valley occurred in the 1850s, and prohibited settlement in otherwise amenable places).

Three historic maps were used to better understand fire frequency as it relates to the pre-settlement forest condition: 1) Historic Oregon Vegetation of 1851 Map produced by the Oregon Natural Heritage Program and The Nature Conservancy of Oregon, which is a map composed of data from GLO section line data and surveyor notes (Christy et al 2003); 2) 1914 Map of the State of Oregon by the State Board of Forestry (Elliot 1914); 3) 1936 Forest Type Map of Oregon (Pacific Northwest Research Station 1936).

Current vegetation type was determined with the Oregon Actual Vegetation Map GIS layer (Kagan and Caicco 1992; landsat data for this map is from 1988). Additionally, I constructed a GIS layer for the fire history sites using universal transmercator (UTM) coordinates that were determined at the time of site installation with a handheld GPS unit.

Each map was downloaded into a GIS and, using ARCMAP (ESRI 2002), site-level vegetation was determined and study area level vegetation change was quantified. The 1851 vegetation map by Christy et al (2003), was particularly useful as it was the first account of pre-settlement vegetation. Forest cover for the historic map of 1851 was defined using distances recorded as points along section survey lines and using distances from witness trees to section corners. The following forest types occurred in the study area according to the historic vegetation map: 1) closed canopy: distances from corners averaged 7m and undergrowth was brushy/ferny; 2) woodland: distances from corners averaged 7-20m (some to 30.5m) and undergrowth was brushy; and 3) savanna: distances from corners averaged 20-81m and undergrowth was herbaceous or graminoid.

2.7 Fire History Reconstruction

2.7.1 Site Sampling

A total of 159 stump wedge samples from 12 plots were collected using fire history sampling procedures similar to those outlined by Arno and Sneck (1977) and Agee (1993). Plots were installed at least 30m from any road and at the highest point on the slope within the clearcut. Plots were $200m^2$ (40 x 50m), with the 50m sides parallel to the slope contour. All plots contained a minimum of 20 stumps that were at least ten inches (24.5 cm) diameter. The following variables were noted for each plot: location (both Township, Range and Section, and GPS coordinates using a hand-held GPS unit); plant association; slope, aspect, and elevation.

All stumps were cleared of debris and pitch with field tools and assessed for species, 10 in. diameter classes (10-19 in., 20-29 in., and so on), fire scar(s) present and age of scar (aged from outer ring of stump to the cambial kill of the scar), trauma ring(s) present and age of trauma ring. Stump quality was assessed to determine if the stump was sound enough to take a sample.

Stump wedges were cut, using a chainsaw, from the first five stumps of each species/diameter class combination encountered. Species/diameter classes were 10 in. diameter classes of all species located in the plot. For example, we collected a sample from the first five 10-19 in. Douglas-fir, the first five 10-19 in. western hemlock, the first five 20-29 in. Douglas-fir, and so on. The purpose of taking the first five was to get an adequate number of samples for lab dating and for estimating the age-size relationship of the overstory trees. Wedges were also taken from all scarred stumps unless there were several with a very similar field-counted scar year. In this case, one to several wedges was taken with a particular field-counted scar year.

In stands that that had particularly short records (young stands, as represented in the plot), stumps were also sampled outside of plots. Opportunistic sampling was limited to looking for stumps that provided evidence of additional fires and that extended the length of record (had an older age class).

2.7.2 Sample Preparation

To permit accurate counting of tree-rings with a dissecting variable power microscope, the surface of each sample was sanded with progressively finer sand paper (24 to 320 grit). An accurate count of the rings is crucial for 1) determining age cohorts of trees, which can in turn be correlated with fires of a similar age (Agee 1993), and 2) for revealing the calendar year of fire scars. Although fire intervals in dry Douglas-fir forests typically range from 50 to 100 years, individual fire intervals can be quite short, for example 2-10 years. Field counting does not produce accurate enough results to capture such frequent fire events. For example, Weisberg and Swanson (2001) found an average counting error of nine years in fire scar identification for scars on Douglas-fir counted in the field and also in the lab using dendrochronological techniques.

2.7.3 Dendrochronology

Dendrochronological methods were used to date the pith and fire scars of prepared samples. This involved the creation of a master chronology and use of the master to crossdate samples.

In total, twenty-five tree-ring series were used to create the master. Of these, fourteen tree-ring series were tree cores from four live stands (two on each side of the valley, with trees estimated to be more than 200 years old). The cores were prepared as described above for viewing under a binocular microscope. Each ring in each core was assigned the correct calendar year (this was possible since the last year, the year of coring, was known) and the ring widths were measured using a sliding stage micrometer. All measurements (mm) were recorded via the program Measure J2X (VoorTech 2000) and stored as text files. In addition to cores, eleven exceptionally old stump samples, collected from fire history plots (from both this study and from a larger study of the entire Willamette Valley foothill area currently in progress), were added to lengthen the most robust portion of the master chronology (1650-2000).

Crossdating was checked using the program COFECHA, which is a computer program that assesses crossdating quality (Holmes 1983, Grissino-Mayer 2001b).

COFECHA uses cross correlation of measured ring-widths to identify possible dating errors. Once any errors are corrected, ring series from individual samples are combined into an index of ring width, or master chronology. This master chronology is used to assign accurate calendar dates to each ring on each sample.

COFECHA compares the relative width measurements of each ring to the width of the neighboring rings to find especially large and especially small rings, called marker rings (in COFECHA marker rings are those that are more than or equal to +/- 2 standard deviations away from the mean value of that particular ring). A master chronology of marker rings is produced in which the measurements are unitless indices that represent the frequency of a marker ring occurring (as opposed to the index representing the actual size of the marker rings). The master was used to cross-date all samples in order to get an accurate calendar year of the pith, scar dates, and/or other injuries of each sample.

Most samples were crossdated on the wood by eye using the master chronology. However, some of the samples that did not cross-date readily on the wood were measured and COFECHA was used to suggest possible dating, which was then checked by eye. These samples included those that were young (<50 years old), were missing several outer rings, and/or had complacent rings. If all samples in a site crossdated well on the wood, three samples were chosen randomly to measure and evaluate using COFECHA.

COFECHA evaluates and assigns the highest correlation (r-value) to the first 50-year segment of a series as compared to the master. For each 50-year segment in the ring series, 11 different 50-year segment correlations with the master are computed. For example, the 50-year-segment 1900 to 1949 in a sample's series, receives 11 r-values, resulting in 11 dating options the user might investigate for correctly dating that segment. The resulting output includes the number of years to add to what the user identified as the correct date (1900 in this example) and the correlation coefficient for each.

COFECHA then advances 25 years and again calculates the highest correlations against the master. This is done for all segments within the length of record measured, giving a 50% (25 year) overlap between successive segments. An average correlation coefficient is computed for the series being tested in which 2 or more segments had the same result (i.e. the same number of years to add). For example, if 5 segments for a series indicated to add 15 years to what the user defined as the calendar year, the output would include: 1) how many segments (5, in this case) have the same "add year" result; 2) how many years to add (15); and 3) the average r-value for the five segments. For this project, crossdating was considered successful (granted that the wood crossdated by eye) if at least half of the total 50-year segments had an average r-value of more than or equal to 0.4226 (Grissino-Mayer 2001b). This is the correlation coefficient at the 99% one-tailed confidence level for a segment length of 30 years; longer segment lengths have a smaller r-value (e.g. a 50-year segment has an r-value of 0.3281), although for this study an r-value of 0.4226 was required for 50-year segments as well.

For samples in which the rings were *not* assigned calendar years (samples that did not crossdate on the wood) the same process as described above was used with the exception that COFECHA evaluated the 11 highest correlations *anywhere* within the master chronology's record as opposed to a particular dated segment. Again, the output provides how many years to add (essentially giving a possible calendar year or years to start with). The dendrochronologist verifies, or not, the suggested year by crossdating on the wood.

It is important to note that COFECHA itself does not crossdate. The program aids in dendrochronology, but all crossdating must be done by eye by the dendrochronologist (Grissino-Mayer 2001b).

Using dendrochronological techniques, the calendar year and season of each fire scar was determined by counting each ring, from the outer most ring (bark edge) to the year of fire scarring. Seasonality of scars is helpful for assessing seasonal patterns of fire occurrence (which may affect plant establishment and mortality) and when combined with fire interval data, seasonality may be useful in planning prescribed burning programs (Baisan and Swetnam 1990). The intra-annual position (season) of each scar was determined by locating the zone of cambial kill within or between annual rings. Seasons were denoted as E (early earlywood, first 3rd of the earlywood), M (middle earlywood, second 3rd of the earlywood), L (late earlywood, last 3rd of the earlywood), A (latewood), and D (dormant season; between rings). A dormant season scar was assigned to the preceding year since contemporary fires are associated with the time of year following the growing season (late summer and fall); for example, if the scar was located between the annual ring years 1949 and 1950, the scar was assigned to 1949. When season could not be determined, it was denoted as U (unknown).

In addition to dating scars, each sample was aged from the outer ring to the pith, if present, or innermost ring if the pith was not present. Age for samples that did not have a pith was estimated using a geometric correction tool (a correction tool is a mylar overlay which has concentric rings at differing widths apart, for example five rings/inch or ten rings/inch, to help estimate the number of rings missing). Correction was used on samples that appeared to have only a few rings missing.

Tree age was not used extensively in this study, therefore the age at stump height was used as the approximate pith age on most sites (excluding sites with cohort fire event evidence). However, to verify that the age at stump height was not significantly different from the estimated pith age, samples from five sites were pith-age corrected following the equation used in Morrison and Swanson (1990):

$$\text{Age} = 0.1852 * SH/RW \text{ (for } RW > 2 \text{ mm) and}$$
$$\text{Age} = 0.1852 * SH/2 \text{ (for } RW \leq 2 \text{ mm);}$$

where

Age = age at stump height (years),
SH = stump height (centimeters), and
RW = average ring width of inner three growth rings (mm)

Age years were added to the age of the tree counted at stump height to get the best estimation of the true age of the pith. Ages at stump height ranged from zero to seven years, with an average of three years on stumps ranging in height from 0 cm to 86 cm (average height 30 cm). Because the average correction was so small, stump age was used to avoid the additional time needed for pith age corrections.

2.8 Fire Event Determination

Some crossdated fire history studies identified fire events using *more than one* scar (Weisberg and Swanson 2001). This rule is based on the assumption that if more than one tree became scarred on a site in the same calendar year it was unlikely to have been caused by anything other than fire. Grissino-Mayer and Swetnam (2000) used more than one scar as evidence of fire with the purpose of removing less wide-spread fire events (i.e. if more than one tree was scarred, it was assumed that the fire was more wide spread). Other studies, however, have determined fire history using several approaches (e.g. all scars, > x-percent of trees scarred, or > x-number of trees scarred) (Brown and Swetnam 1994, Grissino-Mayer 1995, Donnegan, et al. 2001, and Stephens, et al. 2003) or by requiring only one scarred tree as evidence of fire (Baisan and Swetnam 1997, Brown and Sieg 1999, Guyette and Spetich 2003, Taylor and Skinner 2003, and Wright and Agee 2004). When using several approaches, each resulting fire chronology and resulting fire frequency was presented. If it could be established for this study that all lab-dated scars used were fire caused, it would be appropriate to use one scar as evidence of fire (per. comm. J.K. Agee, 8-18-2004).

2.8.1 Tree Injuries Related to Fire

In order to discern fire-caused scars from other scar forming agents, other sources of tree injury were examined. Tree bole injuries are caused by several mechanisms, including fire. Scars are formed when a section of the cambium is killed. After scarring, the bark sloughs off (if it was not removed at the time of injury), exposing the wood and causing the tree to exude pitch. Subsequent rings forming after the injury resemble a heart-shaped pattern (if looking down onto a cross section) as the rings grow in over the wound (Figure 3). Scarring can occur from physical abrasions (such as one tree rubbing against another, rock fall, or by animals, such as bears, deer, and porcupines), frost during the growing season, insects, and fire (Morrison and Swanson 1990, Agee 1993).

It can be difficult to distinguish the causal factors of injuries, but certain reasonable elimination is possible. Black bears (*Ursus americanus*) strip bark off young trees in the spring and the scar tends to occur over 2-5 stripping years instead of a single fire year (Agee 1993). Tree abrasions that actually remove bark are more likely to cause observable damage to the sapwood unlike the "clean" cambium kill of fire scarring. In the study area, frost and insects are not common enough to markedly influence the occurrence of scars; also, frost is unlikely to affect Douglas-fir after a certain age due to the thickness of insulating bark. Douglas-fir bark beetles (*Dendroctonus pseudotsugae*) exist in the area, although bark beetle visible injuries to the tree are very small pitch pockets, not the characteristic scarring pattern seen with fire injuries, and their scars are not typically found on the lower few meters of a tree (per. comm. Darrell Ross, 8-17-2004).

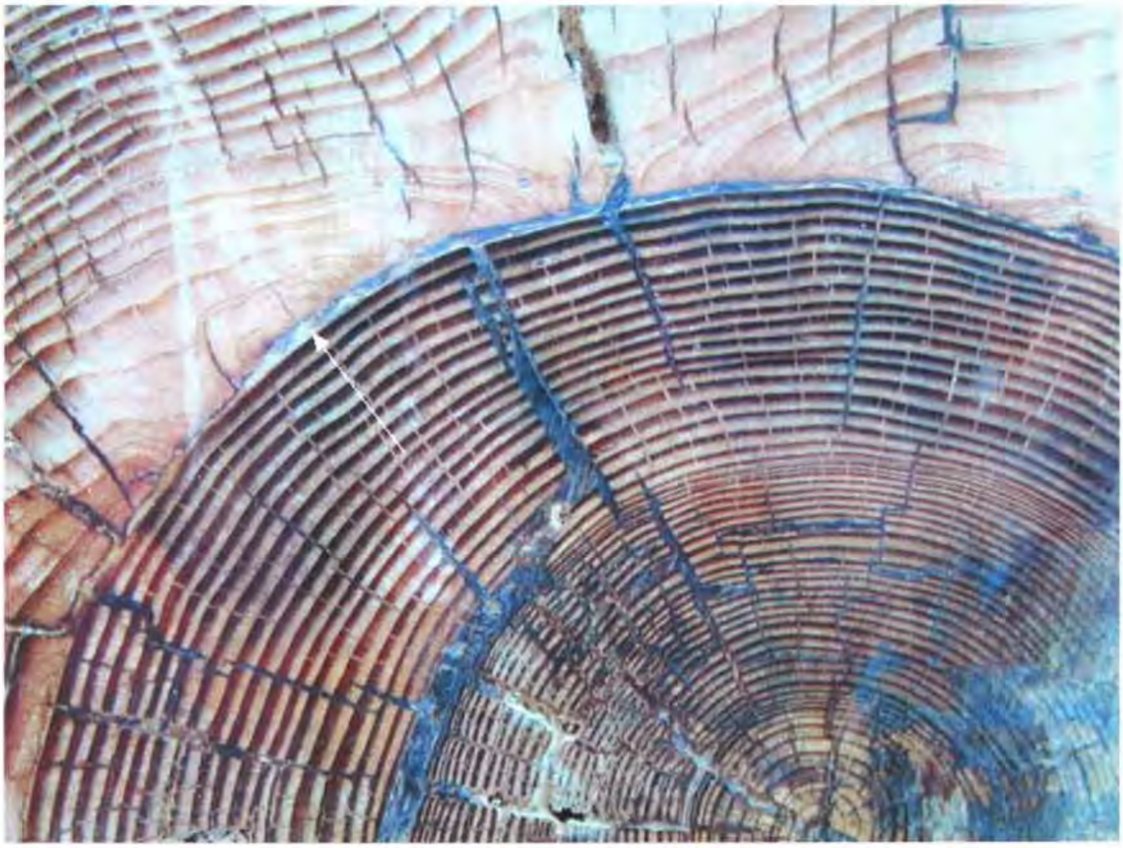

Figure 3. Douglas-fir sample with fire scar. When fire kills the cambium, the following years' growth closes in over the wound (typically forming a heart shape). Pitch can generally be seen between the year of the fire and the wound wood (white arrow). Notice that the fire year's ring (ring to the pith side of injury) is not itself damaged, which can happen with other types of injury such as physical abrasions.

Trauma rings, characterized by the presence of a clear band of resin within, or between, growth rings, are physiological responses to injured cambium (Helms 1998). Causes of trauma rings include ring "shakes", insects, hail, physical abrasions, frost, and fire (Dobbertin 2004). Trauma rings have been associated with fire (Morrison and Swanson 1990, Brown and Swetnam 1994, Grissino-Mayer 1995, and Weisberg 1997); however, no studies to date specifically address this potentially important evidence of fire.

Both fire scars and trauma rings may be present along the same ring from the same fire event. For example, a tree may scar on the uphill side due to the heat remaining longer against the bole, while the downhill side of the tree may show only a trauma ring as evidence of injury. Trauma rings form from heating but not death of cambium due to either non-lethal temperature (fireline intensity) or to the length of heating time on the bole. Additionally, Brown and Swetnam (1994) found that trauma rings (termed "ring separations") could be found at the highest point of the dead cambium (above the healing wood of a scar) on the stem. Their finding is similar to observations made in this study: often on cut stump samples (wedges), a trauma ring was present on the upper side (the side of the sample that was farthest from the ground) with a scar present only on the lower side (the side closest to the ground). The association of trauma rings with fire scars is common in this study; thus, trauma rings are used as corroborative evidence of fire events.

Seasonality of scarring was also used to differentiate fire scars from other scars. Of the 58 scarring events in the study area, 53 scars (91%) were located intra annually in either the latewood or between annual growth rings (dormant season). This timing suggests that these scars were created by fire because in the Pacific Northwest, fires are associated with the drier and warmer conditions of the end of, or after, the growing season, generally summer or early fall. If scarring agents other than fire were common, the intra-annual ring position of scars would be less synchronous.

All lab-dated scars were determined to be caused by fire since other injury causes could be ruled out and because scars were seasonally synchronous. In addition, single scars from one plot on a site were found on additional plots within the same site, indicating that the sampling size may not always be conducive to finding more than one scar, although that scar is, in fact, evidence of fire (see Section 4.1.2).

2.8.2 Fire Scars and Additional Fire Event Evidence

All lab-dated scars, determined to be fire-caused, were used to determine the year of fire events. All fire events required at least one lab-dated scar. Additional evidence was corroborative, not direct, evidence of fire.

Additional fire event evidence included field-dated scars, trauma rings, and regeneration cohorts. Field counted fire dates (termed field-dated scars) were, by themselves, not considered direct evidence of fire. Field-dated scars were used as corroborative evidence if the date was within three years of a lab-dated scar on the same site. The 3-year acceptance error is the average error (2 year s.d.) between field and lab dating of 28 scars (scars that had been counted in the field and in the lab) from 24 samples. Only count differences less than eight years were used to calculate the average error since 85% of all scar errors in the analysis (33 scars on 29 samples) were less than eight years and because a potential field scar was not considered useable as corroborative evidence if more than ten years different from a lab-dated fire event.

Trauma rings were used as corroborative evidence of fire if the ring dated to the same year or to the year following a lab-dated scar. Trauma rings dated to the year following a scar were used, because trauma rings were observed to occur as long as two years after fire events.

Regeneration cohorts were used to establish fire events when scars were lacking on a site. Previous studies have found intervals of initial establishment for Douglas-fir between 20 and 40 years (Yamaguchi 1986, Winter et al. 2002, and Dowling 2004). For this study, a cohort was defined as ≥ 50% of all Douglas-fir, lab-dated samples with origin dates spanning no more than 40 years. Forty years was chosen based on the longest number of years (39 years on Site 7) for cohort regeneration to occur on sites following a fire event.

If no other sampled tree was alive on a site at the time of cohort establishment, cohorts were used to establish an approximate fire event. The fire event was assigned (a) to the year of a fire event from an adjacent site or (b) to one year prior to the oldest pith year of the cohort, if no adjacent-site fire event occurred within the previous 25 years. Twenty five years was chosen as an appropriate period between fire and regeneration based on the longest number of years (22 years on Site 7) between a fire event and the oldest origin date of the subsequent cohort on sites with both scars and regeneration. Since not all fires leave scar evidence and/or not all scars are sampled, it is possible that the regeneration on Site 7 was not from the fire 22 years previous, but from a fire that was not sampled that was closer in time to cohort establishment. For the purposes of this study, however, 25 years was used. Sample pith years were stump-height corrected (described in Section 2.7.2) to ensure the most accurate fire year on sites with fire events based on cohort establishment. Cohorts within 25 years after a fire scar were used as corroborative evidence of a fire.

Assigning a fire year to a cohort age may introduce error to the fire date since regeneration may lag the fire event by several years. Therefore, the relationship between fire and regeneration was determined for this study (see Sections 2.11 and 3.4).

Periods of tree growth release and suppression have been associated with fire occurrence (Morrison and Swanson 1990 and Brown and Swetnam 1994), but in this study, observations of this relationship were limited. Accordingly, release and suppression were noted but not used as supportive evidence of fire.

2.8.3 Comparison of Fire History Using Different Criteria

In order to evaluate the results of using an "all scars" approach, as opposed to a more conservative estimate of fire history, five different rule sets for fire event determination were established (Table 2). Four of the rule sets were conservative estimates (each set being slightly less conservative than the preceding set) and the fifth was the all-scars (most liberal) set. Fire interval distributions were calculated using all five sets, but only set 5 was used to determine fire history for each site and for the study area.

A Fisher's exact test was used to determine if fire interval distributions for the first four sets were similar to set 5. Fire intervals were grouped into bins: <25 yrs, 25-75 years, and >75 years for this analysis.

Table 2. Rule sets for accepting fire event evidence. The first four sets are conservative estimates, each one being successively less conservative. Rule set 5 includes all scars and regeneration cohorts, and is the only one used for data analysis. Letters (A. through G.) are assigned to the same rule in each set.

RULE SET 1

A. > 1 crossdated scar on a site = fire event

RULE SET 2

A. > 1 lab-dated scar on a site = fire event, or

B. 1 crossdated scar + 1 other piece of evidence on a site (field-dated scar or lab-dated trauma ring) = fire event

RULE SET 3

A. > 1 crossdated scar on a site = fire event, or

B. 1 crossdated scar + 1 other piece of evidence on a site (field-dated scar or lab-dated trauma ring) = fire event, or

C. > 1 site with crossdated scar (regardless of # scarred samples/site) = fire event

RULE SET 4

A. > 1 crossdated scar on a site = fire event, or

B. 1 crossdated scar + 1 other piece of evidence on a site (field-dated scar or lab-dated trauma ring) = fire event, or

C. > 1 site with crossdated scar (regardless of # samples/site) = fire event, or

D. > 1 crossdated scar/sample (excluding 1^{st} scar date) = fire event, or

E. 1 crossdated scar on sample, no other possible evidence (sample is only tree alive at scar time), or

F. > 50% of all lab-aged regeneration in a cohort on a site = fire event

RULE SET 5 (Rule set used for analysis)

G. All crossdated scars = fire event, or

F. > 50% of all lab-aged regeneration in a cohort on a site = fire event

2.9 Fire Frequency Determination and Statistics Used

A low to moderate severity fire regime was expected given the prevalence of scars. Therefore, a point frequency approach was used to generate composite fire frequency for each site. The "points" in this case were not individual trees, but the plot. Point frequency is interpreted ecologically as fire burning across that point on the landscape at an average frequency, with some amount of frequency variation

(Agee 1993). A composite frequency captures the fires that a single point (tree) did not record, as no one tree records all fires, and it provides a more comprehensive record of past fires (Dieterich 1980, Agee 1993).

Distributions of fire intervals (in contrast to MFRI) are better descriptions of the general trend of fire frequency, including the most prevalent intervals and range of intervals. Fire interval distributions can be easily evaluated and compared between sites or with other fire history studies. Relative fire interval frequency (RFF), which is essentially a fire interval distribution, was calculated for all sites. For each 10-year interval bin (<10 years, 11-20 years, 21-30 years, …, >100 years), RFF was calculated by dividing the number of times a particular fire interval occurred, by the total number of intervals (number of fires minus one). For example, Site 2 had six intervals (2, 13, 14, 14, 18, and 45 years); one interval fell in the < 10 year bin, four in the 10-20 year bin, and one in the 40-50 year bin. Thus, the RFF for intervals <10 years and 40-50 years was 0.2 (1/6 = 0.02), and for intervals 10-20 years RFF was 0.7 (4/6 = 0.07).

MFRI was calculated for all sites and for the study area to facilitate comparisons among sites and across studies. However, since some sites had only one or two intervals, the MFRI was not a robust measurement of fire frequency. For sites with ≥ 4 fire events (at least 3 intervals), fire frequency was calculated and analyzed in terms of MFRI, which is the average of all fire intervals in a site for a specified time, and the Weibull median probability interval (WMPI), which represents the median interval of a Weibull distribution (half of all intervals are expected to be larger and half smaller than the WMPI). The Weibull distribution's flexibility typically provides a better, less biased model for skewed distributions (Grissino-Mayer 1995, 1999) that are typical of fire intervals. A one-sample Kolmogorov-Smirnov goodness-of-fit test (K-S test) was used to determine if the interval data were better modeled by an empirical or Weibull distribution (Grissino-Mayer 1995). The K-S test was performed in the fire history software package FHX2 (Grissino-Mayer 2001a).

Variability of fire intervals, for sites with 3 or more intervals, was measured using several descriptors: the minimum and maximum intervals; standard deviation (SD) of the MFRI; the lower and upper Weibull exceedance intervals (LEI/UEI); and the Weibull maximum hazard interval (MHI). The Weibull exceedance probabilities represent the 25% (12.5% at each tail) of all intervals considered to be extreme, based on the Weibull distribution of the actual data (i.e. there is a 12.5% or 87.5% chance of obtaining a fire interval of this length simply by chance). MHI denotes the theoretical maximum fire-free period the site can maintain before burning becomes highly probable.

At the study area level, neither point frequency nor area frequency could be determined (however, the mean of site-level MFRI and composite RFF were reported for the study area). Point frequency was not used since points (sites) of the study area were not spaced closely enough to compile a composite frequency. Area frequency is typically used in landscapes of moderate to high fire severity regimes, but this uses forest stand ages with less use of fire scars (Agee 1993). Instead, RFF was used to illustrate fire occurrence over the landscape. RFF was also used to compare fire frequency of the west and east sides of the valley.

2.10 Temporal Change of Fire Frequency

Using composite fire chronologies and fire recurrence (number of fires over time), the following questions were addressed for the study area and for the valley sides: 1) Did fire frequency vary over time? If so, were changes in fire frequency related to 2) changes in land use, and/or 3) changes in climate?

Composite fire chronology graphs of the study area and of both valley sides were visually inspected for increases or decreases in both number of fires and fire intervals over time. Time frames with apparent change were evaluated for concurrence with climate fluctuations and settlement patterns. Time periods with exceptionally long or short intervals (fire event clusters) were also noted.

Fire recurrence, or number of fires over time, was calculated for the three centuries (1700s, 1800s, and 1900s) and the four periods of contrasting land use (pre-1850, 1851-1920, and 1921-present) spanned by the study. The period 1831 to 1910 was also evaluated, in place of 1851-1920, since European settlement may have affected fire as early as the 1830s and while no significant fire suppression was occurring in 1910, humans were actively discouraging the use of fire. There was no difference in results, so only the 1851-1920 period was evaluated further. Since land use time periods were not of equal length, the number of fires in each period was further divided by number of years in that period. Pearson's chi-squared tests were used to assess the significance of differences in fire recurrence among time periods.

Fire-climate associations were investigated and quantified with superposed epoch analysis (SEA; Baisan and Swetnam 1997, Grissino-Mayer and Swetnam 2000). Fire occurrence and a proxy climate index were compared using SEA to determine if, during fire years or for the 5 years preceding fire years, the climate was significantly different from average. The proxy for climate was the Palmer drought severity index (PDSI), grid point 4 (Lat 43, Lon 122.5; Cook, et al 1999). The PDSI was created by reconstructing drought using tree-rings. For years 1895-1978, I calibrated the PDSI values with contemporary instrumental drought measurements from Cook et al (1999) ($R^2 = 0.4243$).

SEA was used to determine if a drought-fire relationship existed by superimposing fire years together and superimposing drought during those years together; SEA averages the mean drought value for each fire year. The climatic characteristics were averaged across all fire event years and the level of confidence was determined using bootstrapping methods on simulated events based upon the actual data. The result was a quantitative average of drought conditions during fire events (Grissino-Mayer 1995).

To evaluate the interactive effect of climate and land use change on fire recurrence, the time periods of climate were combined with the time periods of land use change, to create 4 distinct time periods of climate and land use change: 1700-1800, 1800-1850, 1850-1925, and 1925-1990. These time periods were chosen based on several observations made when climate and land use time periods were combined: 1) 18th century fires were not related to climate and not influenced by Euro-American settlers; 2) between 1800 and 1850, fires were weakly related to climate and the period was one of reduced Native American presence and limited settler influence; 3) between 1850 and 1925, climate was significantly related to fire and settlement was potentially a very influential factor of fire occurrence; and 4) the effective fire suppression period, 1925 to 1990, was also characterized by a relationship between fire and climate, but fire ignition was actively avoided by humans and fires suppressed once started. A Pearson chi-squared test was used to determine the significance of the difference in expected and observed numbers of fires. Expected numbers of fires was determined by equally distributing all fires over time; therefore, twice as many fires were expected for the period 1700-1800 (100 years) as for the period 1800-1850 (50 years).

2.11 Regeneration Following Fire

Examining regeneration following fire was not part of the objectives for this study; however, since regeneration is commonly used in fire history studies as a proxy for fire severity (Morrison and Swanson 1990, Impara 1997, Weisberg 1997, 1998, and Kipfmneller and Baker 2000) or for establishing fire dates based on regeneration (Morrison and Swanson 1990, Impara 1997, and Kimpfmneller and Baker 2000), regeneration following fire was evaluated to the extent that it could be.

Lack of crossdating in previous studies precluded knowing the exact calendar year for germination and for the fire event. Since fire and origin dates were known for this study, the time to regenerate could be further evaluated as 1) the number of years, since fire, for the first individual that was sampled to regenerate and 2) the number of years it took for all members of the cohort that were sampled to regenerate.

3. Results

3.1 Land Use and Disturbance History

3.1.1 Vegetation

Historic vegetation, 1914 and 1936 timber types, and current vegetation percentages were calculated in order to assess vegetation change over time (Table 3). The 1851 map of historic vegetation of the Willamette Valley (Christy et al 2003) was used to compute vegetation cover for the study area. Since this map covered only 90% of the total study area, another historic map (Tobalske 2002), which is not as detailed, was used to determine vegetation of the remaining 10% of the area (which was Douglas-fir closed canopy forest located in higher elevation foothills).

Currently (as of 1988), the southern Willamette Valley study area (1562 km^2) is about 80 to 90% forested, with the remaining area grassland (field) or urban cover. In the past 150 years there has been an increase in Douglas-fir forest cover and a decrease in other forest types and loss of prairie.

Douglas-fir forests have dominated the landscape in this study area over the entire length of record. Historically (based on mapping from the mid and late 1800s), *closed canopy Douglas-fir* forests, including western hemlock and grand fir forest associations, covered 62% (971 km^2) (Figure 4); currently these forests cover 74% (1153 km^2) (Figure 5). Woodlands, including *Douglas-fir* and *Douglas-fir-oak woodlands*, covered 13% (195 km^2) in the mid 1800s. Additionally, 6% (94 km^2) of the study area was savanna (see Figure 4 legend for savanna vegetation types). Today, 8% (121 km^2) of the study area is *oak-Douglas-fir-ponderosa pine-pasture-urban mosaic*.

Grasslands, consisting of *Roemer fescue* and *tufted hairgrass*, covered 16% (247 km^2) of the study area historically. Native grasslands and prairies, however, have long been converted to mostly *agricultural cropland and pastureland*, which cover 8% (122 km^2) today. Historically, *riparian* and *wetlands* (*closed forests*) occupied 4% (54 km^2) and all other vegetation types covered <1% each. Currently, *Oregon ash-*

black cottonwood-bottomland pasture covers 3% (39 km^2) and *mixed conifer / broadleaf deciduous* forest occupies 4% (58 km^2).

Timber types were used for analysis of disturbance history by comparing percentages of timber, burned or cut areas, and non-timber areas. In 1914, *merchantable timber* covered 54% (849 km^2), 12% (180 km^2) was *burned*, 3% (48 km^2) was *cutover*, 28% (443 km^2) was *non-timber*, and *brush* areas covered 3% (40 km^2) (Figure 6). In 1936, Douglas-fir forests dominated, including *old-growth* (32%, 500 km^2), *2nd growth* (32%, 500 km^2), and *seedling/sapling/pole* (3.2%, 49 km^2). *Non-forest* covered 24% (381 km^2), 0.8% (13 km^2) was *burned*, and 7% (103 km^2) had been *cut since 1920* (Figure 7).

Mapped vegetation through time was also determined at the site level in order to track changes; the results were used to compare vegetation and disturbance with the fire history constructed for each site (Table 4).

3.1.2 Early European Settlement

For each site, nearby European settlement, including roads, dwellings, and fields or clearings, was determined using General Land Office (GLO) maps (Table 4). Ten of the thirteen study sites had settlement within 4.8 km (3 mi) that had been established between the mid 1800s and late 1800s. Settlement was more variable on east side sites than west side sites. Sites 8 and 9 had no nearby settlements even in the 1890s. The 1850s map for Site 11 shows settlement within 3.2 km (2 mi), and within 1.6 km (1 mi) on an 1860s map; the Township (19S 1W) was not surveyed at the site in 1890. Sections for Sites 10 and 12 were not surveyed until 1889 and 1890. There was a settlement within 3.2-4.8 km (2-3 mi) of Site 12 on an 1850s map and settlement within 0.4km (¼ mi) of Site 12 by 1890. Site 10 was within 1.2 km (¾ mi) of a settlement by 1890 and a clearing (likely agricultural) was adjacent to the site.

Logging was underway in the more mountainous areas of the eastern portion of the valley foothills by the 1930s (pers. comm. Mike Southard, Eugene BLM, June 2004). A mill located on Lost Creek Rd. was within 3.2-4.8 km (2-3 mi) of Sites 8, 9, and 11.

All sites on the western side of the valley were within 1.2 km (½ mi) to 4.8 km (3 mi) of settlement. Several mills and lumber companies, located in Lorane Valley were established in the early 1800s (Edward et. al. 1987), the first one being the Jost D. Petrie Grist Mill just south of the city of Lorane. A mill site of the Lorane Valley Lumber Co. was located on Gowdyville Rd. just southeast of Lorane in the early 1900s.

3.1.3 Mapped Evidence of Fire and Logging

Early maps are considered accurate, although they are not georeferenced; therefore, sites located adjacent to differing vegetation or timber types may have been in the other type instead of the one the site was mapped as. If age classes or disturbance history within the site correspond to approximate years of fire or logging, then the early observations are more likely accurate for a given site.

Five of the twelve study sites were mapped as having been disturbed by fire and/or forest harvest between the early 1900s and 1936; the remaining sites were mapped as *old-growth Douglas-fir* (Table 4). All sites were mapped as *Douglas-fir* before 1900, except Site 3 which was mapped as *Oak-Douglas-fir*. On the 1914 timber map, all sites were mapped as *merchantable timber* except Site 4, which was *non-timber* (it is noted, however, that the site is located directly adjacent to an area mapped as *burned, restocking*) and Site 9 was mapped as *burned, not restocking*. The 1936 timber map described the dominant tree size class. All of the west side sites were *old-growth Douglas-fir* except Site 7, which was *large 2nd growth Douglas-fir*. Sites on the east side were more variable. Site 8 was mapped as *seedling-sapling-pole Douglas-fir*, Sites 9 and 11 as *recent cut over since 1920*, Site 10 as *small 2nd growth Douglas-fir*, and Site 12 as *old-growth Douglas-fir*.

Table 3. Percentage of forest types, burned area, and cutover areas through time as determined from vegetation maps. Row headings with split names (e.g. "forest / merchantable") are listed with historic first, 1914, 1936, and current last. The historic (1851-1890) map total is >100% because burned area was calculated using a specifically-Willamette Valley historic GIS layer (cite); this map was not used for display or other calculations because it does not cover the entire study area. Consequently, the burned area for historic is calculated for the 90% it did cover of the study area.

Douglas-fir Forest	**Historic (%)**	**1914 (%)**	**1936 (%)**	**Current (%)**
Closed forest / Merchantable Timber / DF OG, 2nd Growth, & seed., sap., pole / Douglas-fir-western hemlock-grand fir	62	54	68	74
Burned	~4	12	1	---
Cutover	---	3	7	2
Other Forest Types				
Woodland	13			
Savanna	6			
Riparian & Wetland (closed forest)	4			
Other Forest (1914 did not define forest types)		---		
Spruce-Hemlock, Large			0.5	
Oak-Douglas fir-ponderosa pine-pasture-urban mosaic				8
Mixed conifer and broadleaf deciduous forest				4
Oregon ash-black cottonwood-bottomland pasture mosaic				3
Non-Forest Types				
Prairie / Non-Timber / Non-Forest / Ag. & grasslands	16	28	24	8
Shrubland / Brush / Shrubland / Urban	0.2	3	—	1

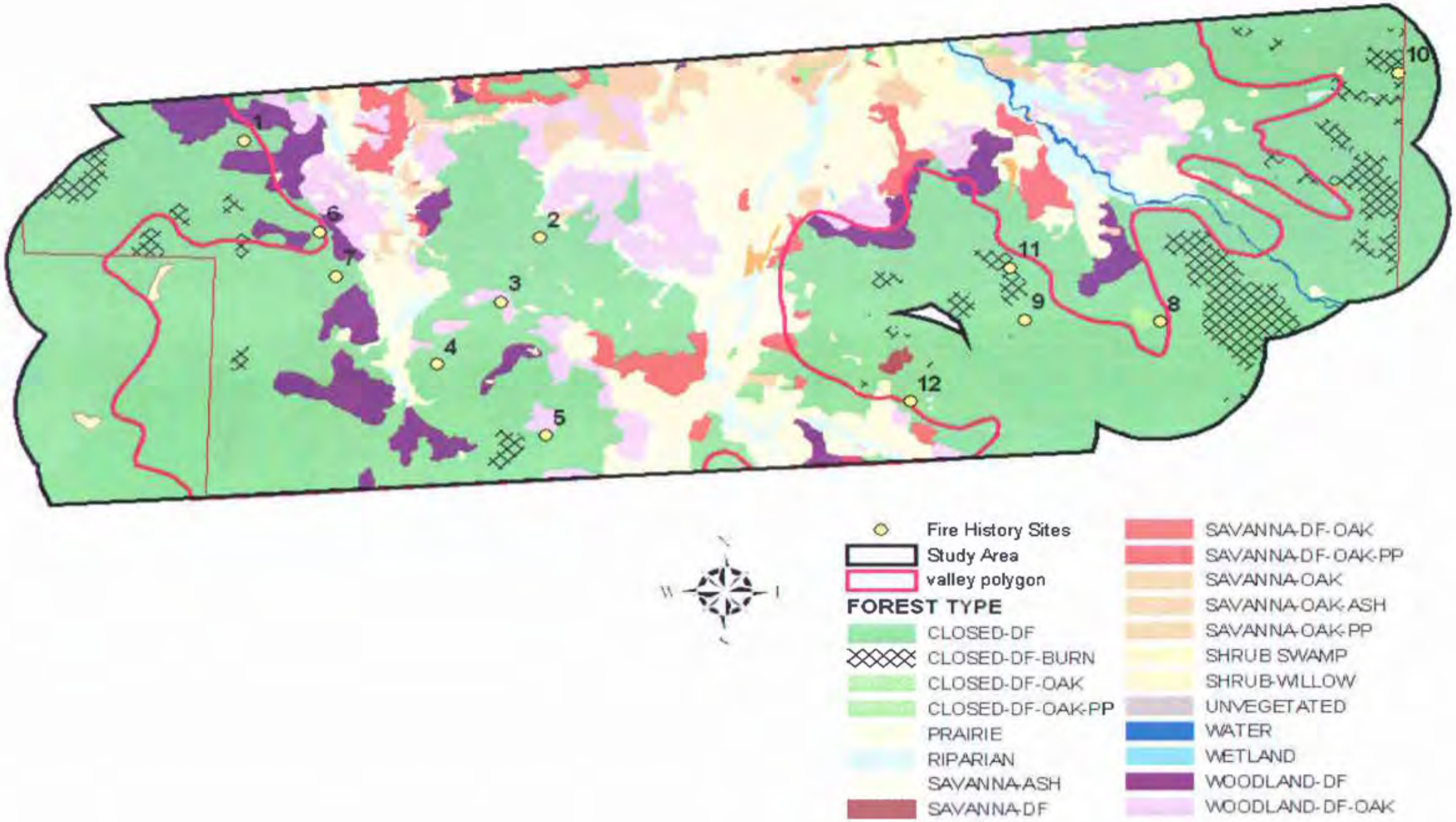

Figure 4. Historic Vegetation Map. Vegetation derived from 1854-1890 GLO maps (Christy et al 2003). The red lines at the west and east sides represent the boundary of the valley-specific map. Historically, the valley foothills were closed canopy Douglas-fir (dark green). The valley floor was grassland and the riparian zones were dominated by hardwoods, such as red alder and Oregon ash. Douglas-fir and Douglas-fir / Oregon white oak woodlands (dark and light purple) were located in the lowlands adjacent to the closed canopy Douglas-fir forests of slightly higher elevations. See text for definitions of savanna, woodland, and closed canopy.

Figure 5. Current Vegetation Map (Kagan and Caicco 1992). Compared to the historic vegetation map, complexity has decreased dramatically. The foothills are still dominated by Douglas-fir, however oak and ponderosa pine (outside of the urban sector) are insignificant now. Douglas-fir/Western hemlock/grand fir forests (DF/WH/GF) are most prevalent. Most of the historic oak savannah and oak woodland are now gone or found in small patches (these patches are lumped in with the oak/Douglas-fir/ponderosa pine/urban (Oak/DF/PP/urban) mosaic). Ag: agricultural land, Decid: deciduous forest, BC: black cottonwood.

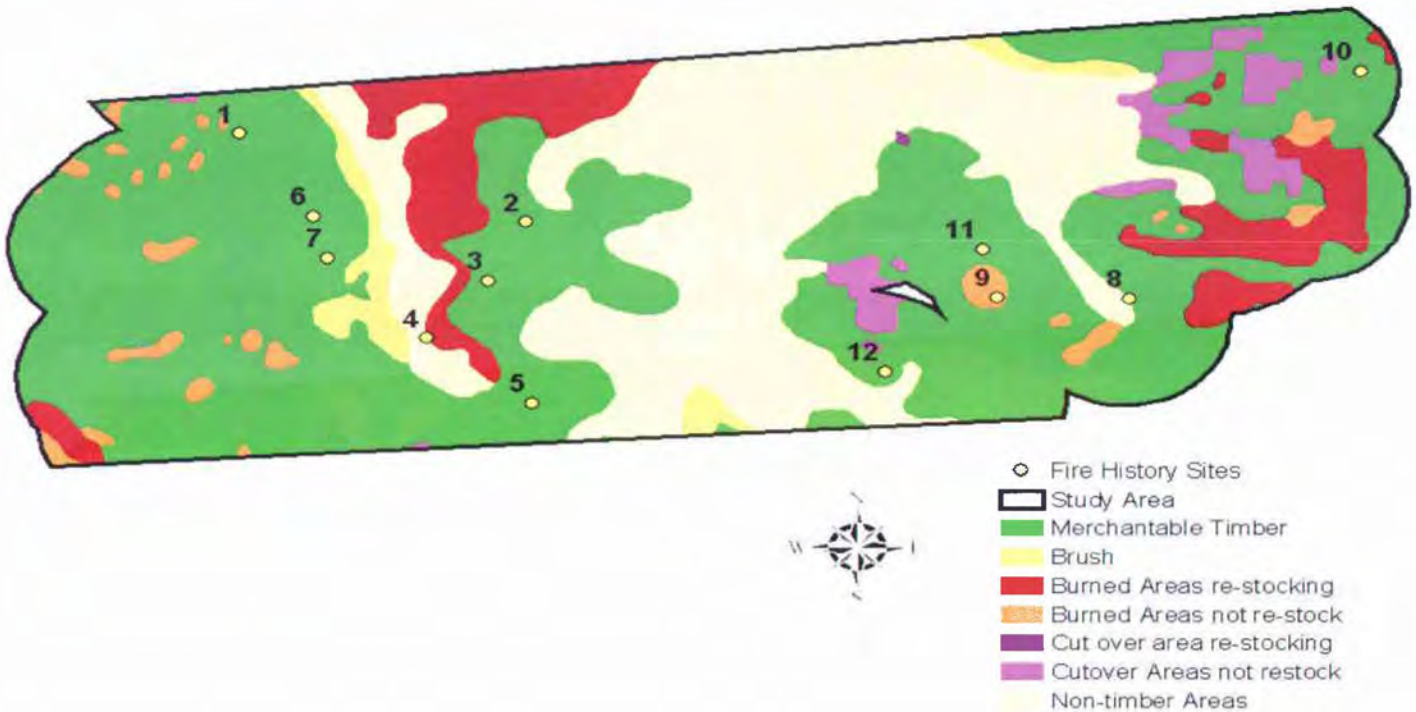

Figure 6. 1914 timber map (Elliot 1914). There is no definition for the "merchantable timber", although it can be inferred that the timber areas were forested. The non-timber areas occupy the same zones as both the grasslands and much of the oak-Douglas-fir and oak-conifer savannah of the historic map. The large "burned areas re-stocking" in the northwestern section of this map correspond to the large oak-Douglas-fir and oak savannah of the historic map. This area, the Lorane Valley, may have been cleared for farming or grazing during European settlement.

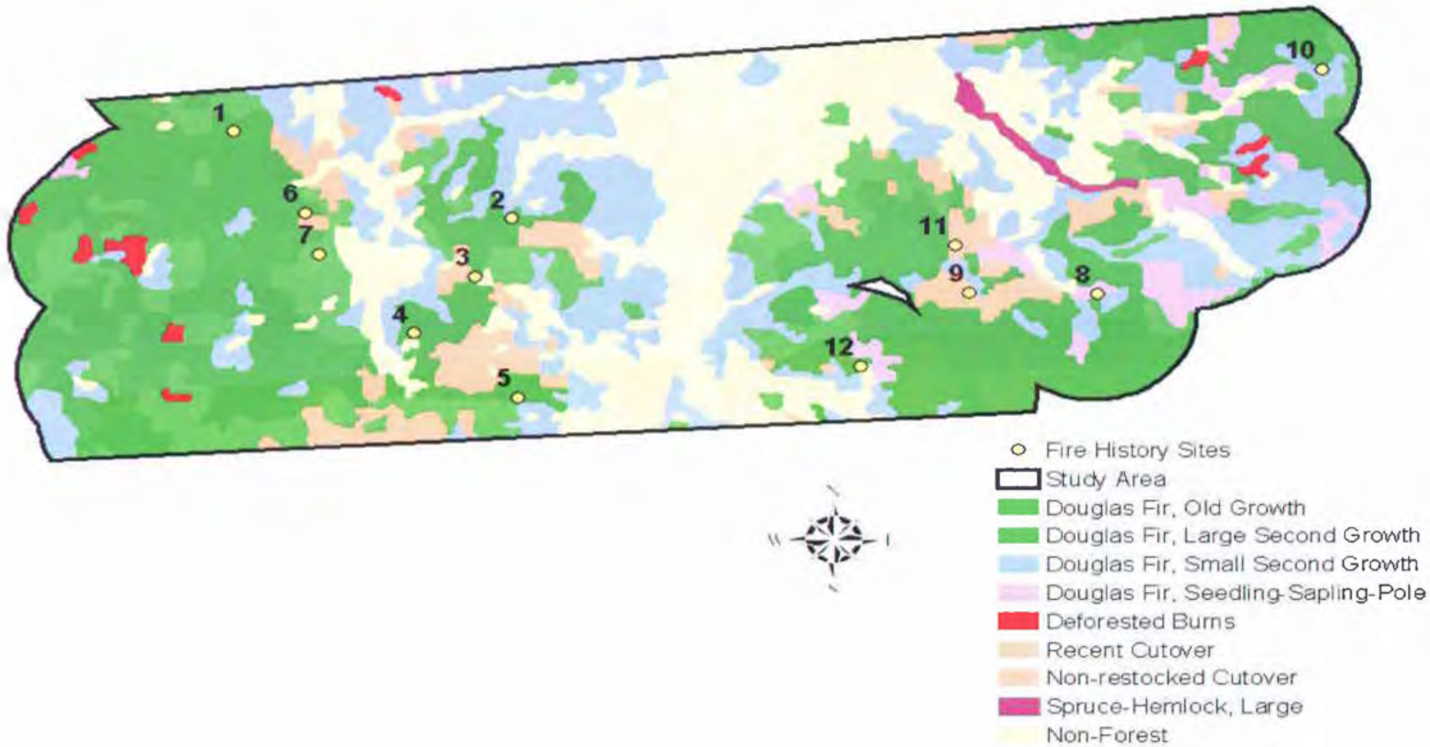

Figure 7. 1936 Timber Map (Pacific Northwest Research Station 1936). This historic map provides a good measure of relative stand ages, burns, and early logging. Most of the west side sites are located in "old growth" forest, while the east side sites are located in younger forests or cutovers. Also of note is the expanse of Douglas-fir forest in areas occupied by oak historically. For example the northern edge of the study area just west of the valley floor was historically oak-Douglas-fir; here it is small 2nd growth Douglas-fir (blue). This may have been from fire suppression and/or lack of frequent Native American burning that possibly contributed to the forest oak component.

Table 4. Early vegetation, timber types, and settlement. Historic maps provided detailed information about vegetation, the amount of forested land, burned areas, and relative age classes. All maps and their sources are listed in Section 3.1. The earliest survey date corresponds to when the actual site location was surveyed. Distance from early settlement was determined by visual inspection of the GLO maps. Column 4 (detailed historic vegetation) lists descriptions, comparable to vegetation associations, that further differentiate stands within the forest type (upland forest or woodland). *OGDF: old growth Douglas-fir. **FF: Douglas-fir or grand fir forest, often with bigleaf maple, vine maple, dogwood, hazel and yew; no other conifers present. †FFHC: Douglas-fir, with various combinations of western hemlock, red cedar, bigleaf maple, yew, dogwood, vine maple, red huckleberry, hazel, and Oregon grape; no oak. ^Denotes a classification that is considered incorrect. The 1914 and 1936 classifications are discussed with the composite graphs for each site (Section 3.2.2).

SITE	EARLIEST GLO SURVEY	HISTORIC VEGETATION	DETAILED HISTORIC VEGETATION	DISTANCE FROM EARLY SETTLEMENT	1914 TIMBER MAP	1936 TIMBER MAP
1	Sept. 1855	Douglas-fir / Upland Closed Forest	Douglas-fir forest, often with bigleaf maple, grand fir, dogwood, hazel, yew. No other conifers present	1855: within 3 miles of road (Terr. Hwy)	merchantable timber	OG DF*
2	Feb. 1855	Douglas-fir / Upland Closed Forest	Low-elevation mesic Douglas fir-western red cedar-western hemlock	1855: settlement within ½ mile to north; many others within 2-3 miles	merchantable timber	OG DF*
3	Sept. 1854	Douglas-fir-oak / Woodland	Scattering or thinly timbered Douglas-fir-white oak woodland. May contain bigleaf maple; brushy understory of hazel, young oaks, oak brush, young fir, bracken.	1854: settlement within 1 ¼ miles	merchantable timber	OG DF*
4	Sept. 1854	Douglas-fir / Upland Closed Forest	Low-elevation mesic Douglas fir-western red cedar-western hemlock	1854: settlement within 1 mile; within 1 mile of road (Terr. Hwy) and several other settlement (20S 5W); 1859: more settlements close by	burned, restocking	OG DF*

Table 4 (cont).

SITE	EARLIEST GLO SURVEY	HISTORIC VEGETATION	DETAILED HISTORIC VEGETATION	DISTANCE FROM EARLY SETTLEMENT	1914 TIMBER MAP	1936 TIMBER MAP
5	**Sept. 1854**	Douglas-fir / Upland Closed Forest	Low-elevation mesic Douglas fir-western red cedar-western hemlock	1854: no settlements	merchantable timber	OG DF*
6	**Sept. 1855**	Douglas-fir / Upland Closed Forest	Douglas-fir forest, often with bigleaf maple, grand fir, dogwood, hazel, yew. No other conifers present	1855: within 2 miles of road (Terr. Hwy); within 1 ½ mile of settlement	merchantable timber	OG DF*
7	**Sept. 1855**	Douglas-fir / Upland Closed Forest	Douglas-fir forest, often with bigleaf maple, grand fir, dogwood, hazel, yew. No other conifers present	1855: several settlements and road (now Territorial Hwy) within 1-2 miles	merchantable timber	DF, large 2nd growth
8	**July 1882**	Douglas-fir / Upland Closed Forest	Low-elevation xeric Douglas-fir-chinquapin-madrone	1882: no settlement	merchantable timber	DF, seedling-sapling-pole
9	**July 1882**	Douglas-fir / Upland Closed Forest	Mesic mixed conifer forest with mostly deciduous understory. May include Douglas-fir, western hemlock, red cedar, grand fir, bigleaf maple, yew, dogwood, white oak, red alder	1882: no settlement	burned, not restocking	recent cut over
10	**Oct. 1889**	Douglas-fir / Upland Closed Forest	FF**, but **burned**, often with scattered trees surviving fire	1889: within ¾ mile of settlement and road (to settle.); "clearing" directly below site	merchantable timber	DF, small 2nd growth

Table 4 (cont).

SITE	EARLIEST GLO SURVEY	HISTORIC VEGETATION	DETAILED HISTORIC VEGETATION	DISTANCE FROM EARLY SETTLEMENT	1914 TIMBER MAP	1936 TIMBER MAP
11	**Feb. 1855**	Douglas-fir / Upland Closed Forest	FFHC[†], but **burned**, often with scattered trees surviving fire	1855: roads and settlements within 2 miles; 1860: settlements within 1 mile	merchantable timber	recent cut over ^
12	**Sept. 1890**	Douglas-fir / Upland Closed Forest	Mesic mixed conifer forest with mostly deciduous understory. May include Douglas-fir, western hemlock, red cedar, grand fir, bigleaf maple, yew, dogwood, white oak, red alder	1856: site not surveyed, settlement within 2-3 miles; 1890: settlement within ¼ mile	merchantable timber	OG DF*

3.2 Fire History of the Southern Willamette Valley Foothills

Fire history is described using composite fire chronologies, quantitative measures of centrality and spread, fire interval distribution, and regeneration following fire. Additionally, the conservative estimates (Rule Sets 1-4) of fire history are compared with the estimate used in this study.

3.2.1 Overview of Fire History

Four hundred and eighteen stumps were identified on 12 sites throughout the study area (Table 5). Stump samples were removed from 38% (159) of all stumps and used for lab analysis; 141 origin years were dated using crossdating methods. Of the 159 samples, 34% (54) had fire scars, and 78 fire scars were dated (Table 5). COFECHA was used to aid in, or verify, crossdating of 63 samples (40%) for the accurate dating of origin and fire scar years.

Fire history is described using the terms fire "event", fire "date", and fire "interval"; to avoid confusion between these terms they are defined here. Fire event refers to a fire that occurred on a site and fire date refers to the date of fire. For example, Sites 2 and 3 both had fire events in 1849, but this is referred to as a single fire date; thus, there are more fire events than fire dates for the study area (58 events and 44 dates). Fire interval refers only to the interval between two fire events on a site. No intervals were calculated between two events on two different sites, so no two fire dates have an interval.

Fire history for the study area was reconstructed using 58 fire events from lab-dated scars of 12 sites. Forty-four fire dates spanned from 1658 and 1979 (Figure 8), occurring between 1466-1997 (1466 is the age of the oldest tree, and 1997 is the last year in the tree ring record). The period of record evaluated for fire frequency changes was 1700 to 1990 since the fire record was very weak until 1700. The number of fire events ranged from two to eight events per site (Table 6). Fire intervals ranged from two years to 191 years (Table 6). Six sites (Sites 3, 5, 6, and 7) had evidence of mixed severity fire as indicated by regeneration cohorts following fire. Two sites

(Sites 8 and 9) had stand-replacing fires as indicated by a regeneration cohort consisting of all sampled stumps plus a lack of scar evidence. Eight fire dates (18%) occurred on two or more sites; these events were called fire episodes.

Fires were concentrated in the dormant season, based on their intra annual ring position. Fifty-eight fire events occurred in the following seasons: dormant season (D) 55%, latewood (A) 36%, early-earlywood (E) 2%, late-earlywood (L) 2%, and unknown (U) 3%; regeneration cohorts, as evidence of fire, were not assigned a season (3%) (Table 6). In western Oregon, the dormant season usually refers to fall; latewood refers to summer; and the growing season refers to spring.

Table 5. Sampling summary. "Total stumps" refers to the total number of stumps found in all plots. "Sampled stumps" refers to the number of stumps from which a sample was removed. The lower part of the table refers to samples. Column 1 is the number of samples with a scar; column 2 is all scars that were crossdated; column 3 is all crossdated pith ages; and column 4 is all samples that required measurements and COFECHA for assistance in dating of the pith and/or scar.

	Total Stumps		**Sampled Stumps**	
	#	**%**	**#**	**%**
Total	**418**		**159**	**38**
Douglas-fir	341	82	150	94
western hemlock	40	10	1	1
western red cedar	11	2.5	3	1
incense cedar	14	3	3	2
grand fir	2	0.5	2	2
big leaf maple	10	2	0	0

# scarred samples	# lab-dated scars	# lab-dated origin dates	# measured / COFECHA - assisted dating
54	78	141	63

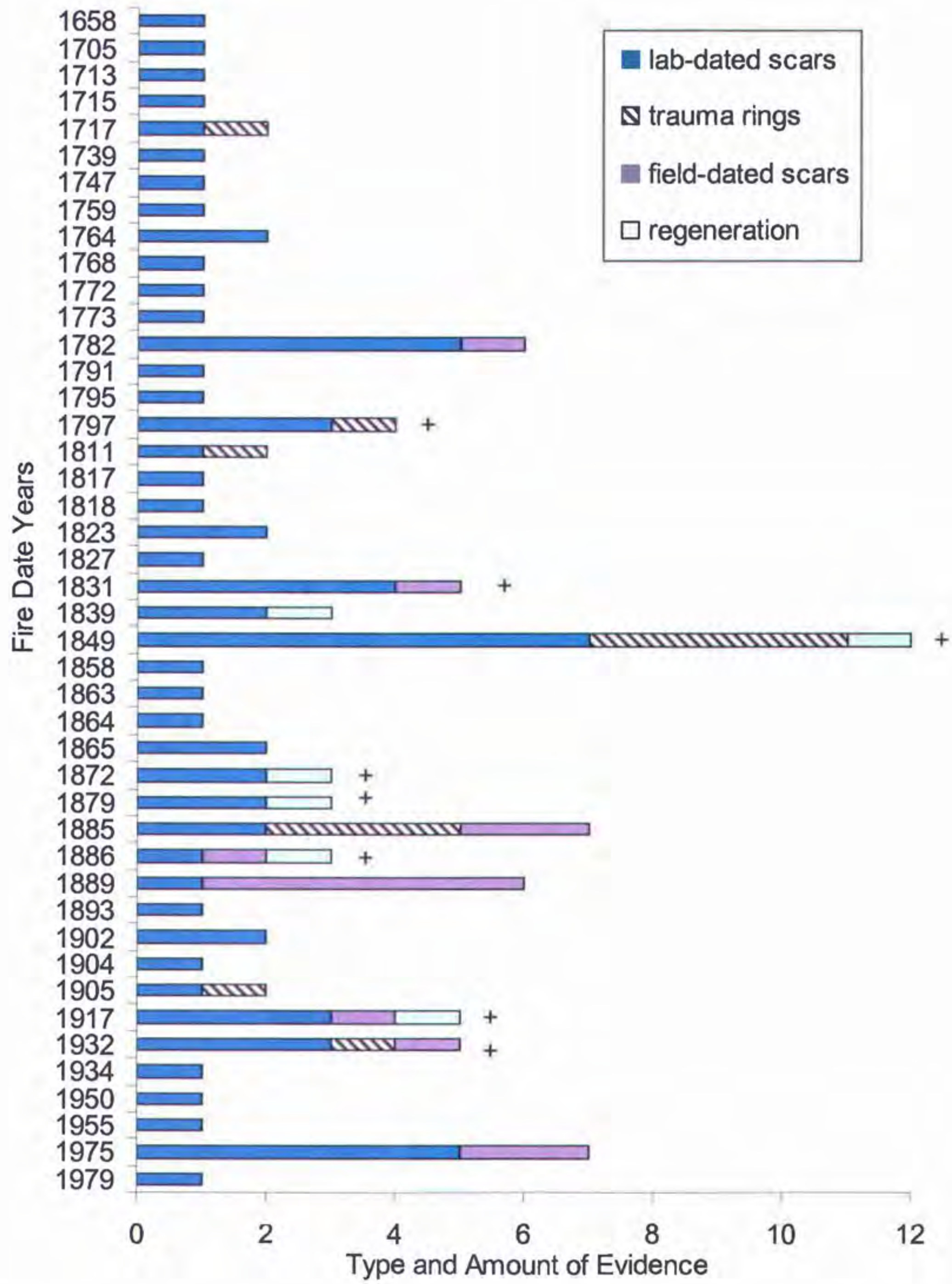

Figure 8. Fire date evidence. All fire dates and the type and amount of lab/field scar, trauma ring, or cohort each is evidenced by. Plus signs (+) indicate fire episodes (fire at more than one site).

Table 6. Fire history for each site. Each fire date is listed along with the season of fire: latewood, dormant, unknown, first 1/3 of earlywood, last 1/3 of early wood (A, D, U, E, L). "R" represents a regeneration cohort without scar evidence. The interval between each fire date is listed to the right of the younger date (for example for Site 1, 1849-1658=191 years).

Site	Fire	Int	Site	Fire	Int
1	1658 D		**8**	1886 R	
	1849 U	191		1975 A	89
	1955 E	105			
			9	1872 R	
2	1772 A			1905 D	27
	1817 A	45		1932 D	33
	1831 A	14			
	1849 D	18	**10**	1872 D	
	1863 D	13		1885 A	13
	1865 A	2		1893 A	8
	1879 D	14		1950 D	57
3	1818 D		**11**	1713 D	
	1831 D	13		1715 D	2
	1849 D	18		1782 D	67
	1864 D	15		1827 A	45
	1872 D	8		1849 D	22
	1879 D	7		1932 A	83
	1902 A	23			
	1934 L	32	**12**	1705 D	
				1717 D	12
4	1764 A			1739 D	22
	1773 D	9		1759 D	20
	1858 D	85		1797 A	38
	1904 A	46		1831 D	34
	1917 A	13		1886 A	55
				1889 D	3
5	1791 D				
	1795 D	4			
	1797 A	2			
	1811 D	14			
	1849 D	38			
	1917 A	68			
6	1747 A				
	1768 D	21			
	1849 A	81			
7	1823 A				
	1839 A	16			
	1979 D	140			

3.2.2 Fire Chronology

Composite fire chronologies for each site and for the west side, east side, and study area were created using FHX2 (Grissino-Mayer 2001a; Figures 9-23). Each sample is represented by pith and bark dates (├ and ┤) (or inner-most and outer-most rings (half-arrow shape)) and the length (in years) of information is symbolized by a horizontal line. The number of each sample is in the right hand column. Red hatch marks represent fire events and blue hatch marks represent trauma rings and suppression or release rings. The composite axis at the bottom of each graph shows each fire event and the resulting intervals. Each site level chronology is scaled to the origin date of the oldest sample or to the cohort fire date. Multiple-site graphs are all scaled to 1466 (oldest origin date in the study area).

The fire chronology at Site 1 was 449 years long (Figure 9). Both fire intervals were over 100 years long, resulting in the longest MFRI of all sites. A cohort appeared circa 1775, but there was no scar evidence on the older tree; consequently this was not considered a cohort resulting from fire for this study. No change in vegetation was noted over the period of history; settlement was within 3 miles by the mid 1800s.

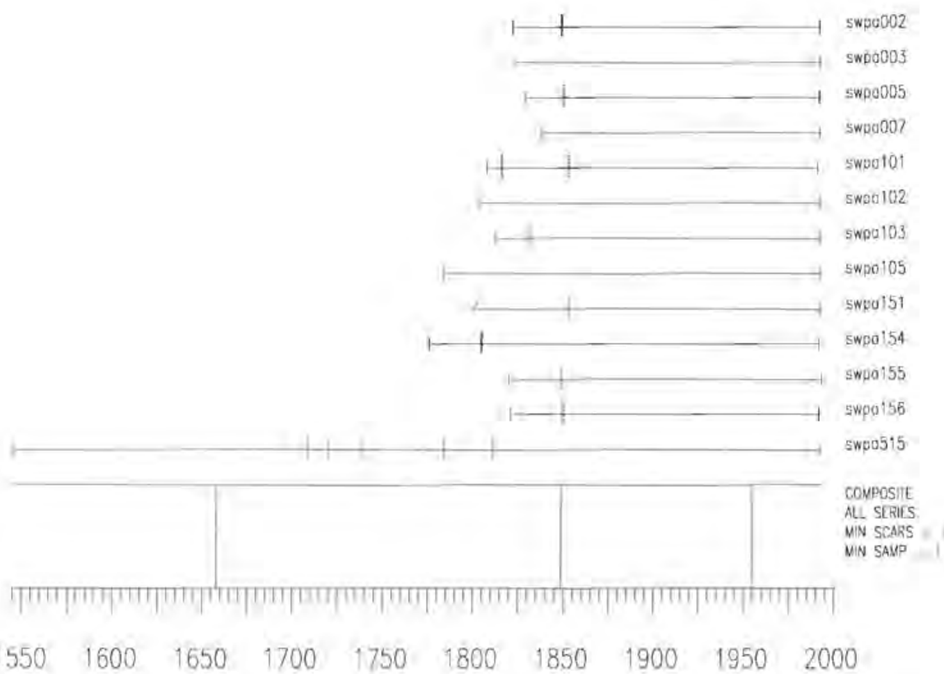

Figure 9. Site 1 Composite fire chronology. Each sample is represented by pith and bark dates (├ and ┤) (or inner-most and outer-most rings (half-arrow shape)) and the length (in years) of information is symbolized by a horizontal line. The number of each sample is in the right hand column. Red hatch marks represent fire events and blue hatch marks represent trauma rings and suppression or release rings. The composite axis at the bottom of the graph shows each fire event and the resulting intervals.

The fire chronology at Site 2 was 531 years long, resulting in the longest history for all sites; however, the fire record does not begin until almost 1775 (Figure 10). Trauma rings were found on the oldest tree prior to scarring and were likely fire related (possibly these fires were of substantially lower severity thus not actually killing the cambium). Fire intervals were relatively short, although variable, ranging from 2 years to 45 years.

No change in vegetation was noted for the period of history. Settlement, however, was within one-half mile by 1855.

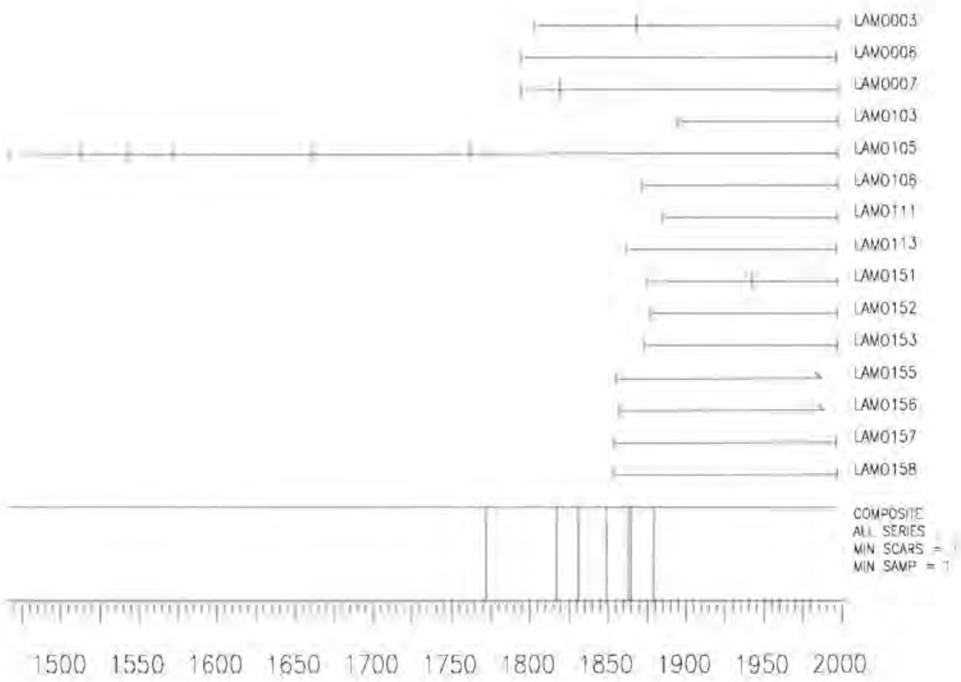

Figure 10. Site 2 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 3 was 197 years long (Figure 11). Even though Site 3's history is less than 200 years, there were eight recorded fire events. In the late 1800s a large pulse of regeneration followed the 1879 fire. Since this site had a relatively short MFRI (17 years), it would seem unlikely to experience a stand replacing fire; however, since plots are relatively small (.5 acre), it is feasible that a half acre area within a stand would experience high severity in a mixed severity fire. Another possible explanation is that the stand was intentionally burned by settlers. The last two fire intervals were longer than that of the preceding ones, possibly owing to effective fire suppression.

Site 3 was the only site mapped as *Douglas-fir and oak woodland* in the mid 1800s. By 1936, it was mapped as *old-growth Douglas-fir*, which may still have included an oak component. There was an Indian trail very close to, if not directly through, this stand. Unfortunately, the length of record for this site is too short to capture possible Native American influence on fire occurrence. Euro-American settlement was within just over one mile by 1854.

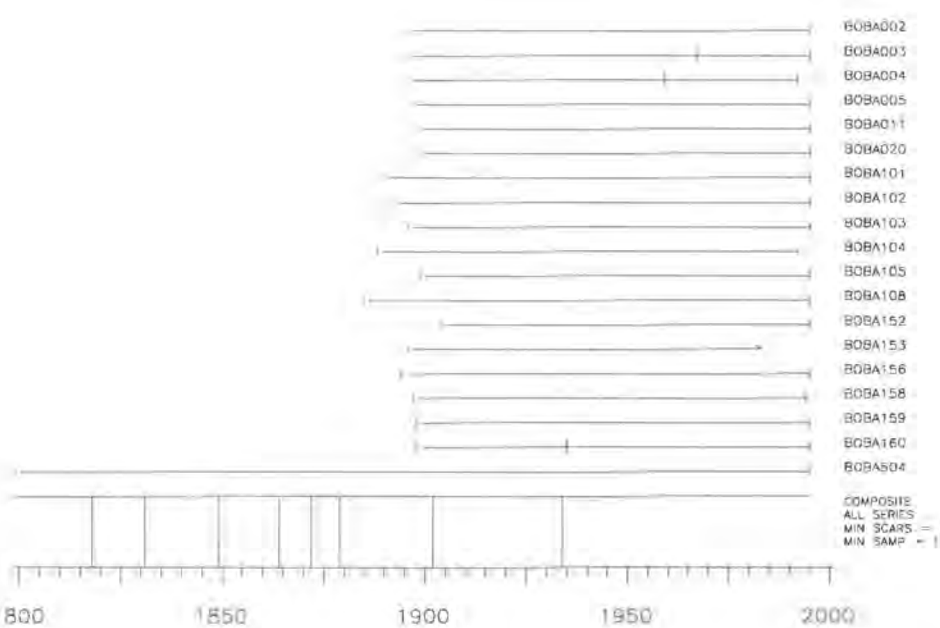

Figure 11. Site 3 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 4 was 244 years long (Figure 12). Fire intervals were represented equally by relatively short and long intervals. No fire has occurred since the onset of fire suppression.

Site 4 was *burned, restocking* according to the 1914 timber map and mapped as *old-growth* in 1936. Fire in 1904 corroborates the 1914 map. This stand in 1936, however, would have been composed mostly of 50-year-old trees, which, depending on tree diameters may have been considered old-growth at the time. There is no definition of old-growth from the 1936 map, although 50 year old trees can be quite large, so it is feasible that it was classified correctly or this sight may have been adjacent to an old-growth stand. Settlement was within 1 mile by 1854; this site was also within 1 mile of the old California Road (now called Territorial Highway) in 1854, which was the main travel route between California and the Willamette Valley. An 1859 GLO map shows increased settlement in the vicinity.

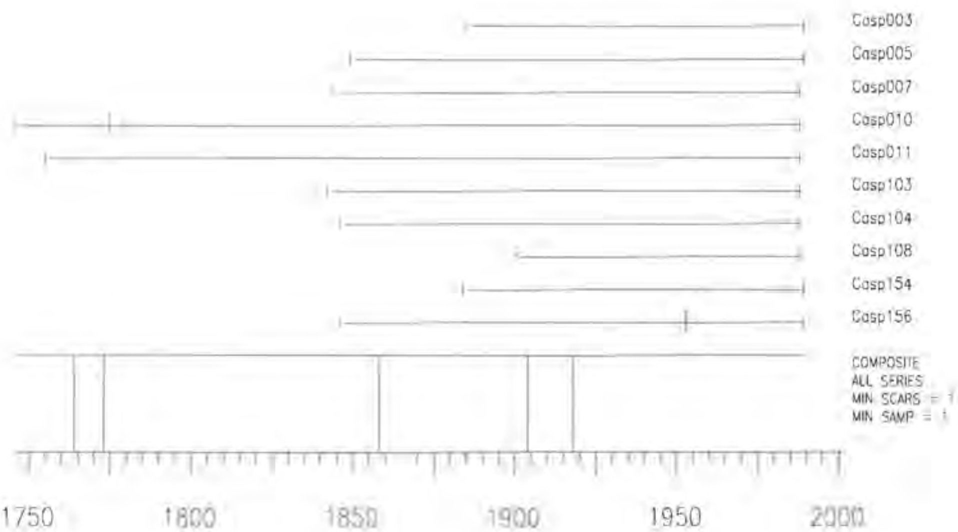

Figure 12. Site 4 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 5 was 230 years long (Figure 13). Fire intervals were progressively longer through time, with quite short pre-settlement intervals (2, 4, and 14 years) and a virtual end of fires following the settlement period. GLO maps showed no settlements nearby in 1854. A regeneration cohort followed the fire of 1917, indicating a high severity fire, although this site was mapped as old-growth in 1936.

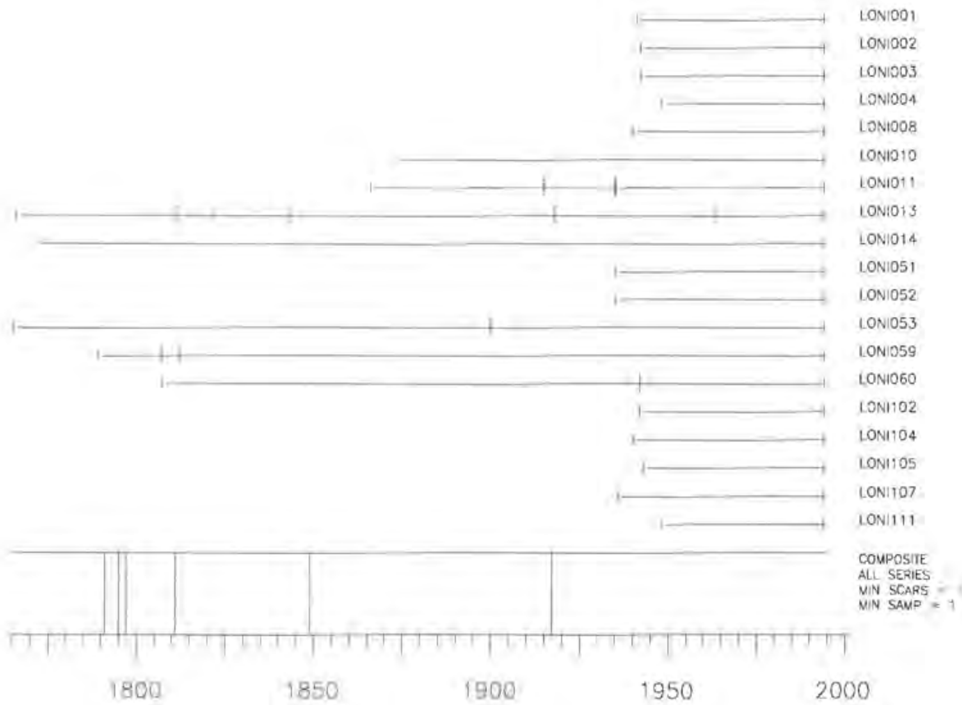

Figure 13. Site 5 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 6 was 251 years long (Figure 14). The only two fire intervals were quite disparate, although both intervals of this length were found on other sites. A cohort regenerated followed the 1849 fire, then fire evidence ceased abruptly. This site was an exception with regards to fire during and after settlement (all other sites had fire after settlement).

No vegetation change was noted for the period of history. The site was located within 1½ miles of settlement and within 2 miles of the old California Road in 1855.

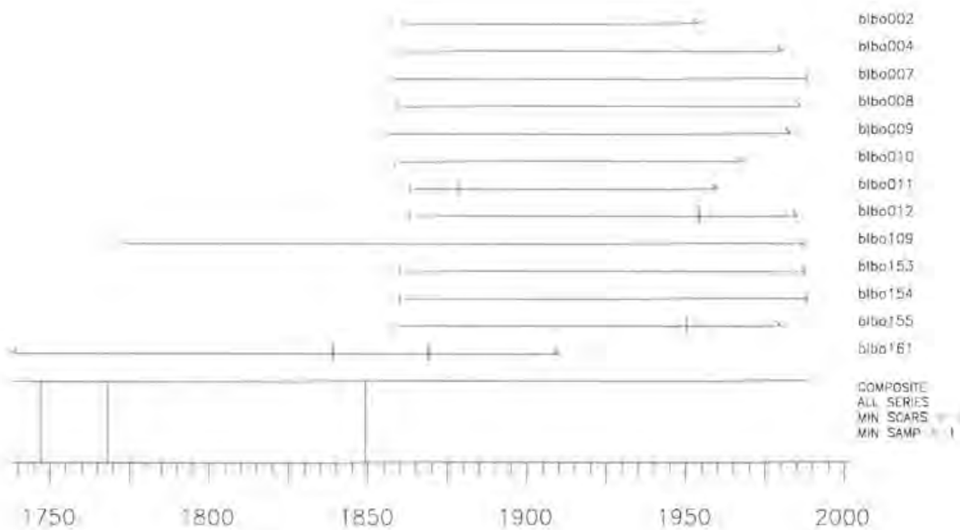

Figure 14. Site 6 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 7 was 270 years long (Figure 15). Site 7 burned twice within 16 years in the early 1800s and then experienced a rather long fire free period following settlement. A cohort followed the fire of 1839. This site had the longest time between fire and the onset of regeneration (22 years) and the longest time for cohort establishment (39 years) of all sites with post-fire cohorts.

No vegetation change was noted for the period of history. This site was mapped as *merchantable timber* in 1914 and as *large second growth* in 1936 even though this site had mostly younger trees. Several settlements and the old California Road were within 11/2 miles by 1855.

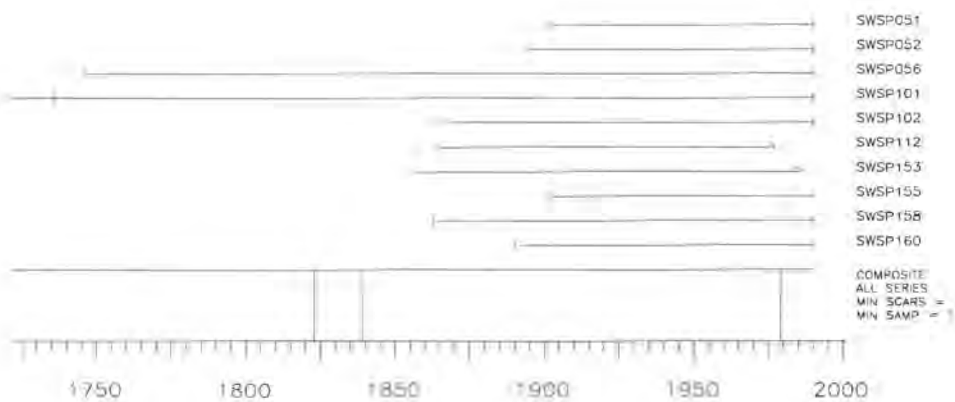

Figure 15. Site 7 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 8 was 110 years long (Figure 16). Historically, there was a small finger valley to the west of Site 8 was Douglas-fir, the head of which was *Douglas-fir-oak-ponderosa pine* (directly adjacent to this site; see Figure 4). By 1914 the valley was *non-timber* and by 1936 was a mix of *non-timber* and *seedling/sampling/pole* (this site was mapped as the latter in 1936). Based on these maps, this valley may have been cleared and burned in the late 1800s for grazing, resulting in the 1886 stand replacing fire on this site. By 1936 the site would have had trees (40 years old) pole sized or slightly larger, which *may* support the mapping classification as seedling/sapling/pole. No settlement was nearby when mapped in 1882.

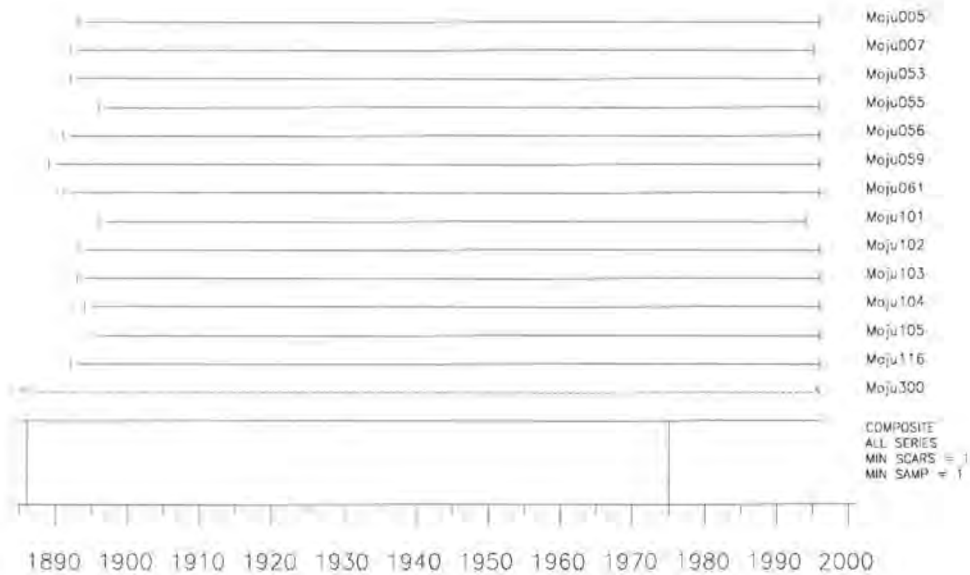

Figure 16. Site 8 Composite fire chronology. The last sample line (Moju 300) is not a sample, but the regeneration cohort year added for graphing. See Figure 9 for graph description.

Site 9's fire chronology was 123 years long (Figure 17). In 1914, Site 9 was mapped as *burned, not restocking*. The fire of 1905 supports that classification. In 1936 the site was mapped as *cutover since 1920*. It is unclear whether the burn in 1932 was called cutover or possibly the site was cut after the burn; there were no old stump remnants present during sampling, so the site appears not to have been cut (although the surrounding area may have been cut). There was no settlement nearby in 1882.

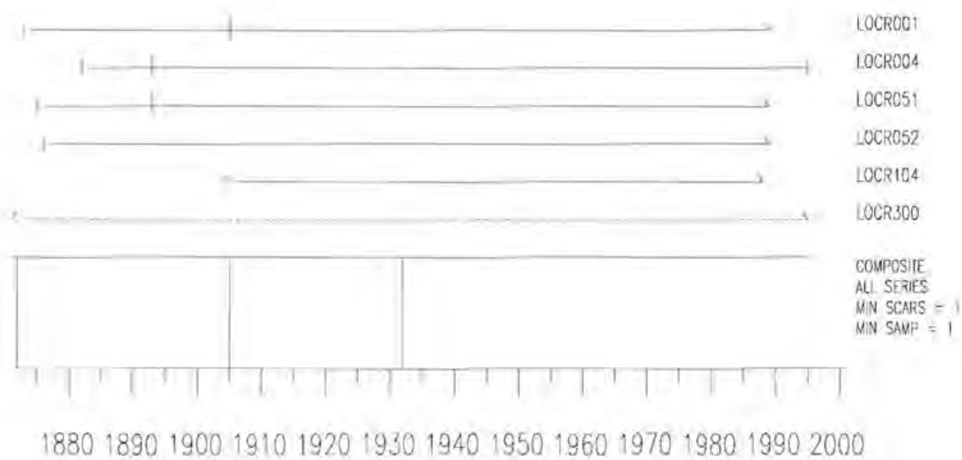

Figure 17. Site 9 Composite fire chronology (123 years). The last sample line (LOCR 300) is not a sample, but the regeneration cohort year added for graphing. See Figure 9 for graph description.

The fire chronology at Site 10 was 139 years long (Figure 18). All intervals, excluding the last, were similar (less than 25 years) and fire ceased abruptly around the turn of the 20th century. In 1889, surveyors described this site as "burned and with a scattering of surviving trees" (from surveyor notes). Two fires in the late 1800s (1872 and 1885) corroborate this mapping classification. Settlement was less than a mile away and a human-made clearing was directly below the site in 1889. This site was mapped in 1936 as *small 2nd growth*; ages of sampled trees were 60 to 80 years around 1930, which likely corroborates that classification (the size of "small 2nd growth" is not known, although a reasonable deduction can be made).

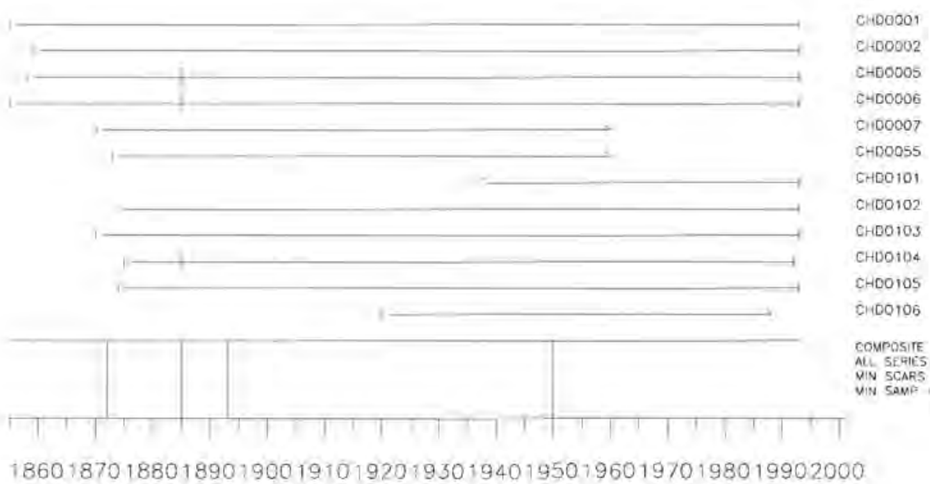

Figure 18. Site 10 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at site 11 was 351 years long (Figure 19). Fire intervals were quite variable for Site 11, ranging from 2 to 83 years. The site was mapped in 1855 as *burned* "with scattered surviving trees". Sampling revealed fires in the mid 1800s (1831 and 1849). In 1936, the site was mapped as *recent cutover*; there is no evidence to suggest that this classification was correct. Settlement and roads were located within two miles of the site in 1855 and within one mile by 1860.

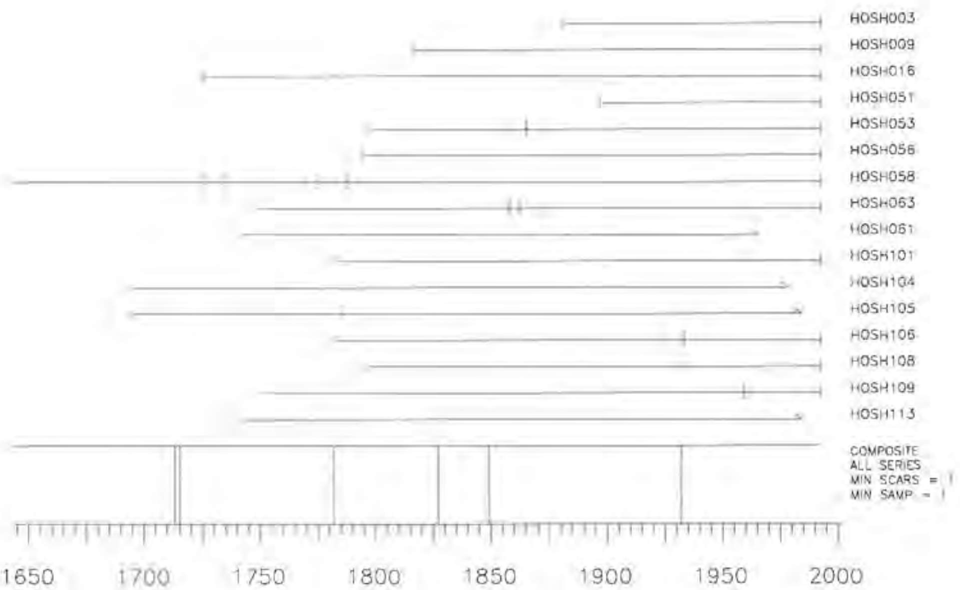

Figure 19. Site 11 Composite fire chronology. See Figure 9 for graph description.

The fire chronology at Site 12 was 322 years long (Figure 20). The fire return intervals were relatively short, ranging from 3 to 55 years and fire ceased following the settlement period (late 1800s). The actual site was not surveyed until 1890, although settlement was within 2-3 miles on an 1856 map and within ¼ mile by 1890. No change in vegetation was noted for the period of history.

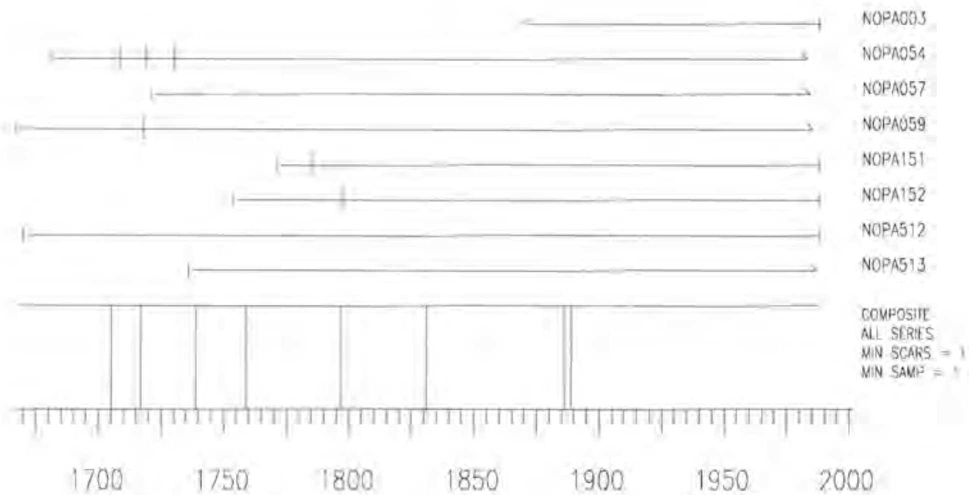

Figure 20. Site 12 Composite fire chronology. See Figure 9 for graph description.

The composite fire chronology for the west (Coast Range) side of the valley contains the combined fire history of seven sites (Figure 21). West side sites were located in or adjacent to an abundance of Douglas-fir or Douglas-fir-oak woodlands, which were situated very close to the valley floor before the 1850s. Most sites were also adjacent to Lorane Valley, which is a smaller north-south oriented valley to the west of the Willamette Valley. The old California Road (now called Territorial Highway), which was the main route between California to the Willamette Valley during the 19th century, passed through Lorane Valley; consequently, settlement was well established there by 1860.

West side sites, collectively, had periods of high fire occurrence interspersed with periods of no fire occurrence. Periods of high fire occurrence include 1764-1773 and 1791-1797. The decade following 1800, which would be a time of very limited Native American burning, lacked fire; however, fire-free decades (or longer) were not rare, as there had just been a fire free period from 1775 to 1790. The period between 1811 and 1879 was characterized by at least one fire every decade, including half of the fire episodes for the study area. There was no fire recorded for almost 25 years following this period of increased fire. Fires occurred again in the early 1900s, corresponding to a very dry climatic period when regional fires were known to have occurred. The 1900s, while not lacking fire, had considerably longer fire intervals.

The East (Cascades Range) side composite fire chronology contains the combined fire history of five sites (Figure 22). Four of the five sites (Sites 8, 9, 10, and 11) were located relatively far from the valley floor; Site 12, while also in the closed canopy Douglas-fir forest, was located closer to the valley and to Douglas-fir-oak woodlands.

East side sites, collectively, generally had regularly spaced fires with intervals 20-25 years long. In the early 1700s and around the settlement period (1885-1895) the number of fires increased from the norm.

The study area composite fire chronology contains the combined fire history of all twelve sites (Figure 23). Between 1700 and 1905, fires occurred regularly at least once every ten years with the exception of a 22 and 14 year break (1717-1739 and 1797-1811). During the fire suppression era fires decreased dramatically, as expected. By visual assessment of the composite fire chronologies, there does not appear to be changes in fire occurrence concurrent with changes in land use or climate over the period from 1700 to 1905.

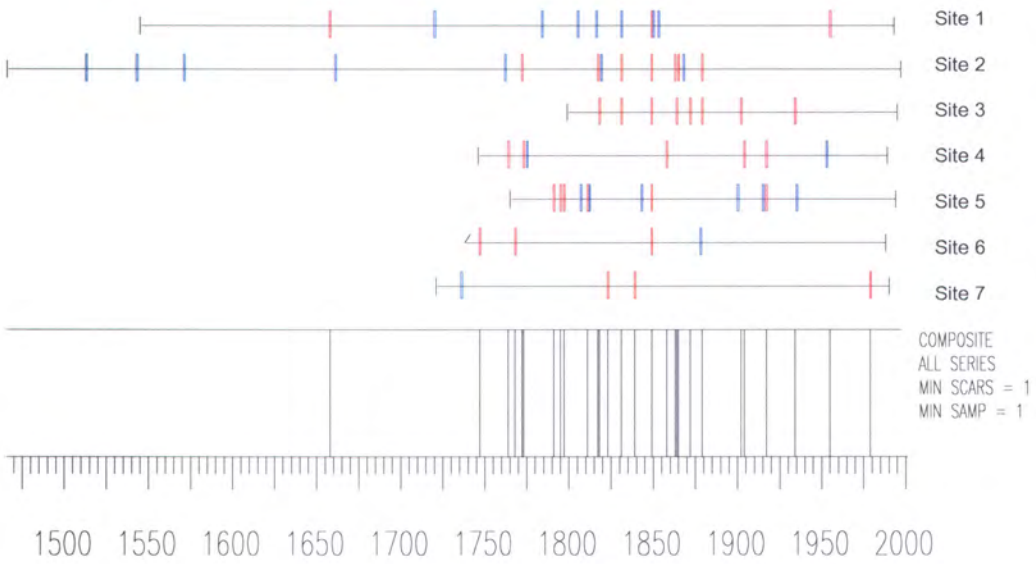

Figure 21. West side sites composite fire chronology. Note: blue hatch marks represent trauma rings only.

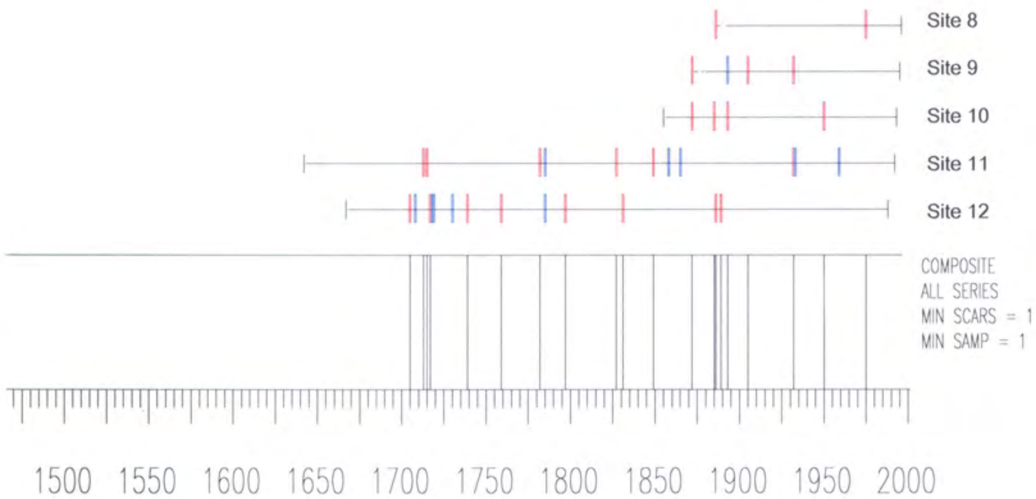

Figure 22. East side sites composite fire chronology. Note: blue hatch marks represent trauma rings only.

Figure 23. Study area composite fire chronology. Note: blue hatch marks represent trauma rings only. The land use and climate change timeline shows the time periods when change would be expected in the fire chronology. I.: no Euro-American influence and no drought-fire relationship; II: Native American influence low and no drought-fire relationship; III: very little human influence (Euro-American or Native American) and climate beginning to warm (drought-fire relationship weak); IV: Euro-American influence and significant drought-fire relationship; V: effective fire suppression efforts and significant drought-fire relationship.

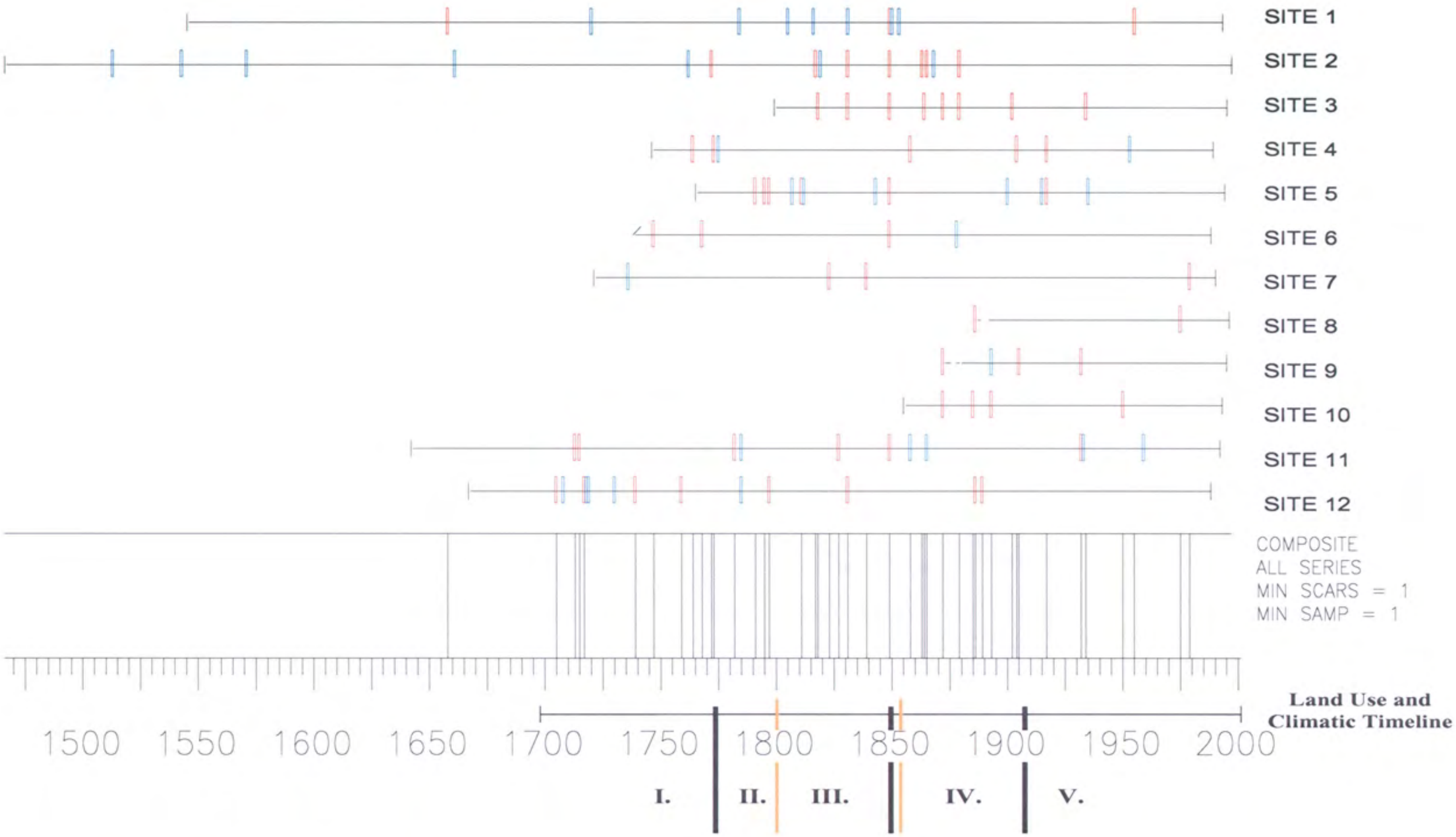

Figure 23. Study area composite fire chronology.

3.2.3 Fire Frequency

Seven sites (Sites 2, 3, 4, 5, 10, 11, and 12) had three or more fire intervals, four sites (Sites 1, 6, 7 and 9) had two intervals, and one site (Site 8) had only one fire interval. The mean of all site-level mean fire return intervals (MFRI) was 49 years (with a standard deviation (SD) of 39 years) and MFRI ranged from 17 to 148 years (Table 7). MFRI differed between the west (54 years) and east (43 years) sides of the study area.

Weibull median probability intervals (WMPI) were also calculated for the sites with three or more fire intervals. WMPI ranged from 15 to 33 years with an average of 22 years (Table 7). Using the Weibull interval for sites that had a lower d-statistic than the empirical distribution d-statistic (6 of 7 sites, 4 of which were significant), the average fire frequency was 47 years for all 12 sites. The average difference for site-level MFRI and WMPI was 5 years, +/- 3 years (only for sites with lower Weibull d-statistics).

Relative fire frequency (RFF) is graphically represented to show the fire interval distributions by site (Figure 24) and for the east side, west side, and study area (Figure 25). It is important to remember that fire intervals were computed only within, not among, sites. Therefore the RFF for several sites combined (east, west, or study area) is simply the compilation of each site's intervals. For example, on the east side graph, the "0-10" year intervals from Sites 10, 11, and 12 were combined to produce 3 intervals, which when divided by the total of all east side intervals (18) resulted in an RFF of 0.17.

Fire frequency on the east side of the valley was more evenly distributed than west side intervals (Figure 25). On the east side, intervals between 1 and 40 years represented 68% of all intervals and were uniformly distributed among fire interval classes. The remaining 38% of fire intervals on the east side were somewhat evenly distributed between 40 and 90 years, although 70-80 year intervals were not observed (Figure 25). On the west side, fire intervals less than 20 years long constituted 57 % of all intervals. The next most frequent class of fire intervals were uniformly distributed between 20 and 50 years (21%) (Figure 25). The only fire intervals over 100 years long (11%) occurred on the west side (Figure 25).

The fire frequency distribution for the whole study area was positively skewed; 70% of all intervals were less than 40 years in length. Almost half (48%) of all intervals were less than 20 years, and 16% of all intervals were over 80 years.

Table 7. Statistics for each site. Sites are separated by number of intervals: the top 7 sites have ≥ 3 intervals and the bottom 5 sites have < 3 intervals. Beginning and ending years are the earliest origin date and the cut date, # int is the number of fire intervals, MFRI is the mean fire return interval, Med Int is the median fire return interval, WMPI is the Wiebull median probability interval, SD is the stand deviation of the MFRI, Min and Max Int are the minimum and maximum fire intervals, LEI and UEI are lower and upper Weibull exceedance probabilities, empirical and Weibull d-stats and probabilities are the last four columns. Bolded numbers in the d-stat columns are the lowest d-statistic for each site with both an empirical and Weibull d-statistic.

Site #	Begin Yr	End Yr	# Int	MFRI	Med Int	WMPI	SD	Min Int	Max Int	LEI	UEI	MHI	emper d-stat	emper prob>d	Weibull d-stat	Weibull prob>d
2	1466	1997	6	18	14	15	14.37	2	45	5	33	>1000	0.435	0.14	**0.181**	0.97*
3	1799	1995	7	17	15	16	08.77	7	32	8	26	63	0.219	0.89	**0.144**	0.99*
4	1746	1989	4	38	30	31	35.30	9	85	8	74	>1000	0.335	0.75	**0.275**	0.92
5	1765	1994	5	25	14	16	27.88	2	68	2	54	>1000	0.394	0.42	**0.212**	0.98*
10	1855	1993	3	26	13	21	26.96	8	57	5	51	>1000	0.439	0.61	**0.344**	0.87
11	1642	1992	5	44	45	33	32.78	2	83	8	86	>1000	**0.207**	0.98*	0.216	0.97
12	1667	1988	7	26	22	23	17.44	3	55	8	46	>1000	0.171	0.98	**0.133**	0.99*
	mean	-----	---	**28**	-----	**22**	-----	-----	-----	----	-----	-----	-----	-----	-----	-----
1	1545	1993	2	148	148	-----	60.81	105	191	----	-----	-----	-----	-----	-----	-----
6	1738	1988	2	51	51	-----	42.43	21	81	----	-----	-----	-----	-----	-----	-----
7	1721	1990	2	78	78	-----	87.68	16	140	----	-----	-----	-----	-----	-----	-----
8	1886	1996	1	89	X	-----	X	X	89	----	-----	-----	-----	-----	-----	-----
9	1872	1995	2	30	30	-----	04.24	27	33	----	-----	-----	-----	-----	-----	-----
	Mean (all sites)	-----	---	**49**			**39**									

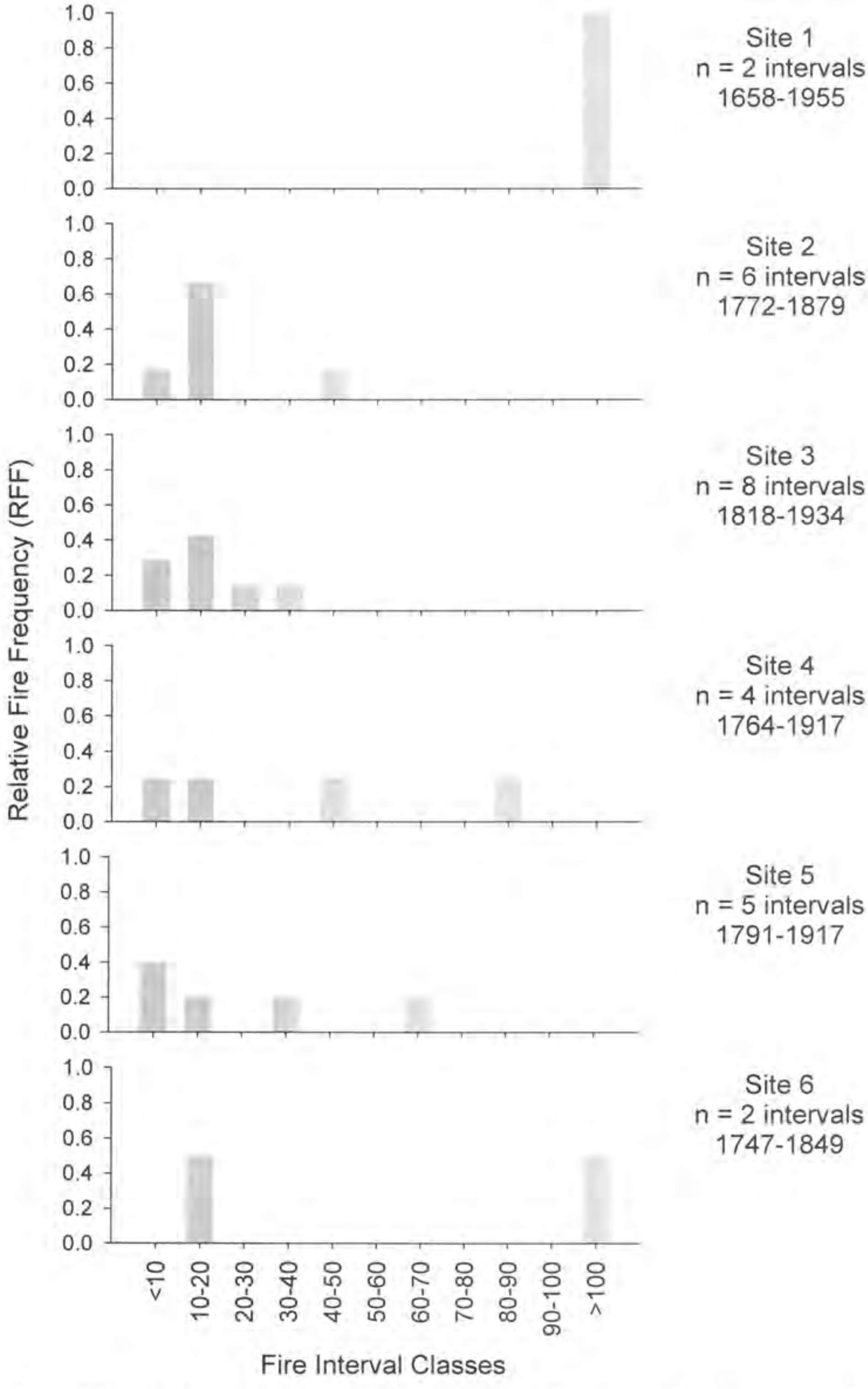

Figure 24. Site level relative fire frequency (RFF) for 10-year fire interval classes. For each site, the number of intervals is listed as well as the first and last fire dates.

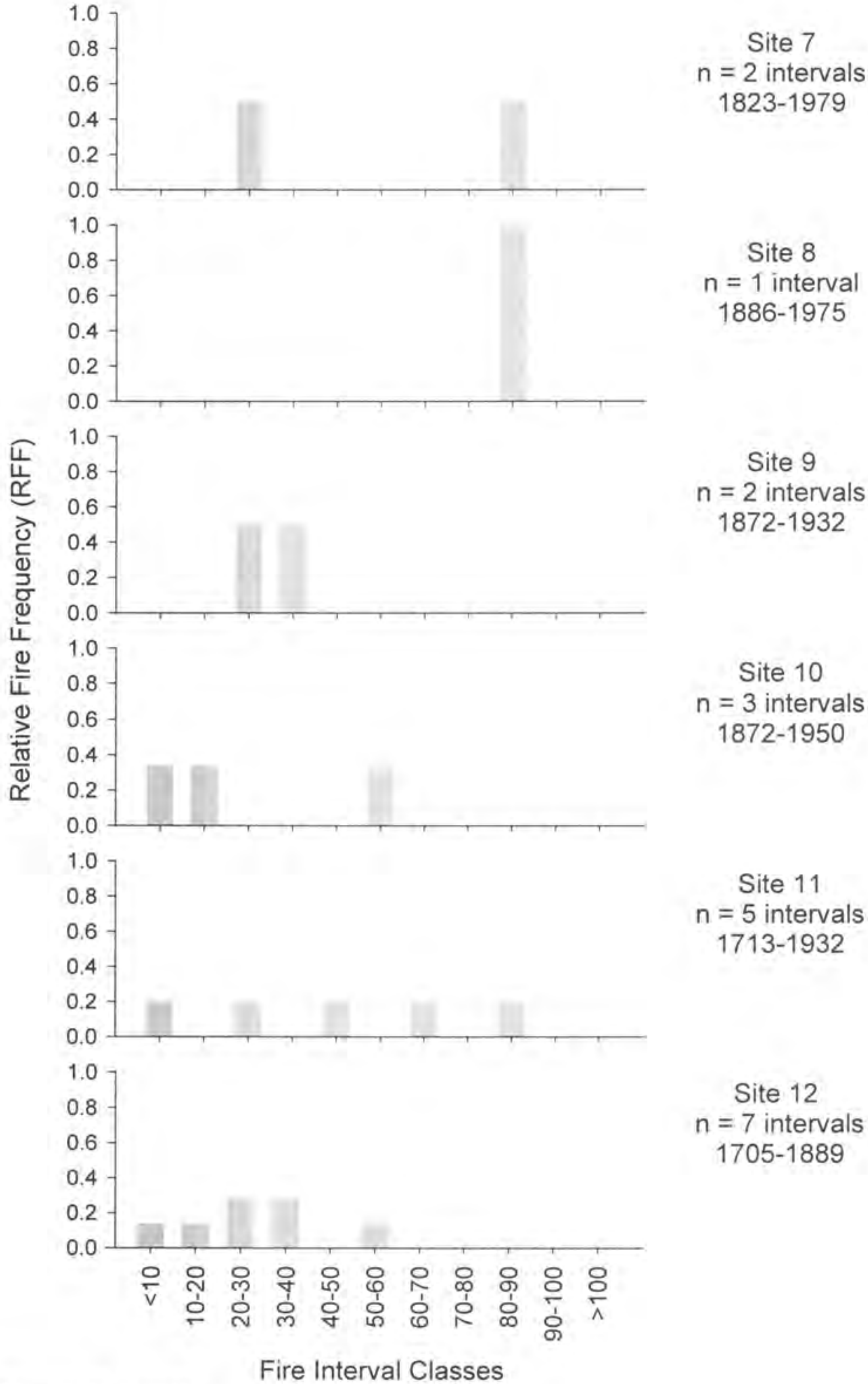

Figure 24 (cont).

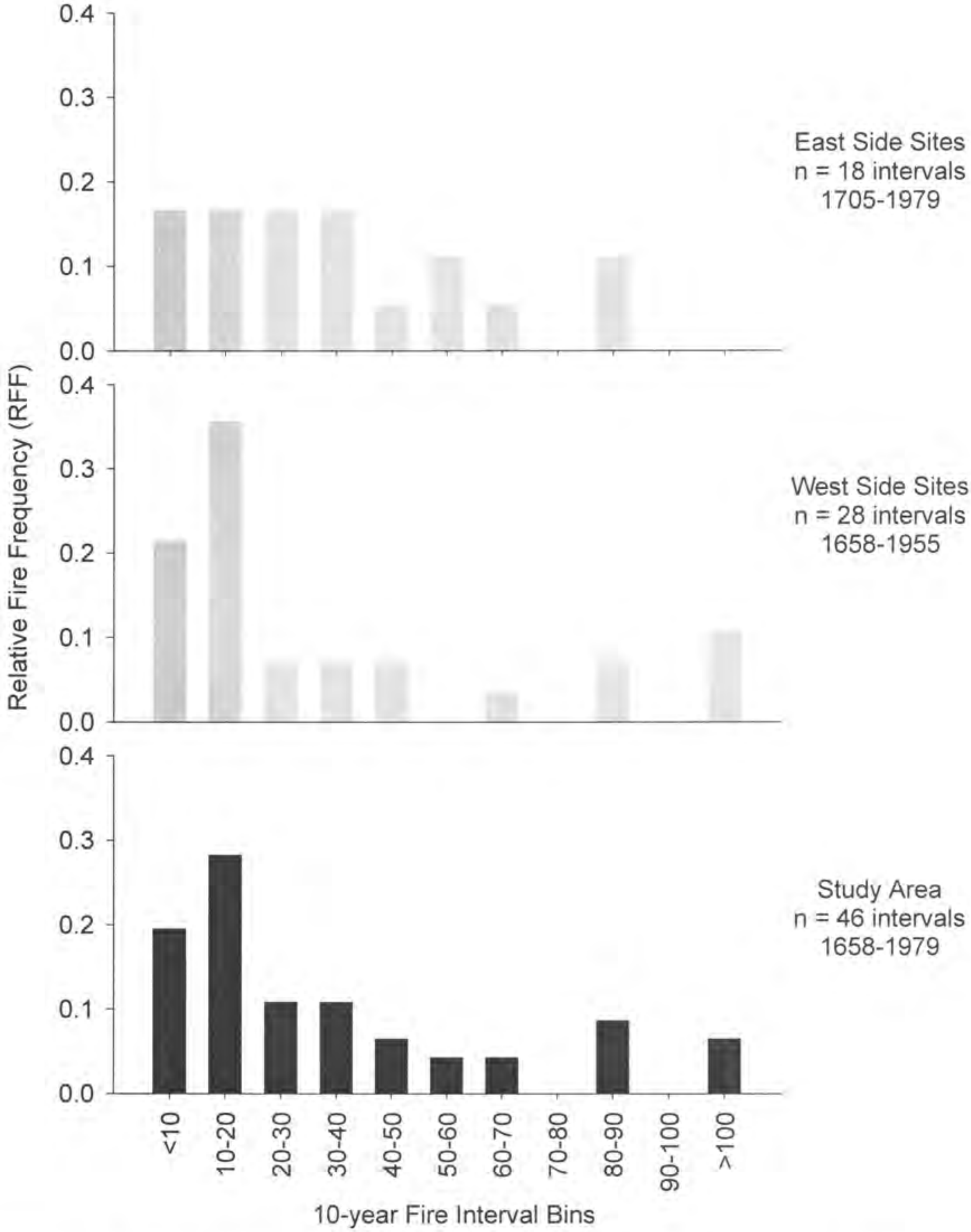

Figure 25. Multiple-site relative fire frequency (RFF). Note that the RFF percentage scale (0-0.4) is different than that of site-level RFF (0-1) since no one interval bin represents more than 40% of all intervals. Intervals for the east side are much more evenly distributed than west side sites. Composite fire frequency distributions are positively skewed, with the majority of intervals less than 40 years long.

3.2.4 Fire Severity

Sampling was not conducted with the goal of determining fire severity; however, moderate and high severity was estimated based on regeneration cohorts. Regeneration in this study was limited to only mixed severity fire events. Fifty percent or more of all samples had to regenerate after a known fire or were used to establish a fire event. It was assumed that large pulses of Douglas-fir regeneration occurs in high severity patches located within mixed severity fire events.

Using the 50% cohort rule, six fire events on six sites (Table 8) were considered mixed severity events. The number of samples equaling 50% ranged from five to 18 samples per site, with an average of eleven samples. Had a more relaxed cohort rule been used, several more sites would have had fire events with regeneration evidence, for example, Site 2. (see Site 2 text and Figure 9 in Section 3.2.2). Five of the six mixed severity fire events occurred on more than one site (fire episodes), but they were mixed severity on only one site.

Table 8. Site and year of mixed severity fires.

Site #	Fire Event	Multiple-site	Number of samples
3	1879	Yes	18
5	1917	Yes	12
6	1849	Yes	11
7	1839	No	8
8	1886	Yes	13
9	1872	yes	5

3.3 Regeneration Following Fire

Regeneration times were based on the calendar years of fire and cohort pith ages of 6 fires from 6 sites. The time since fire for the first individual of a cohort to regenerate ranged between 1 and 22 years with an average of nine years; 2/3 were less than 6 years. The time for a cohort to regenerate ranged from 7 to 39 years with an average of 16 years; five out of the six were less than 20 years.

3.4 Change of Fire History over Time

Fire history of the study area and of each valley side, including fire frequency and fire interval change over time, was qualitatively described in Section 3.2.2 by a visual assessment of the composite fire chronologies (Figures 21-23).

Site-specific fire intervals became longer over the period of record, but only minimally so (Figure 26). No significant difference in fire frequency was found for the study area, by century or by land use time periods (1700-1850, 1851-1920, and 1921-1990), despite a visually apparent difference (Figures 27 and 28). A Pearson chi-squared test for difference in the number of fires was computed for each time period (Table 9). More fires than expected occurred during the 1800s and less than expected occurred in the 1900s; however, the difference was not significant ($p = 0.52$, 2 d.f.). In addition, more fires than expected occurred during the settlement period (1850-1920) and less fires than expected since the start of fire suppression (1920) although these changes were not significant ($p = 0.20$, 2 d.f.). In each case, the number of fires for the first temporal bin (1700s and 1700-1850) was exactly as expected (15 and 23 fires respectively).

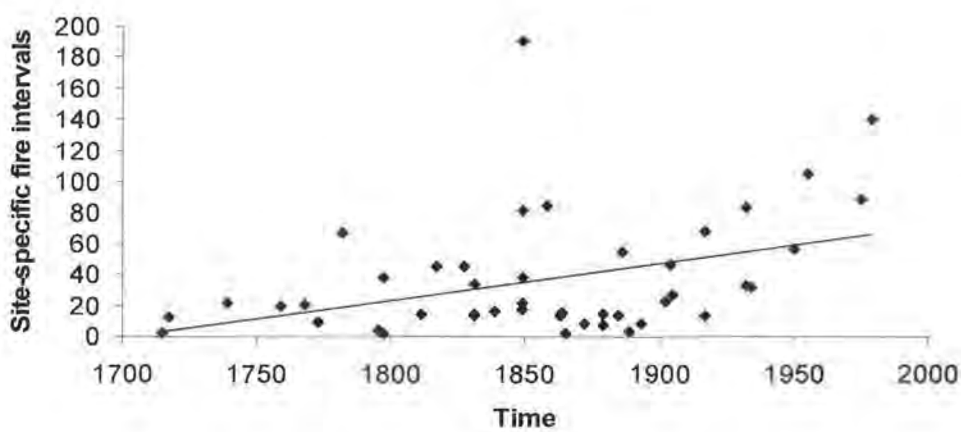

Figure 26. Length of site-specific fire intervals over time. $R^2 = 0.15$.

Table 9. Pearson chi-squared tests for difference in number of fires through time. Numbers in parenthesis are the expected values. Expected values were determined by evenly distributing fires over time.

Century	**1700-1800**	**1800-1900**	**1900-1990**	**Test statistic**
# fires	15	18	10	x^2= 2.38
	(15)	(15)	(13)	p = 0.52, 2 d.f.
Land Use	**1700-1850**	**1850-1920**	**1920-1990**	
# fires	23	14	6	x^2 = 3.2
	(23)	(10)	(10)	p = 0.20, 2 d.f.

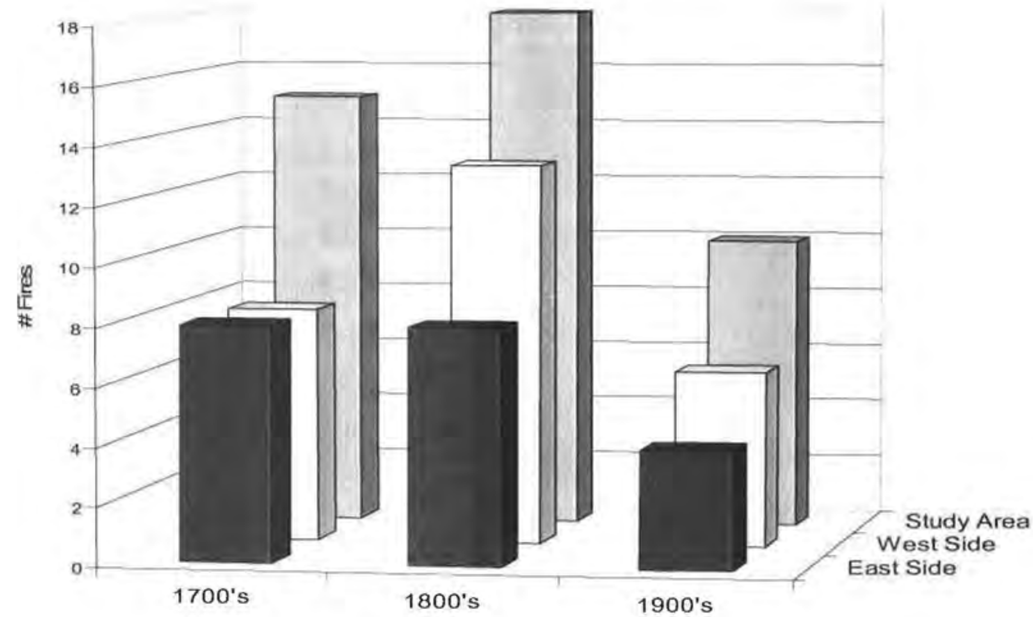

Figure 27. Fire recurrence over the past three centuries for the study area and for each valley side. East and West side fires do not add up to study area fires since these are fire events not fire dates.

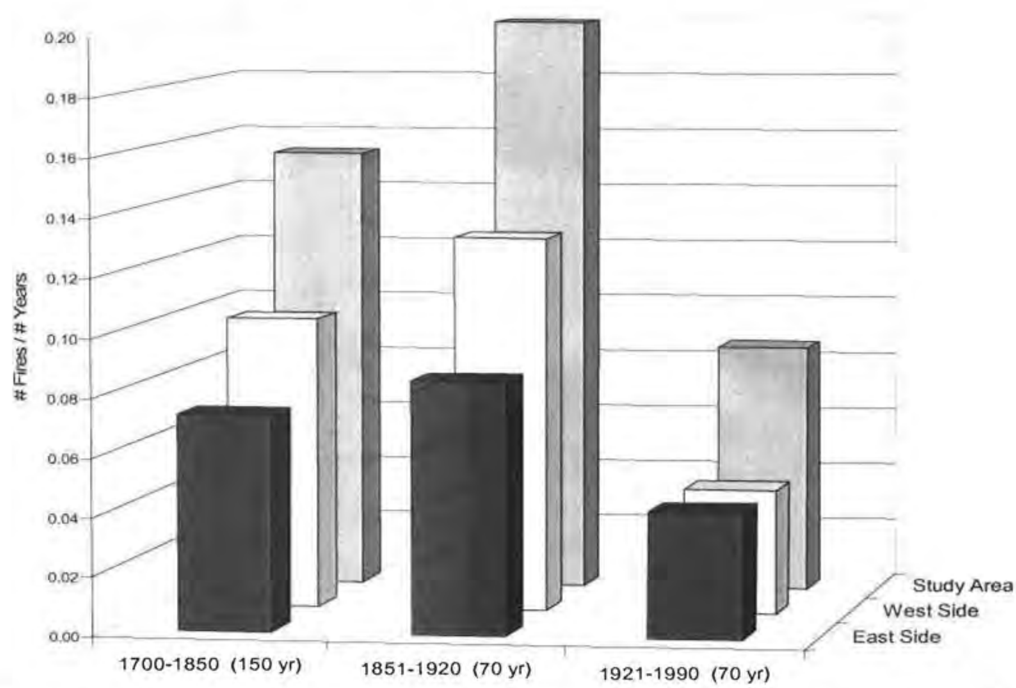

Figure 28. Fire recurrence during land use change temporal bins. Number of fires is divided by the number of years in the bin since the bins are of different length.

The relationship between climate, specifically drought, and fire events was evaluated using the superposed epoch analysis (SEA; Baisan and Swetnam 1997, Grissino-Mayer and Swetnam 2000). Using all fire dates (1700 to 1990) the year of fire was very weakly related to drought but this relationship was not statistically significantly at the .05 level (Figure 29a). The year of fires before 1850 were not related to drought, although the 3rd year prior to fire appeared weakly related (Figure 29b). Fire dates after 1850 were significantly related to drought (Figure 29c).

The effects of climate and land use on fire recurrence were evaluated using a Pearson chi-squared test for difference between the number of fires in four time periods corresponding to the combination of climate and land use changes (Table 10). There was no significant difference in fire recurrence during the four time periods. For the time periods 1700 to 1800 and 1800 to 1850, the number of fires that occurred was as expected. During the time period 1850 to 1925, the number of fires that occurred was higher than expected, but not statistically significant. During the time period 1925 to 1990 the number of fires that occurred was less than expected, although not statistically significant. Figure 30 depicts the number of fires per decade for the study area.

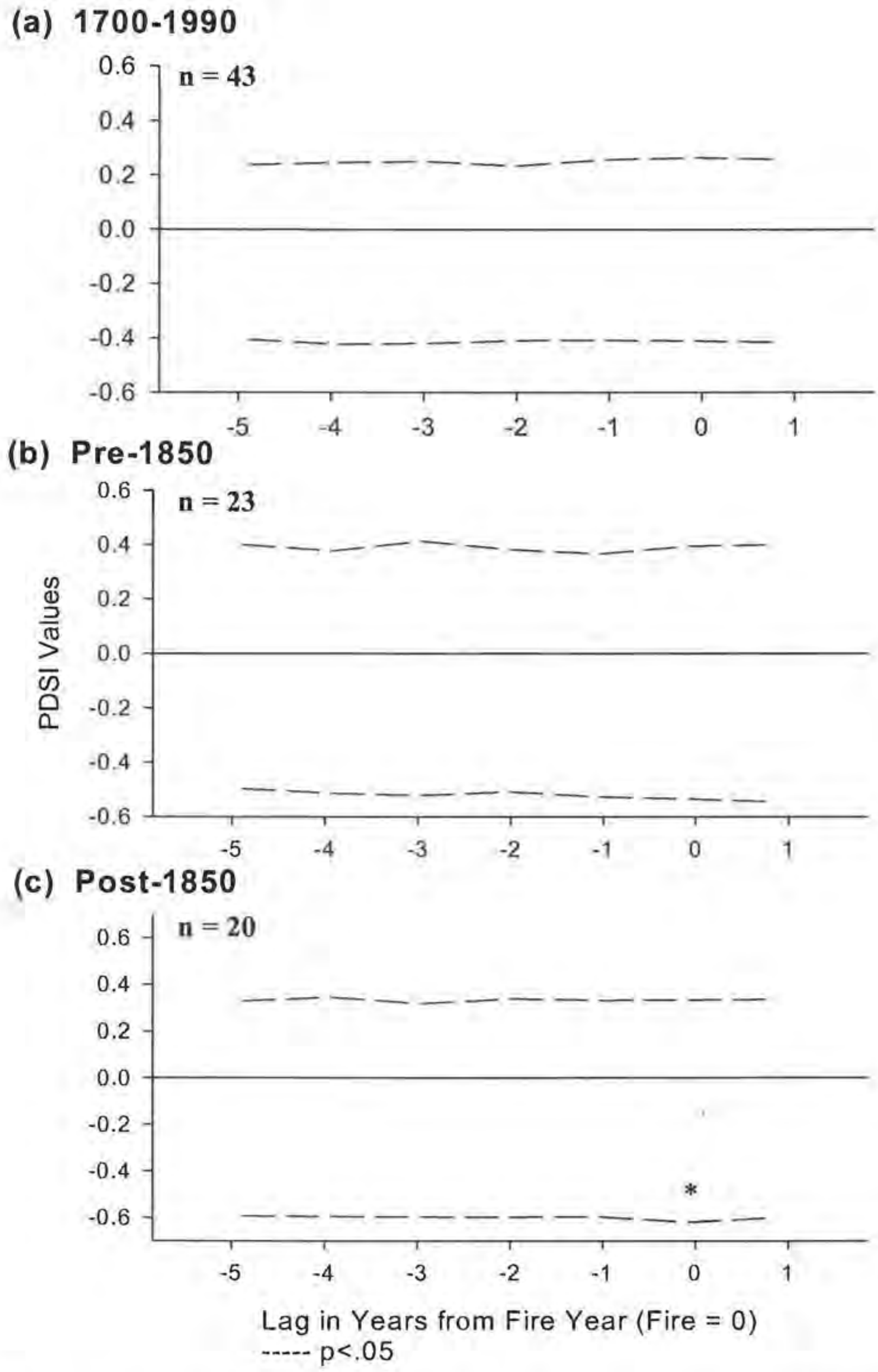

Figure 29. Superposed epoch analysis of fire dates compared with Palmer drought severity index (PDSI) constructed from tree rings. PDSI values less than zero are more droughty than average and values more than zero are less droughty than average. The fire year is "0"; "-1" is one year prior to the fire year, and so on. [* = significant at .05]

Table 10. Pearson chi-squared tests for difference between number of fires through time. Expected values (in parenthesis) were determined by distributing the number of fires evenly over time.

	1700-1800 no climate * native	**1800-1850** weak climate	**1850-1925** climate * settle	**1925-1990** climate * supp	**Test statistic**
human	15	8	14	6	$x^2 = 2.56$, 3 d.f.
	(15)	(7)	(11)	(10)	$p = 0.46$
climate	15	8	--------------20--------------		$x^2 = 0.19$, 2 d.f.
	(15)	(7)	(21)		$p = 0.91$

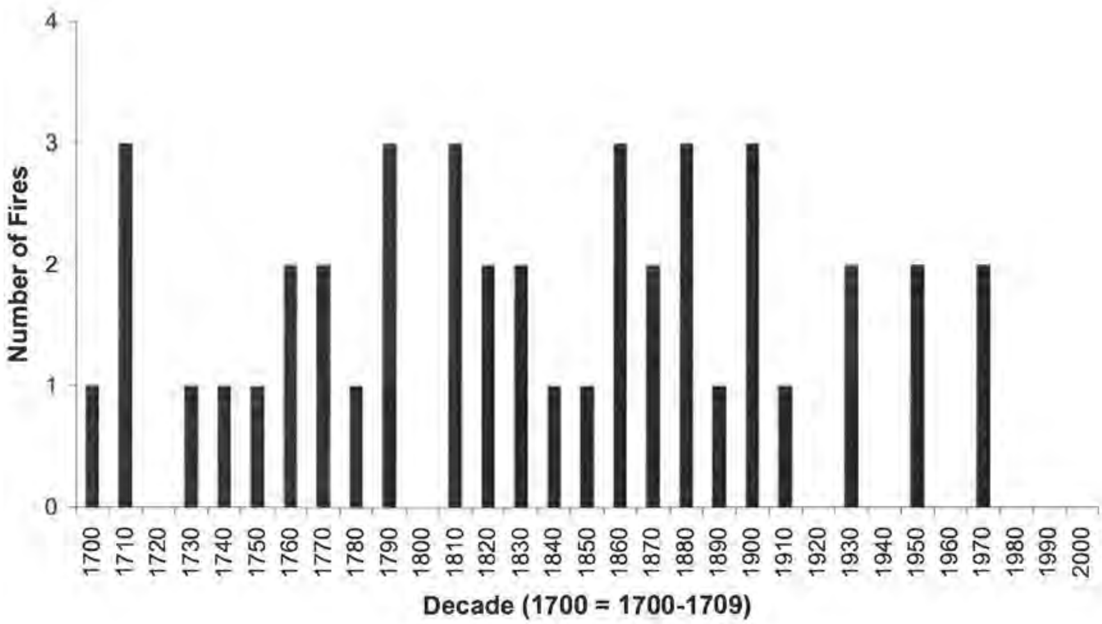

Figure 30. Number of fires per decade for the study area.

4. Discussion

4.1 Limitations for Fire History Reconstruction

This study was part of larger effort to reconstruct fire history for the entire Willamette Valley fringe. Therefore, sampling was designed at a courser scale than would have been used for this study alone. Potential stands for plot installation were limited by land ownership, lack of older age classes of trees, and age of cut (which influenced stump quality and vegetation growth, limiting plot installation). Accordingly, if this project had been stand-alone, I would have installed plots in any possible stand instead of only one plot per quarter township. Additional opportunistic sampling for fire information, instead of plot sampling, may have been more appropriate for the objectives of this study since fire scars can be spatially heterogeneous. However, typical vegetation growth after clearcutting can inhibit this type of sampling, since finding stumps in thick brush is difficult. Sampling within a plot was helpful in accounting for all of the trees in a topographically similar area and for retrieving stump samples. Also, I would have taken stump samples from all scarred stumps. Several samples were not useable due to either rot or too much pitch, which inhibited the dating of some fire events. Some fire dates that were lost may have been represented on another stump and thus accounted for with additional sampling of scarred stumps.

4.1.1 Using Historic Maps to Determine Past Forest Conditions

The historic map GIS layers used in this study generally agreed with the fire history constructed for each site. Several sites had been mapped as burned in the past and the reconstructed fire history corroborated those classifications. There was only one instance in which a map seemed completely incorrect (for Site 11: cut, according to the 1936 map), although a couple of sites had questionable mappings since there were no definitions of timber types for the 1914 and 1936 maps. In many cases, knowing the vegetation type before and after possible land use changes, made interpretation of fire history more tangible. For example, spatial arrangement of historic vegetation became a key element in interpreting why fire history was different between the valley sides (see Section 4.4).

Determining percent burned for the study area *could* be a method for determining the general size of past fires. For example, the total area burned in the mid 1800s was roughly 4%, while in the early 1900s three times the area was mapped as burned (12%). Even though the number of fires did not significantly change from the 1800s to the early 1900s, the amount of area burned increased dramatically, indicating that earlier fires in this area may have been relatively small. The well-documented, widespread fires of the early 1900s were adequately represented on the 1914 timber map, which was the least detailed of the four vegetation maps. Following effective fire suppression, the area burned was very low (1% in 1936 and none in 1988), which reflected both the low number and smaller size of the fires.

Using this method would be limited temporally, however, since there were only a few maps generated over a short time. Also, generally only stand-replacing fires were mapped, thus many of the low and moderate fires that were common in the study area would not have been mapped.

For these reasons, using GIS was a good way to corroborate fire history reconstruction and to assist in interpretation of past disturbance and land use patterns. Additionally, forest managers can utilize the knowledge of change in vegetation cover when trying to formulate management objectives with historic fire information. Current forest conditions are not similar to past forest conditions; therefore, management should not be based solely on historic disturbance patterns, it should also include the forest structural context in which historic fire occurred.

4.1.2 Adequate Sampling of Fire Events

Due to the limited area involved in constructing site-level fire histories (half acre plots), the chances of finding more than one scar for a given fire event were assumed to be low. To test this hypothesis, a total of five plots (one plot every five acres; including the fire history plot used in this study, now termed "the original plot") was installed on Site 3. The same field and lab methods, as described for this study, were employed to establish fire history in all plots. In addition, to determine whether sampling at the half-acre level produced a fire frequency measure similar to that found with five half-acre plots (stand level), the site-level and stand-level MFRI were compared.

Within the original plot there were two scar events (dated 1902 and 1934). On an opportunistic stump, located outside of the plot boundary, six additional scar events (1818, 1831, 1849, 1864, 1872, and 1879) were used in the fire history of Site 3. Of these eight fire dates, five (1864, 1872, 1879, 1902, and 1934) were found on at least one other plot (i.e. additional scars were found on other plot(s)); two dates (1818 and 1831) had one scar and one trauma ring (i.e. a trauma ring was found on another plot); and one date (1849) was not found elsewhere on the site (Figure 31). Of note is that 1849 was the year of the most wide spread occurrence of fire in the study area; six different sites, on both sides of the valley, had evidence for fire in this year.

Both of the two fire dates located within the original plot (1902 and 1932), occurred at other plots on the site. The 1902 date occurred on two plots (including the original) and the 1932 date was found on three plots (the original plot had one scarred sample). Five of the six scar dates on the opportunistic sample also occurred on other plots based on either another scar (1864, 1872, and 1879) or on a trauma ring (1818 and 1831). Four of the six scar dates were synchronous with fire events at other sites in the study area (fire episodes).

This exercise illustrates that a single scar was sufficient evidence for a fire event and more sampling did not inevitably provide additional fire dates to change fire frequency. Fire scars that occurred on several plots in the stand reveal the spatial heterogeneity of fire effects and scarring.

Site-level MFRI for site 3 (the original plot) was 17 years (s.d. = 9 years). The stand-level MFRI for all 5 plots combined was 11 years (s.d. = 8). There was no difference between frequencies ecologically or statistically.

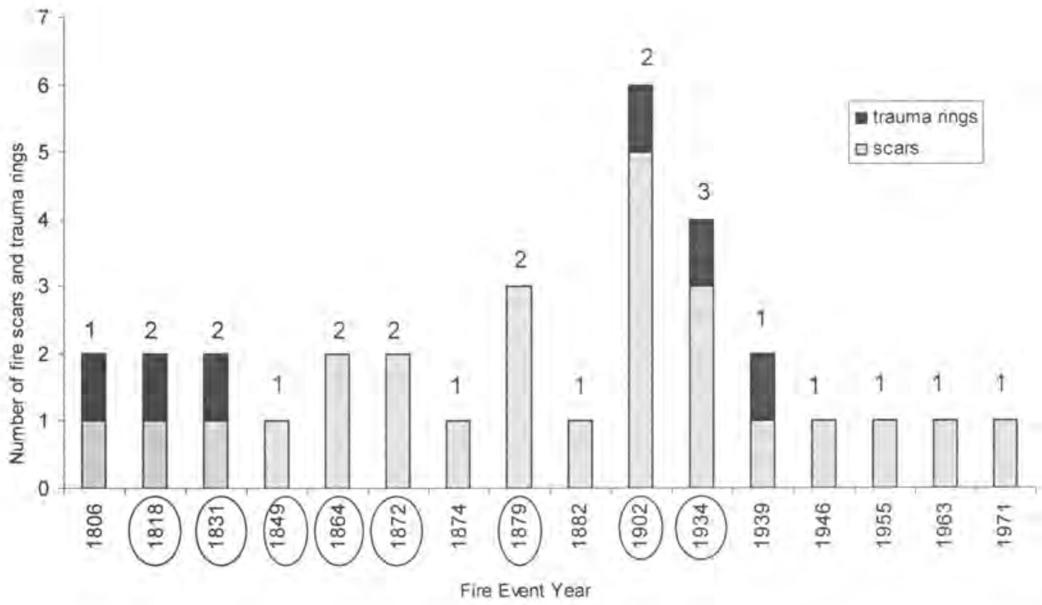

Figure 31: Fire event evidence analysis for Site 3. Five plots were installed (1 plot/5 acres) and evaluated for additional evidence of fire. The 8 circled fire years are the events that were on the original plot *and* the opportunistic stump. Numbers above the bars correspond to the number of plots on which evidence for that year was found.

4.1.3 Adequate Sampling for Computation of Site Level Fire Frequency

If sampling had been inadequate for a particular site (i.e. fire scars were not sampled to represent the true fire frequency of the site) then too few fires would have been documented, producing longer fire intervals than what was found over the study area. I tested whether certain intervals were disproportionately affecting the study area MFRI by breaking down the study area fire interval distribution (RFF) according to the number of fires per site (more than and less than 4 fires / 3 fire intervals).

Longer fire intervals were more likely to be found at sites with less fire evidence, although longer intervals were common for the study area (i.e. the 80-90 yr interval bin was represented equally by sites with more and with less evidence; Figure 32). Short (<30) and long (>80) intervals could be found on sites with *and* without substantial fire evidence.

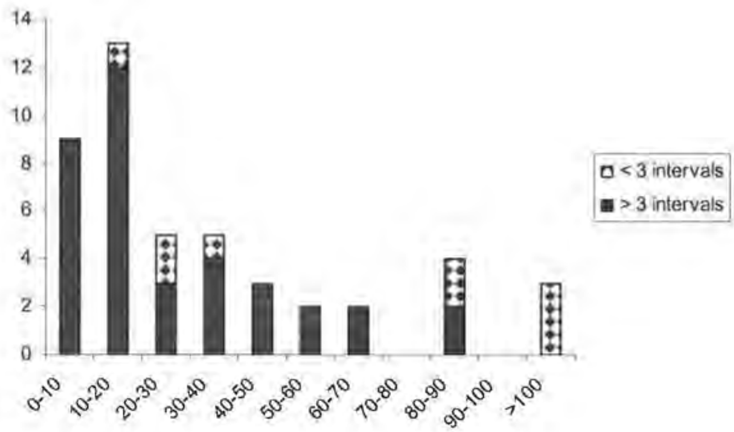

Figure 32. Fire Interval distributions for sites with more than 3 intervals (solid) and less than 3 intervals (checkered).

In addition to site-level fire return intervals, it was important to ascertain whether or not exceptionally long site-MFRIs were outliers. The MFRI of nine of the twelve sites was less than 52 years (mean = 31 years, +/- 12 years), so the MFRI of the remaining three sites (78, 89, and 148 years) may have been higher than the true means of those sites. Using the study area MFRI (49 years, s.d. = 39 years), the MFRI for Site 1 (148 years) was not within three standard deviations, which statistically encompasses 99.7% of all values. Removing Site 1 as an outlier, the MFRI for the remaining 11 sites would be 40 years (s.d. = 24 years), a decrease of one-fifth for the study area MFRI. Site 1 may have had a much longer MFRI due to a) inadequate sampling, or b) its location (Site 1 was the farthest site to the west, so perhaps the fire regime there was more similar to Coast Range fire than foothills fire).

Even though longer intervals were over represented by sites with less fire evidence, relatively long intervals are probable in this fire regime. Consequently, site level MFRIs were generally less than 50 years, but longer MFRIs can be expected. Therefore, all twelve sites were used in reconstructing fire history.

4.1.4 Effect of Rule Sets on Accepting Fire Events

Rule sets were used to determine which fire events to include and were therefore a potential source of error. To investigate just how different the results would be, the effect of fire identification criteria on fire frequency distribution was examined. I compared the fire frequency distributions obtained from Rule Set 5 to four fire histories constructed using more demanding rule sets (see Table 2). With each successive rule set, from 1 to 5, more fire dates were added as the amount of evidence required lessened. Rule Set 5 had the most fire dates.

Compared to the Rule Set 5 estimate, the conservative estimates substantially diminished the amount of fire information upon which to build a fire history (Table 11) (see Appendix for a full list of fire dates for each rule set). However, p-values (non-significant p-values indicate no difference between estimates) from Fisher's exact tests for difference in interval distributions between Rule Set 5 and Rule Sets 3 and 4 were not significant at the 0.05 level ($p = 1.0$ and 0.95, respectively) (Table 12), thus the distributions for sets 3, 4, and 5 were very similar. The p-value for difference between Set 5 and Set 1 was not significant ($p = 0.35$), although this result is considered incorrect due to Rule Set 1 having a lower than recommended value for using a chi-squared test (there were only four fire intervals for Set 1). The p-value for Rule Set 2 was weakly significant ($p = 0.057$) (Table 12). For a visual comparison, Figure 33 shows the relative fire frequency (RFF) of each rule set (refer to Figure 25 for the RFF of Rule Set 5).

Table 11. Fire history produced using each rule set.

	Rule Sets				
	1	**2**	**3**	**4**	**5**
Total # Fires	14	22	32	43	58
# Fire Dates	13	18	20	29	44
# Intervals	4	11	20	31	46
# Sites	10	11	12	12	12
Ave. Interval	50	54	39	40	49

Table 12. Fisher's exact tests for difference of fire interval distribution between Rule Set 5 and Rule Sets 1-4. ^Even though Rule Set 1 appears non-significant, this was probably due to the low number of intervals in Rule Set 1, which was lower than the suggested number of values for using Fisher's exact tests.

Rule Set	p-value
1 v. 5	0.352^
2 v. 5	0.057
3 v. 5	1.000
4 v. 5	0.950

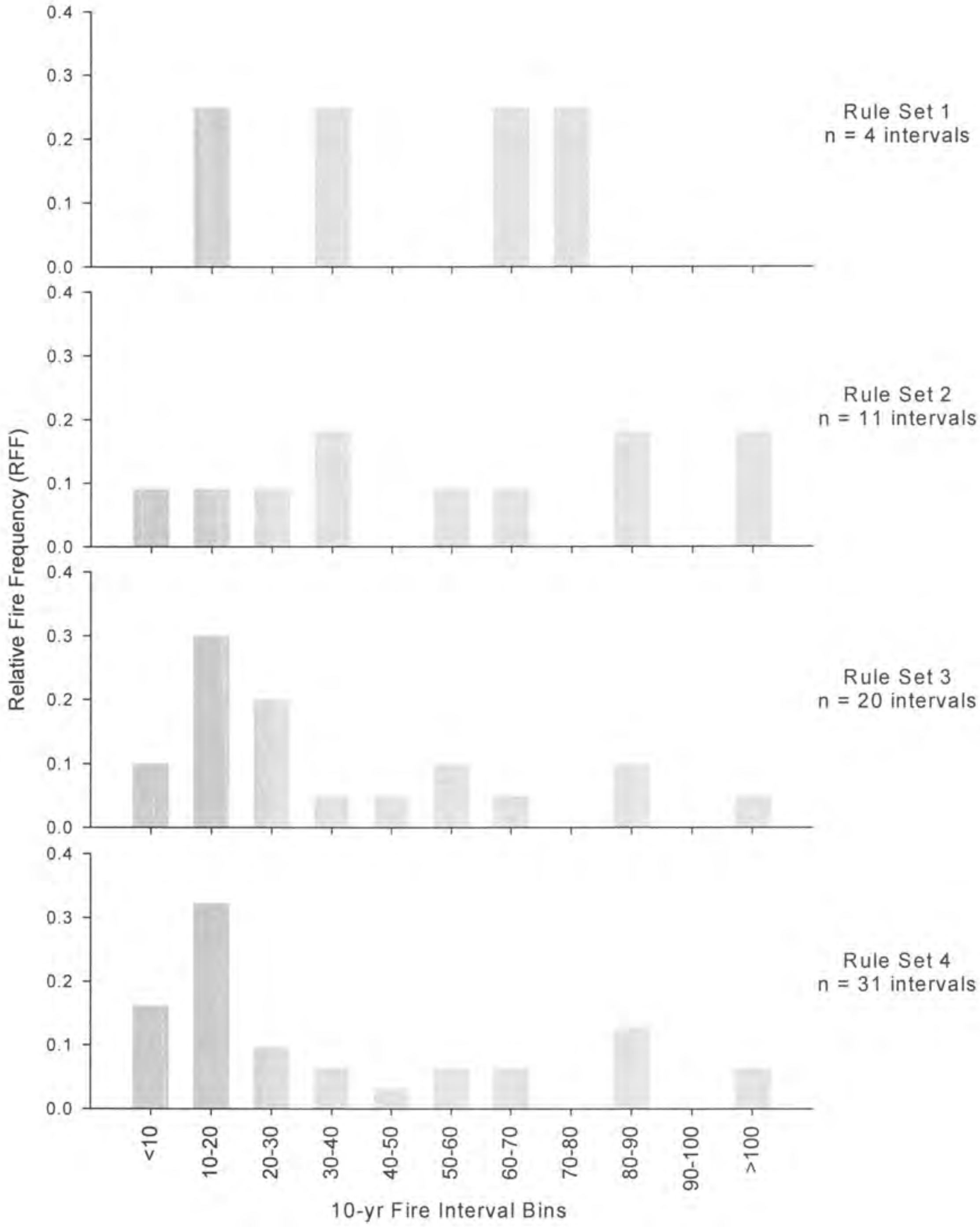

Figure 33. Multiple-site relative fire frequency (RFF) for Rule Sets 1-4. RFF for Rule Sets 1 and 2 were not similar to Rule Set 5. RFF for Rule Sets 3 and 4, however, were very similar to Rule Set 5 (see Figure 25).

The difference between the fire interval distribution of Rule Set 5, used to determine the fire chronology, and the other rule sets was most evident between Rule Sets 2 and 3 (i.e. the fire interval distributions of Rule Sets 5 and 2 were the most dissimilar and distributions of Sets 5 and 3 were the most alike). The distinction between Rule Sets 2 and 3 was the inclusion of multiple-site scarring events in Set 3 (i.e. if more than one site had evidence of fire, regardless of the number of scars per site, the fire date was accepted).

Ten additional intervals were established between Sets 2 and 3; nine of the ten intervals were less than 25 years and three-quarters of the intervals (6 of 9) were added to Sites 2 and 3 (2 and 4 additional intervals respectively). Sites 2 and 3 had a substantial amount of fire evidence and a high number of recorded fire episodes (3 and 4 episodes respectively); Site 3 was also evaluated for sampling accuracy at the stand level (see Section 4.1.2), giving this site additional credibility.

The intervals eliminated by using Rule Set 2 were mostly less than 25 years long; consequently, some high frequency fires were not being represented in Rule Set 2. These high frequency fires, which were added since they were fires found on more than one site, were added in Rule Set 3 by including fires that were either (a) spatially large or (b) were spatially localized at the site level, but took place during a time of high fire occurrence.

Were these high frequency fires "noise" or were they "signal" and being eliminated unnecessarily due to decision sets? Since several short intervals were added to particularly credible sites and I am confident that the fire history for these sites was as accurate as could be expected, it is likely that high frequency fires were not "noise", but the essence of the fire regime and using Rule Set 5 resulted in a more adequate measure of fire frequency than by using more conservative rule sets.

4.1.5 <u>Adequate Sampling for Computation of Fire Frequency</u>

It can be difficult to determine if the sample MFRI is a good estimate of the population MFRI or if increased sampling would provide a more accurate estimate (or would just add insubstantial fires). Baker and Ehle (2001) suggest that a restricted composite MFRI (restricted method was defined as requiring >10% of trees and at least two trees scarred to determine a fire event) is the best way to estimate the true mean since restricting evidence eliminates very small fires that possibly burned only one or two trees (e.g. lightning strikes affecting only one tree). However, had a >10% scarred rule had been used in this study, the 1902 fire found on Site 3 would *not* have been counted as a fire event. This fire would have been discounted without grounds since the year 1902 was evidenced by five fire scars and one trauma ring with additional sampling of the site (yet still would not have met the > 10% rule). The year 1902 was also identified as a fire year for several other fire history studies (Morris 1934, Weisberg 1996, and Impara 1997), apparently affecting a large portion of the region.

In addition, it is generally thought when reconstructing fire history, that higher fire frequency (shorter MFRI) is computed with an *increase* in the number of fires found on a site; this notion may not always be true. Had Rule Set 3 been used in this study, the study area would have had a shorter MFRI with a *decrease* of fire evidence (39 year MFRI using 20 fire intervals) than was computed with Rule Set 5 (49 year MFRI using 46 fire intervals). Of note is that the fires included in Set 3 spanned 1717 to 1975 and fires in Set 5 spanned 1705 to 1979, thus the period of analysis is similar between rule sets.

No one method will produce the exact fire history for an area, although reasonable estimates can be made. Short fire intervals were the most prevalent in this fire regime, although longer intervals were also present, and restricting the criteria for accepting fire scars resulted in excluding fire dates unnecessarily. Sampling opportunistically over an entire stand, wherein *all* fire scars are sampled, may be the best estimate of the true MFRI of a stand; the financial cost and the feasibility of such sampling in abundant vegetation, however, would preclude this type of intensive sampling.

4.1.6 Effect of Rule Sets on Computation of Fire Frequency Change Over Time

Since Rule Set 3 produced a fire interval distribution similar to that of Rule Set 5, change in the number of fires over time was also evaluated for Rule Set 3. The effects of climate and land use change on fire recurrence was quantified using a Pearson chi-squared test for difference between the number of fires in four time periods corresponding to climate and land use changes (Table 13).

Fire occurrence was weakly associated with human effects during the four time periods ($p = 0.06$, 3 d.f) (Table 13). There was no difference in the number of fires associated with climate effects only. The time period 1700-1800 experienced less fire than expected, and from 1800-1850 there were slightly more fires than expected. Twice as many fires as expected occurred during the settlement period (1850-1925) and there were half as many fires as expected during the suppression period (1925-1990).

Decreasing the number of fires used to reconstruct fire history resulted in a more significant finding than when all fires were used. This suggests that methodology plays a large role in the reconstruction and interpretation of fire history (see Section 4.3.3 for a discussion of methodology and results).

Table 13. Rule Set 3: Pearson chi-squared tests for difference in numbers of fires through time. Expected values (in parenthesis) were determined by distributing the number of fires evenly over time.

	1700-1800 no climate * native	**1800-1850** weak climate	**1850-1925** climate * settle	**1925-1990** climate * supp	**Test statistic**
human	4	5	9	2	$x^2 = 7.20$, 3 d.f.
	(7)	(3)	(5)	(5)	$p = 0.06$
climate	4	5	--------11--------		$x^2 = 2.70$, 2 d.f.
	(7)	(3)	(10)		$p = 0.44$

4.1.7 The Weibull Distribution

The Weibull distribution is widely used as the best distribution with which to model fire intervals due to the typically skewed nature of fire intervals. For more mesic regions, such as western Oregon, however, fire intervals are typically not short enough or the length of record is not long enough to have an adequate number of intervals (≥ 3) on which to base the Weibull distribution. Seven of twelve sites for this study met the above criteria for computing a WMPI. A Kolmogorov-Smirnov test indicated that the fire frequency distribution was better fit by a Weibull distribution than an empirical distribution for these sites, except Site 11 (see Table 7).

The average fire interval was an average of five years shorter (+/- 3 years) when using the Weibull distribution for these sites than when using the empirical distribution. However, since this forest system was disturbed by fire on average every 40 to 50 years, two to eight years difference in the mean fire frequency was not ecologically significant enough to warrant using the Weibull distribution for these sites.

4.2 Comparison of Local Fire History Studies

Results from the fire history studies of Weisberg (unpub. 1996) and Impara (1997) were compared with the results of this study since they specifically determined fire frequency for a portion of the foothills. The MFRI for this study (49 years) was very similar to the MFRI that Weisberg (unpub. 1996) found (53 years) and dissimilar to the MFRI that Impara (1997) found (75 years) (Table 14). In this study, I found a relatively shorter MFRI for all west side sites than for east side sites, while Impara (1997) (west side) found a longer MFRI and Weisberg (unpub. 1996) (east side) found a short MFRI.

Differences in sampling, which include sample design, determination of fire events and crossdating, size of area sampled, and sampling intensity, may hinder direct comparison between studies of fire frequency and the factors affecting frequency.

However, despite differences in sampling intensity, I found a similar MFRI to that of Weisberg (unpub. 1996), thus sample design was not likely a major source of error.

Crossdating was used in this study but not in the studies of Weisberg (unpub. 1996) or Impara (1997). Crossdating eliminates the need to cluster fire events into one date; thus short intervals (<10 years), as was common in this study, are included in determining fire frequency. Crossdating can increase the number of fire dates and intervals for a given study area and shorten the MFRI. Additionally, the period of time analyzed by Weisberg (unpub. 1996) and Impara (1997) was substantially longer (450 years and 516 years, respectively) than the time period for this study (290 years). Surprisingly, even though Weisberg (unpub. 1996) used almost half as many fire dates (26 fires) as I did for this study (43 fires), the MFRI was similar. In contrast, Impara (1997) used the same amount of fires as Weisberg (27 fires) and computed a longer MFRI. In this case, it appears that Weisberg found few, if any, long fire intervals (>100 years), which produced a short MFRI even over a much longer time period than was used for this study; thus, crossdating did not necessarily produce shorter fire intervals with more fire events.

It is not clear why the fire history results for this study were different from that of Impara (1997), and similar to that of Weisberg (unpub. 1996). Impara and I both reported that over 70% of all site-level MFRIs were less than the mean of all MFRIs. However, several very long intervals may have influenced the results that Impara (1997) found (see Section 4.1.2 for a discussion of longer than average MFRIs and fire intervals). Additionally, the study area Impara (1997) used extended west from the valley fringe up to nearly nine miles out, while for this study, sites were no further than three miles from the fringe. Thus, the fire regime Impara found may more closely resemble the Coast Range fire regime than the short-interval regime found in this study for the foothills.

Table 14. Comparison of local fire history studies. MFRI is the study area mean fire return area and SD is the standard deviation of the MFRI.

Study	Study Area	Study Period	# Fire Dates	MFRI (yrs)	SD (yrs)	Area (Km2)	# Sites
Weisberg (unpub. 1996)	Cascade foothills	1545-1995	26	53	15	400	35
Impara (1997)	Coast Range foothills	1478-1994	27	75	---	426	44
This study	Cascades and Coast Range foothills	1700-1990	43	49	39	1561	12

4.3 Temporal Change of Fire Frequency

4.3.1 Overview of Temporal Changes in Fire Frequency

Fire occurred every decade or so with occasional longer intervals (see Figure 23) until after 1905, at which time fire occurred roughly every 15 to 20 years until 1979. On the west side of the valley, fire frequency increased beginning in 1810 and remained relatively short until around 1880. On the east side of the valley, fire frequency remained relatively constant throughout time (including the post-suppression era) with the exception of a slight short-lived increase during the settlement period (late 1800s). The period of Euro-American settlement was characterized by a higher than expected number of fires, although this was not statistically significant. The effective fire suppression period was characterized by a less than expected number of fires, also a non-significant find.

There was no clear relationship between fire frequency and drought during the study period (1700-1990). However, before 1850, fire was more likely to occur three years following a drought year, whereas after 1850, fire was significantly more likely to occur *during* a drought year (see Figure 29).

4.3.2 Comparison of Regional Fire History Studies

Several studies have investigated fire in western Oregon, including both the central western Cascades (Burke 1979, Teensma 1987, Morrison and Swanson 1990, Connelly and Kertis 1991, and Weisberg unpub. 1996, 1997, 1998) and the Coast Range (Morris 1934 and Impara 1997). One of the objectives for this study was to compare, with other regional studies, changes in fire frequency and whether change was attributed to climate and/or land use change. Regional studies conducted in western Washington, southwestern Oregon, and eastern Oregon are not discussed here due to differences in settlement and climatic patterns.

Weisberg and Swanson (2001) consolidated the results from 10 regional fire history studies (8 of which were in western Oregon) and determined climatic and land use associated temporal periods that correspond with changes in the fire regime. Weisberg and Swanson used temporal bins (1700-1775, 1775-1850, 1850-1925, and 1925-2000) that were similar to those concluded for this study (1700-1800, 1800-1850, 1850-1925, and 1925-1990).

Both Weisberg and Swanson (2001) and this study used a chi-squared test for difference in number of fires over time (see Table 10). An important difference between the two studies is that Weisberg and Swanson (2001) used widespread fire episodes, while this one incorporated all fires regardless of size.

Both this study and Weisberg and Swanson (2001) concluded that climate was not significantly related to fire for the whole period of record. However, superposed epoch analysis (SEA) results reported in this study indicated that climate was weakly related to fire, although not statistically significant, for the entire length of record (see Section 3.3 and Figure 29). For the period 1700 to 1850, fire years were drier than average but only minimally so. Furthermore, there was a relationship (non-significant) between drought and the 3rd year before fire. This may indicate a different relationship between drought and fire during climatically wetter, cooler periods (1700's) than the relationship we see today (drought and fire coinciding) during a climatically warmer, drier period. This hypothesis was not tested nor thoroughly researched for this study. In the American Southwest, studies have found time periods in which fire occurred three to four years following a wetter-than-average year, indicating fuel build up prior to drought years at which time fires occurred (Grissino-Mayer 1995, Grissino-Mayer and Swetnam 2000).

It is important to note that the spread of the confidence intervals produced in SEA is highly influenced by the number of fire dates used in the analysis (Baisan and Swetnam 1997). Therefore, a higher number of fire dates for the whole period of record (290 years) resulted in smaller confidence limits than when drought-fire relationships were analyzed for time periods pre- (150 years) and post-1850 (140 years)). Also, statistical significance is based on probabilities, so results from SEA analyses can be erroneous.

During the 1700s, there was no difference between observed and expected number of fires in this study, yet Weisberg and Swanson (2001) found an observed value substantially lower than their expected value. For the period of climatic and human transition (1800-1850 / 1775-1850), this study found a minimal difference in number of fires found and expected (8 fires found and 7 expected); Weisberg and Swanson (2001) reported an increase of one-third in the expected number of fires (9 fires found and 6 expected).

Weisberg and Swanson (2001) found that human effects and the interactive effect of humans and climate were very significant, while I did not find a significant effect. Location of study and/or methodology may have resulted in these differences. The two studies were done in different localities with respect to topography, vegetation, and local weather, as well as having different human histories. Topography, vegetation, and local weather influence fuels, fire behavior, and fire effects. For example, areas with steeper slopes may be prone to faster moving fire due to more effective preheating of fuels. This may affect tree fire-scarring, since heat residence time affects whether a tree scars or not (the temperature pulse must be long enough to kill the cambium, thus forming a scar). North-facing slopes generate higher biomass thus produce more fuels; however, south-facing slopes have a lower fuel moisture content during fire, so the effect on fire behavior, with respect to fuels, may be similar to that of the north slopes. The foothills overstory vegetation, at the time of settlement, was a gradient of woodland, to scattered timber, to closed canopy forest, moving away from the valley. These more open forest types had a different fire regime than what has been found in the western Cascades. Additionally, the foothills have a longer fire season since there is minimal snow pack. The naturally higher frequency of fire in the foothills in tandem with human influence for several centuries may dilute changes in fire related to climate or humans, whereas in the Cascades changes may be more apparent. These differences were not quantified in this study, however, and would be an objective for future studies.

In addition to physical and human influence on the fire regime, methods for analysis may explain differences in findings. For example, during the suppression period, Weisberg and Swanson (2001) included only one fire due to fire size restrictions (fires were suppressed, so large areas would not have burned), whereas there were six fires recorded for this study. The following section explores this hypothesis further.

4.3.3 Deciphering Non-significant Results of Temporal Fire Frequency Patterns

Based on (a) hypotheses postulated from land use patterns over time and (b) the results of previous regional fire histories, I anticipated observable changes in fire frequency related to changes in land use. I expected that the number of fires would decrease during the period 1800 to 1850 due to a reduction in the Native American population. However, the number of fires actually increased. Morrison and Swanson (1990) and Connelly and Kertis (1991) also found that fire frequency increased during this transitional time.

All regional fire history studies listed in Section 4.3.2, with the exception of Teensma (1987), found an increase in fire following Euro-American settlement (mid to late 1800s) in the Coast and Cascades Ranges and in the foothills. Teensma (1987) found no difference in NFR before and after settlement, although he did find change during the fire suppression period. I found an increase of nearly a quarter more fires than expected during the settlement period, although I expected a significantly higher increase due to the combined effects of climate and humans. Weisberg and Swanson

(2001) suggest that, regionally, climate was influencing fire and white settlers intensified the effect.

For the period of effective fire suppression (1925 to present), I expected the number of fires to decrease. Even though climate was drier and warmer during this period than any other time between 1700 and 1990, only six fires occurred during the 65 year fire suppression period, while fourteen fires occurred from 1850 to 1925 (75 years); still, the results were not conclusive. Regardless of statistical results, a less than expected number of fires combined with a climate favorable of fire, strongly suggests that fire occurrence decreased considerably due to fire suppression efforts. No other fire history study has found dissimilar results for the region.

Since there was not a statistically significant change in fire frequency related to the Euro-American settlement period and to the fire suppression period (as was found in other regional fire histories), I hypothesized that the use of crossdating and a lenient rule set for accepting fire events may have precluded strong evidence of fire frequency change.

Determining fire events by using Rule Set 3, which increased the stringency of accepting fire events and included more widespread fire events (thus, was more similar to other fire history studies), resulted in a weakly significant effect on fire considering human effects ($p = .06$, 3 d.f.) (see Table 13). Rule Set 3 resulted in a lower than expected number of fires during the 1700s and post-suppression period (1925-1990) and more fires than expected during the transition period (1800-1850) and post-settlement period (1850-1925); this pattern is very similar to that found by Weisberg and Swanson (2001).

Crossdating and changing the rule set for accepting fire events produced a more similar outcome (compared to previous non-crossdated fire histories) of temporal change of fire frequency. Therefore, it would be prudent to continue using dendrochronological methods for reconstructing fire histories in western Oregon in order to evaluate not only methods used in the past, but to also re-evaluate determining fire regime changes over time (i.e. the temporal changes that other studies found may not be as conclusive if fire history was reconstructed using all fires, not just widespread or long-interval fires). This may be an important research goal if trying to determine the effects of high frequency fires in western Oregon forests.

Regardless of methodology, the valley foothills have been adjacent to a human-populated area for many centuries. The fact that humans have always been a potential ignition source may be an alternate reason why significant change in fire frequency was not found for the foothills, while in the western Cascades, the human timeline had more distinct periods of influence.

4.3.4 Effect of Native American Burning on Fire Frequency

According to the reconstructed fire chronology, there was no conclusive evidence of Native American influence on the fire regime since fire occurrence did not decrease following the decline of the Native American population. On the other hand, climate did not explain fire occurrence during this period (in the way that we expect drought and fire to temporally coexist today), which suggests that Native Americans were burning in the valley foothills.

Two hypotheses were constructed to help explain why the results of the fire event reconstruction were not conclusive with respect to Native American burning: 1) the period of possible Native American influence (pre-1800) was under represented at the site level and in the fire chronology of this study due to record erasure; therefore, that part of the chronology was not accurate; and 2) sampling for this study was insufficient in capturing the real fire chronology over the whole period of time (this hypothesis, while listed here, has been refuted as the source of fire chronology error (see Section 4.1)).

Record erasure is a common problem when conducting fire history studies. The result is typically under representation of older fires. Since the southern Willamette Valley forests have been extensively logged, converted for agriculture, or urbanized, the length of time recorded in tree rings for this study was relatively short. The west side chronology was represented by only two sites prior to 1725 and there was no evidence of fire until almost 1750 (even though Site 1 recorded a fire in 1658, it was before 1700, so was not considered in this discussion). In contrast, two sites also represented the east side for much of the length of record, yet east side evidence of fire began in 1705 (50 years earlier than the west side). Since the east side of the valley produced a long record of fire with only two sites representing the first 100 years, it is unlikely that record erasure led to under representation of early fires. However, the limited number of individual samples from which fire history could be reconstructed for the 1700s may still be biasing the fire record for that time period. Less than 20% of all samples were able to record fire events until the late 1700s (Figure 34). Since few older trees were sampled, which were alive during the 1700s, there may have been many more fires that occurred that could not be sampled. Still, the number of sampled fire events before 1850 (23) were higher than the number of sampled fires after 1850 (20), so even though there were few samples, sampled fire events were abundant; another reason to deem that record erasure did not overly bias the fire record before 1800.

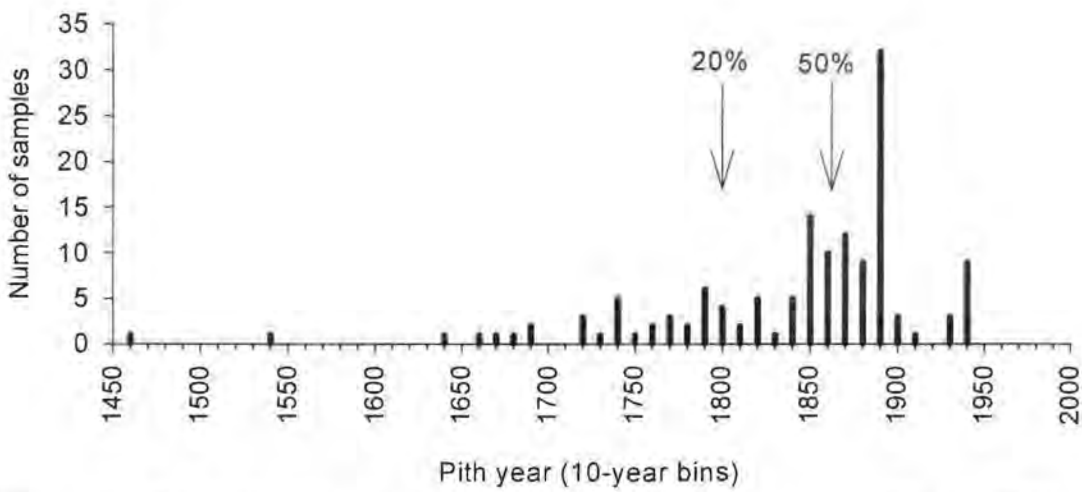

Figure 34. Origin dates, in 10-yr bins, for all sampled stumps (n = 159). The 20% and 50% marks represent when 20 and 50 percent of all samples were accounted for.

Although not conclusive, the results of this study do not support the theory of extensive Native American burning of southern Willamette Valley foothill forests (which is *not* to say that Native Americans were not burning in the Willamette Valley). If Native Americans were burning the forests to a significant degree, I would expect the number of fires to noticeably decrease during and after the late 1700s/early 1800s when the Native American population was low; however, based on what was expected, fire increased, not decreased (for Rule Sets 5 and 3). Furthermore, the number of fires in the 1700s was as expected (Set 5) or lower than expected (Set 3); had Native Americans been burning the forests with any regularity, I would anticipate fire to have occurred *more* than expected.

This still leaves the question of why climate was not directly related to fire occurrence during this time. One hypothesis is that the fire-climate relationship was different during this climatic period. As discussed above, in this study I found that during the period 1700 to 1850, drought occurred three years *preceding* fire, on average (see Figure 29b). While this was not a significant finding, it spurs additional investigation of the notion that drought and fire always occur in the same year, barring other fire ignition sources (humans).

No tree-ring based fire history study has concluded that Native Americans were influencing the western Oregon fire regime of forested lands to a significant extent. However, "knowing" whether or not humans were partly responsible for the historic condition of the forests may or may not be entirely relevant with respect to the future goals for foothill forests. If there was maintenance of forest types or forest structure by human means, then returning the fire regime to such historical levels may not be considered necessary as it does not reinstate the "natural" forest condition. However, we know that the historic fire regime produced forest conditions conducive to contemporarily valued forest attributes, such as perceived forest health, viable wildlife habitat, and severe-fire effects mitigation; therefore, returning fire (in some altered version of the historic regime) is still a viable goal. Also, the standard practice for historic fire research today is to include human-caused fires, thus the argument for not recognizing Native burning as natural is irrelevant.

4.4 Spatial Heterogeneity of Fire Frequency Distribution

Fire frequency distribution differed on the east (Cascades Range) and west (Coast Range) sides of the valley. The east side foothills were characterized by fire intervals that were generally less than 40 years long (67% of intervals), while the west side foothills typically experienced fire intervals of less than 20 years (57% of intervals). Also, even though fire intervals were shorter on the west side, the only fire intervals longer than 100 years were found there.

Fire frequency differences between the west and east sides of the valley may be attributed to dissimilarities in historic vegetation, topographic, or human influences. The west side sites were, on average, lower in elevation and located adjacent to what was historically Douglas-fir and Douglas-fir-oak woodlands, whereas the east side sites were well within what was mapped historically as closed canopy Douglas-fir (see Figure 4). Assuming that early accounts of Native American use of fire in the prairies, savannas, and woodlands were accurate, the higher fire frequency of the west side sites could be attributed to Native American burning. However, as discussed above, there was no obvious decrease in fire occurrence with the decline of Native American populations. On the contrary, there was an increase in fire occurrence beginning in the early 1800s, perhaps because of a warming climate. The east side sites showed no such climatic trend although it is possible that climate affected the west side and not the east side due to vegetative differences (i.e. closed canopy Douglas-fir forests could have responded differently, ecologically, to increased drought than forests that were woodlands or adjacent to woodlands). Early Euro-American settlement on the west side (sites were considerable closer to the valley floor on the west side than on the east side) may also have played a role in the continuously shorter fire intervals. Finally, because west side sites were located nearer to woodlands, those sites may have experienced higher fire frequency from different fuel loading (grasses) than east side sites.

4.5 Regeneration Following Fire and Fire Severity

Douglas-fir regeneration following fire on the west side of the Cascades has been studied previously, although the fire event dates were unknown (Tappeiner 1997, Poage 2001, and Sensinig 2002), or were estimated by pooling field counts of fire scar dates (Morrison and Swanson 1990, Impara 1997, Weisberg 1998). Accordingly, there are wide ranging estimates of the time it takes for a cohort to establish in old growth or naturally regenerating stands following fire (20 to over 100 years).

This study found that regeneration began after fire in an average of 9 years and took on average 16 years for a cohort to regenerate; therefore, total average time to regenerate following fire was 25 years. This is different from the *longest* times to regenerate (25 years between a fire and stand reinitiation and 40 years for cohort establishment) used for determining cohorts for fire history reconstruction in this study. It is important to note that the sample size for determining these time lengths was very small (six sites). However, since 2/3 of the times between fire and regeneration were less than six years and five out of six of the times for a cohort to come in were less than 20 years, it is likely that these relatively short times would be typical of regeneration following fire.

The relationship between fire and an individual tree or cohort is imprecise since not every fire is recorded and the number of trees to survive, or regenerate following a fire, is variable. The consequence of this affects the use of regeneration to estimate fire severity. For example, the 1772 fire on Site 2 (see Figure 10) appears to be stand-replacing followed by regeneration, including samples 003, 006, and 007. Fires in 1817 and 1831 likely killed much of the previous cohort and were possibly followed by regeneration, although no stumps from that time were sampled. The 1849 fire was followed by regeneration of another four samples (155-158) and so on for another three fire dates.

If the fire events after 1849 (1863, 1865, and 1879) had not been sampled and had all of the regeneration following the 1849 fire been attributed to that fire (>50% of regeneration occurred after 1849), the effect of fire severity would have been erroneous when determining how fire affected the forest structure (i.e. the four high frequency, low severity fires that occurred may have been misinterpreted as one high severity fire). This same rule applies to the regeneration time lengths that I reported for this study (25 and 40 years). Not all fires were recorded in tree rings, and not all fire that were recorded were sampled, thus these time lengths may have been calculated as longer (particularly the longest times) than what they really were. For example, 25 years is a long time for regeneration to begin unless the high severity patch size was large. Regeneration cohorts are certainly related to fire, thus essential to fire history reconstruction. However, additional research is needed for a more accurate assignment of what represents a cohort and how fire relates to tree cohorts.

4.6 Management Implications

Historically, fire was a driving force of landscape-level forest succession until recent extensive forest harvesting and fire suppression. Much of Eugene BLM lands have been cut and are currently in varying stages of 2nd growth forest succession (pers. comm. Peter O'Toole, Eugene BLM, 10-12-2004). Forty-two percent (42%) of the Eugene BLM land base is designated as late successional reserve. The primary objective for LSR lands is to protect and enhance conditions of late successional and old-growth ecosystems. Maintaining a forest system somewhere within its historic range of variability (HRV) is believed to provide a high probability of producing conditions that are suitable to most (if not all) of the species that were there pre-settlement, including those not known or those we know little about (Wallin et al. 1996).

Part of determining the historic range of variability is knowledge of both the historic role of fire and the change in vegetation that resulted from changes, over time, in the historic fire regime. Assuming that to be within the HRV is essential for maintaining ecosystem productivity, historic fire frequency can be used as one of many guidelines for determining the HRV. However, since there has been a substantial reduction in "natural" vegetation, due to conversion to agricultural land, short-rotation logging, and urbanization, future management options are constrained. For example, frequent fire intervals maintained Douglas-fir as the dominant tree in the foothills, but with the reduction of historic fire intervals, there has been an increase in tree species considered fire avoiders (i.e. grand fir and western hemlock) and the forest structure has become considerably more closed canopy; consequently, frequent fire would do little good at maintaining ecosystem productivity if the trees were killed by repeated burning or if the closed-canopy structure precluded frequent burning.

However, reintroducing historic forest composition and structure without burning is an option.

Cissel et al. (1999) proposed an example of how historic fire regimes can be used in landscape management of the western Cascades forests. Long term (>200 years) active management prescriptions were created, which include timber harvest, riparian/aquatic and old-growth reserves, and sensitive species habitat. Three "landscape areas" with different prescription elements were used with the following parameters based on fire history: 1) rotation age, based on fire frequencies of the study area (100, 180, and 240 years); 2) landscape block sizes, based on fire extent (<40, 40-80, and 80-160 ha); and 3) retention level, based on fire severity of potential stand replacing fires (15, 30, or 50%). Their approach is limited by factors such as the occurrence of unplanned disturbances and potential climate change. However, it is a good example of how fire history can be utilized by forest managers.

Following this example, in the southern Willamette Valley foothills, managers might use shorter-interval burning and/or rotations with a low to moderate "severity" in the lower elevation forests (i.e. those stands that had been Douglas-fir woodland or were adjacent this type of forest, like on the west side of the study area). In the higher elevation, historically closed-canopy Douglas-fir forests (stands comparable to the sites of the east side of the study area), a longer-interval burning and/or rotation with a low to moderate "severity" would be more appropriate.

According to the Integrated Natural Fuels Management Strategy (USDA Forest Service 2000), prescribed fire is useful in the southern Willamette province, which includes Eugene BLM, for mitigation of numerous fire-related concerns. Issues include but are not limited to wildlife habitat quality and quantity, fuels reduction, and increasing landscape pattern and diversity (for example, restoring oak, pine, and meadows). Mechanical treatments are recommended for the wildland urban interface and for areas where fuel loads preclude prescribed burning.

The historic disturbance regime of the southern Willamette Valley foothills included fires that were more frequent (typically 20 to 40 year fire return intervals) than what we can allow today due to close-proximity of wildland urban areas. Additionally, today's fragmented landscapes do not allow for rehabilitation of most forests to their historic state (Wallin et al. 1996, Franklin and Agee 2003), although the small patch size of historic disturbances in the foothills may allow for restoration efforts not be viable on landscapes with large-scale disturbance regimes. Historically, the southern valley foothills consisted of a patchy landscape with differing vegetation compositions and forest structures. It is unlikely that we can restore the forests to this type of complexity due to the presence of urban areas, logging, and agriculture over the landscape. Prime examples include urban sprawl replacing the last existing woodlands and the prevailing practice of mono-culture Douglas-fir plantations for logging on private lands (which make up a large portion of land ownership in this area).

It is not practical to think of restoring the *full* range of landscape conditions that existed in pre-settlement times, but Wallin et al. (1996) suggest that we can use the historic range of variability as a frame of reference for evaluating and implementing potential management directives. And, as mentioned above, understanding how vegetation has changed as the fire regime has changed is helpful when making management plans for a desired future forest condition.

5. Conclusions

1. The study area mean fire return interval (MFRI) was 49 years and 70% of all site level fire intervals were less than 40 years long. These results are at the low end of what was expected for a dry Douglas-fir forest in western Oregon: 50 to 100 year MFRI (Agee 1993); and similar to what was expected using the Forest Service fire regimes for northwestern Oregon (USDA Forest Service 2000), which included Fire Regimes I and IIIA (<35 year and < 50 year return intervals with low and moderate fire severity).

2. Fire frequency distribution was different between the east and west sides of the valley. The cause of spatial disparity could not be determined since both human and vegetative factors were potentially influencing the fire regime. The west side sites were located within or adjacent to Douglas-fir and Douglas-fir-oak woodlands, thus the fire regime may have had a naturally higher fire frequency. These sites were also closer to potential Native American burning ignition sources as well as earlier Euro-American settler ignition sources. The east side sites may better represent fire frequency in the upper foothills due to being farther from the valley floor and human fire ignition sources.

3. This study provides interesting, but inconclusive, findings regarding the relationship between Native American burning and fire occurrence. The number of fires was as expected during the 1700s and higher than expected during the transition period from 1800 to 1850 (period of low Native American population), implying that Native Americans were not burning in the foothills. However, the climate-fire relationship between 1700 and 1850 was such that drought and fire were not occurring during the same year, which suggests that Native Americans may have been the source of fire ignition. Additionally, the sample size was small for the period before 1800, which may have prevented detection of a Native American influence on fire frequency in this study.

4. Euro-American settlement and later fire suppression were associated with weak but discernible effects on fire frequency. Fire recurrence was higher than expected during the settlement period (1850 to 1925) and lower than expected during the fire suppression period (1925 to 1990), although not statistically so. Moreover, drought was significantly related to fire from 1850 to 1979. Climate and human effects on fire could not be separated for the period 1850-1925. However, during the period 1925-1990, it is clear that fire suppression was effective at eliminating fire over the landscape.

5. The relationship between fire and drought could not be separated from human influences on fire over the period of this study (1700 - present). Fire occurrence was average during the apparently cooler, wetter period of 1700-1850, and both higher (from 1850 to 1925) and lower (from 1925 to the present) than average since Euro-American settlement. Fires were more likely to occur in drought years after 1850, but before 1850, fires tended to occur three years after drought. It is possible that there was a different relationship between fire and drought during the 1700s when the climate was generally cooler and wetter than after 1850, or Native American burning may have been the prime ignition source for fires during this time, obscuring a climate effect on fire frequency. Similarly, the lower than expected fire frequency after 1925 indicates that fire suppression probably obscured any climate-fire relationship during these continuing relatively warm, dry climate conditions.

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Appendix

Appendix. Fire history for each site based on more stringent rule sets for determining fire events than Rule Set 5, which was used in this study to construct fire history.

	Rule Set 1		Rule Set 2		Rule Set 3		Rule Set 4	
Site	Fire Event	Int	Fire Event	Int	Fire Event	Int	Fire Event	Int
1	1849	X	1849	X	1849	X	1658	
							1849	191
2	1865	X	1831		1831		1772	
			1865	34	1849	18	1817	45
					1865	16	1831	14
					1879	14	1849	18
							1863	14
							1865	2
							1879	14
3	1902	X	1902	X	1831		1818	
					1849	18	1831	13
					1872	23	1849	18
					1879	7	1864	15
					1902	23	1872	8
							1879	7
							1902	23
4	1764	X	1764		1764		1764	
			1917	153	1917	153	1773	9
							1917	144
5	1917	X	1764		1797		1797	
			1811	47	1811	14	1811	14
					1849	38	1849	52
					1917	68	1917	68
6	X	X	X	X	1849	X	1747	
							1768	21
							1849	81
7	1823		1823		1823		1823	
	1839	16	1839	16	1839	16	1839	16

Appendix (cont).

	Rule Set 1		Rule Set 2		Rule Set 3		Rule Set 4	
Site	Fire Event	Int	Fire Event	Int	Fire Event	Int	Fire Event	Int
8	1975	X	1975	X	1975	X	1886	
							1975	89
9	X	X	1905		1905		1872	
			1932	27	1932	27	1905	33
							1932	27
10	1885	X	1885	X	1872		1872	
					1885	13	1885	13
11	1782		1782		1782		1782	
	1849	67	1849	67	1849	67	1849	67
	1932	83	1932	83	1932	83	1932	83
12	1797		1717		1717		1717	
	1831	34	1797	80	1797	80	1797	80
			1831	34	1831	34	1831	34
			1886	55	1886	55	1886	55
			1889	3	1889	3	1889	3
Total # Fires	**14**		**22**		**32**		**43**	
# Fire Dates	**13**		**18**		**20**		**29**	
# Intervals	**4**		**11**		**20**		**31**	
# Sites	**10**		**11**		**12**		**12**	
Ave. Interval	**50**		**54**		**39**		**40**	