AN ABSTRACT OF THE THESIS OF

Sheryl K. Giglia for the degree of Master of Science in Geography presented on March 1, 2004.
Title: Spatial and Temporal Patterns of "Super-old" Douglas-fir Trees of the Central Western Cascades, Oregon.

Abstract approved:

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Julia A. Jones

Old-growth in the Pacific Northwest is generally defined as trees that are more than 200 years old. A great deal of analysis and discussion about old-growth forests in western Oregon, however, has focused on the relatively widespread 400 to 500 year age class of primarily Douglas-fir (*Pseudotsuga menziesii*) trees. The existence of older trees, with establishment dates prior to 1450, though rare, is documented in tree-ring based fire history studies conducted in the central western Cascades of Oregon. These trees, referred to in this study as "super-old growth," embody significant information about forest and climate history extending nearly a millennium into the past.

The primary objectives of this study were to assay where and why super-old trees persists on the landscape, and to develop a predictive model for their occurrence. I synthesized spatial and temporal data related to super-old trees from previous tree-ring based fire history studies conducted in the central western Cascades of Oregon. I

then created a composite, geographically referenced database, which was used to analyze the synthesized data.

Super-old Douglas-fir trees were found at ~ 12% of 874 sample sites, mostly on north-facing aspects and on gentle slope gradients. Even-aged stands of super-old trees were more likely to exist in areas that are prone to long fire intervals and high-severity fires. Single, remnant super-old trees were more likely to exist in areas that are prone to more frequent, lower-severity fires.

This study identified landscape positions that provide a refuge where Douglas-fir trees can attain maximum longevity. This information may be useful in determining optimal locations for late-successional reserves, as directed by the Northwest Forest Plan.

Over 350 hectares of unsampled terrain within the study area were identified where more super-old trees could likely be found. Efforts to locate more super-old trees using these data could facilitate future paleoclimate research and other tree-ring based studies.

Spatial and Temporal Patterns of "Super-old" Douglas-fir Trees
of the Central Western Cascades, Oregon.

by
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1. Introduction

The value of old-growth forests as a source of insight into the function and dynamics of natural systems has become widely recognized among scientists and land managers in recent years (Orwig 2001). Interest in the preservation and management of old-growth forests and efforts to restore this type of ecosystem are increasing in many regions of the world (Botkin & Talbot 1992; Kaufmann *et. al.* 1992; Lorimer & Frelich 1994; Ingersoll & Nolan 1995; Shao & Zhao 1998; Bobiec *et. al.* 2000; Allen *et. al.* 2002; Nordlind & Östlund 2003; Arsenault 2003; Villeneuve & Brisson 2003). The study of old-growth forests, however, is particularly well developed in the Pacific Northwest region of the United States (Franklin *et. al.* 1981; Spies & Franklin 1996; Winter *et. al.* 2002; Poage & Tappeiner 2002; Franklin *et. al.* 2002).

In the Pacific Northwest, the term "old-growth" generally refers to Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) trees older than 200 years (Old-Growth Definition Task Group 1986). Most of the remaining old-growth forests in this region are on federal lands, including the national forests (Franklin *et. al.* 1981). The Northwest Forest Plan (NWFP), adopted in 1994 and implemented by federal land management agencies in Oregon, Washington and northern California, allows for preservation of these old-growth ecosystems. More than 7 million acres were designated as "late-successional reserves" in the NWFP, with the objective of conserving old-growth ecosystems mainly for the purpose of native habitat protection (NWFP Record of Decision 1994).

This study focuses on the forests of the central western Cascade Range of Oregon, where estimates of pre-European settlement levels of old-growth forests range from 61% to 90% of the historical forested landscape (Rasmussen & Ripple 1998). A great deal of analysis and discussion about old-growth forests in this area has focused on the relatively widespread 400 to 500 year age class of primarily Douglas-fir (*Pseudotsuga menziesii*) trees. However, the existence of trees with establishment dates prior to 1450, though rare, is noted in tree-ring based fire history studies previously conducted in this area. These trees embody significant information about forest and climate history extending nearly a millennium into the past.

The relative scarcity of very old trees in the central western Cascades is well documented. In a comparison of ten fire history studies conducted in a broad area of the central Cascades and Coast Range of Oregon and Washington, Weisberg and Swanson (2003) noted that most old-growth forests date from the period of the late 1400s through 1650, presenting a challenge to the reconstruction of forest history for earlier periods. As a possible explanation for this phenomenon, Weisberg & Swanson (2003) identified a regional, "synchronous nature" to historical fires recorded in this area. Widespread fire was common from the 1400s through ca. 1650, followed by a period of reduced fire activity from ca. 1650 to 1800, followed again by widespread fires ca. 1801 to 1925. The 400- to 500-yr. old-growth age class that is common in the central western Cascades today was likely established following widespread, possibly high-severity, stand-replacing fires in the late 15th and early 16th centuries. The rare trees and stands that predate this time period are biological legacies that have persisted for many centuries. We refer to them in this study as "super-old growth" (SOG).

The primary objectives of this study were to assay where SOG persists on the landscape, what factors enabled it to survive for more than 550 years, and to develop a predictive model for the occurrence of SOG. To meet these objectives, I synthesized data from prior fire history work done in the central western Cascades of Oregon (Morrison and Swanson unpublished; Teensma 1987; Morrison and Swanson 1990; Weisberg 1998). The study involved the following steps: (1) the collection of primary data and maps from each study, (2) the creation of a master database, and (3) analysis of the synthesized data. The analysis addressed three primary research questions:

1. What are the spatial patterns of SOG occurrence?
2. How is SOG related to fire history?
3. What factors affected the discovery of SOG by fire history researchers?

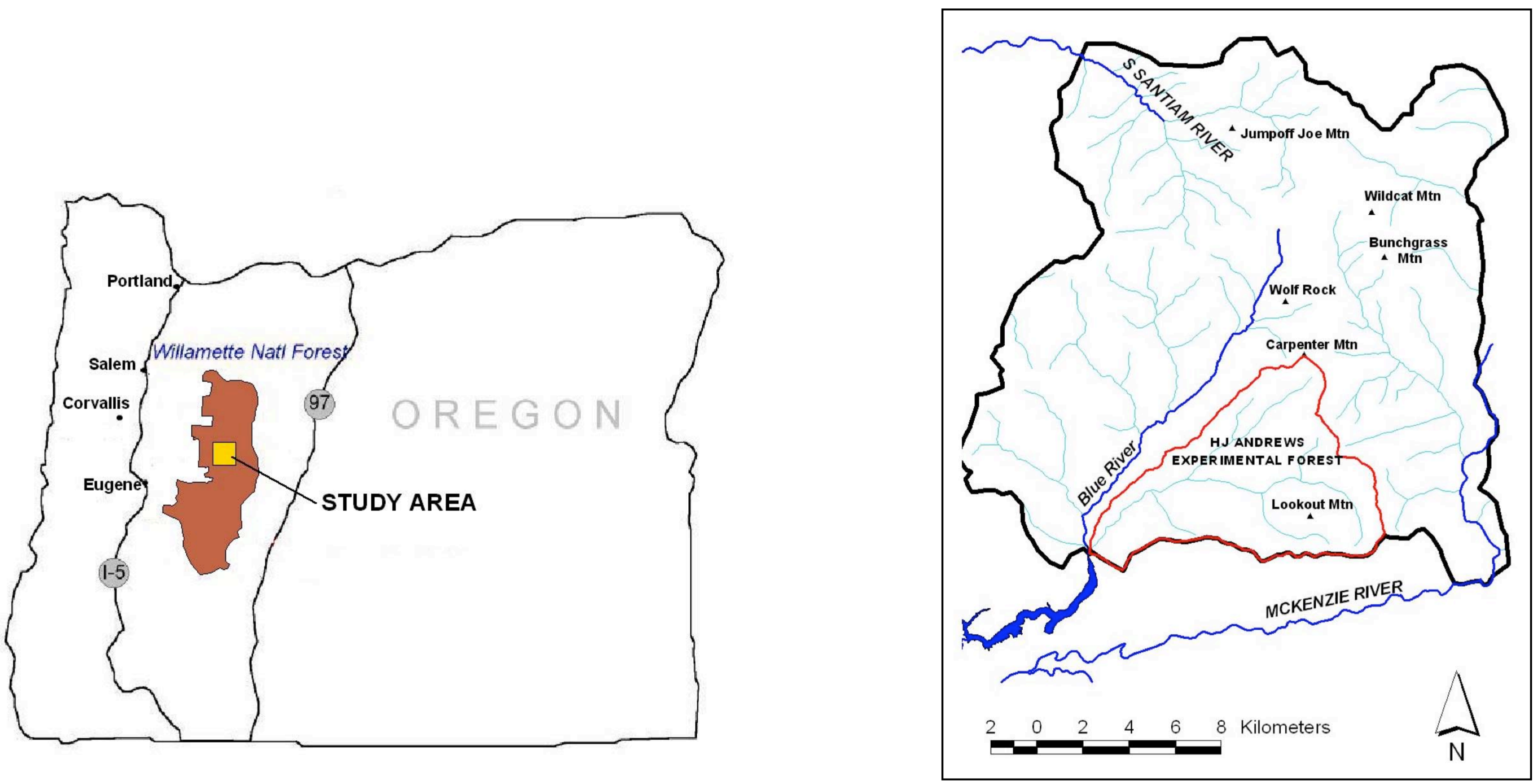
Previous tree-ring based fire history studies often documented the presence of trees we have classified as SOG, but did not examine the significance of SOG as a rare and valuable historical record of forest history. This study focuses on SOG as a unique entity at the tree, stand, and landscape scale that can contribute to our understanding of historical forest ecosystem processes and variability in climate and fire regimes, which in turn can inform management decisions for Pacific Northwest forest ecosystems.

2. Study Area

The study area covers approximately 414 km^2 of forested landscape in the central western Cascades of Oregon. It includes several basins within the McKenzie River and the South Santiam River watersheds, and the H. J. Andrews Experimental Forest, which occupies 64 km^2 in the south central portion of the study area (Figure 1). The study area also includes all or portions of the study areas of four earlier fire history studies (Figure 2).

Elevations in the study area range from 302 m to 1774 m. The landscape consists primarily of ancient, highly eroded volcanic flows, most of which originated more than 20 million years ago. The topography of the area is steep and dissected, with deeply incised stream valleys. Glacial deposits are also common in major river and stream valleys throughout the region (Franklin and Dyrness 1988).

The majority of the study area is located within the western hemlock vegetation zone (300 – 1050 m elevation), with Douglas-fir as the principal early seral tree species and western hemlock as the principal late seral species. Higher elevation areas fall mostly within the Pacific silver fir zone (1050 – 1550 m elevation), with Douglas-fir and noble fir (*Abies procera)* as the principal early seral tree species and Pacific silver fir *(Abies amabilis)* as the principal late seral species (Franklin and Dyrness 1988). The highest, subalpine regions of the site (above 1500 m) represent a very small percentage of the landscape, and were not sampled. Douglas-fir is by far the most abundant tree species within the study area (Weisberg 1998).



a. b.

Figure 1: Location of (a) study area within the Willamette National Forest; and (b) Landscape features and relative location of study area to HJ Andrews Experimental Forest.

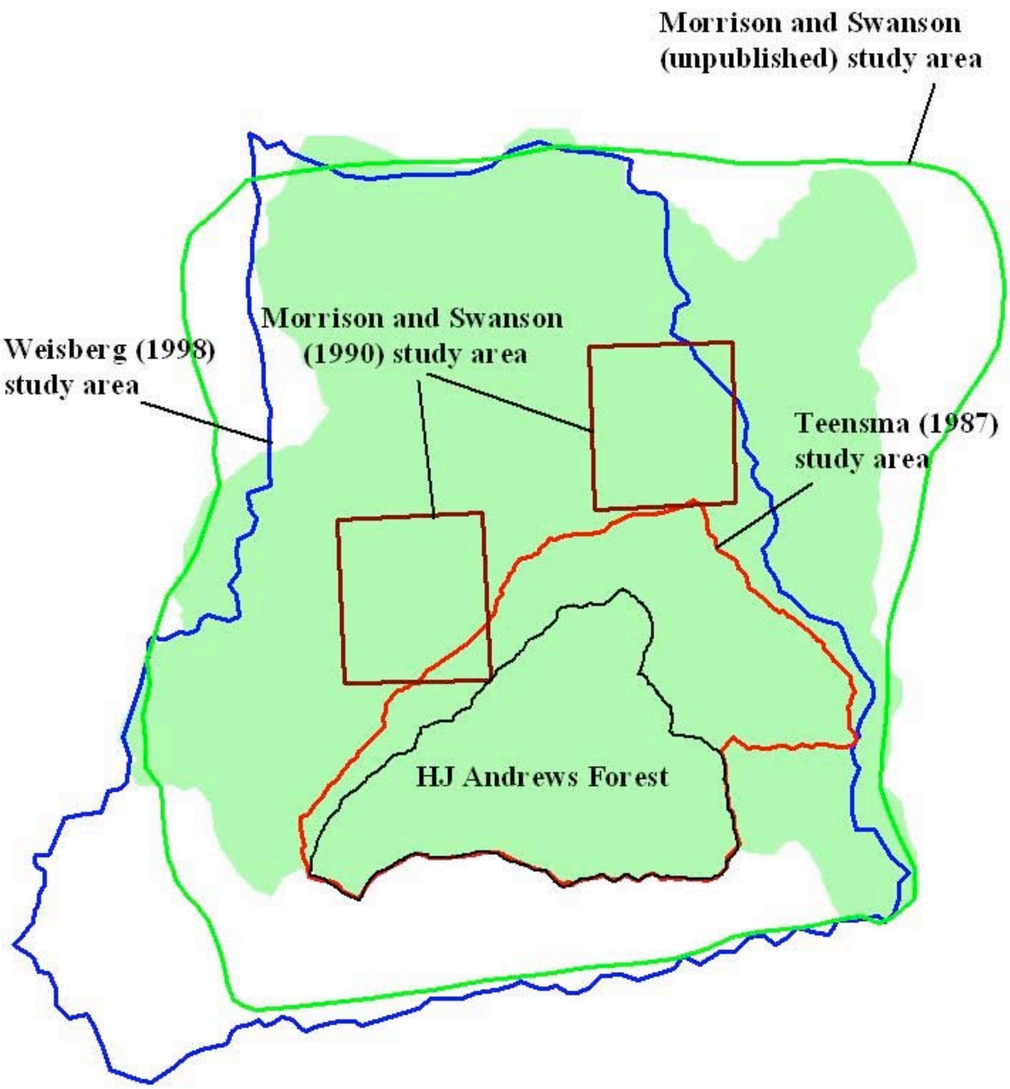


Figure 2: Study area boundaries of SOG study (shaded) and previous fire history studies

Mild, wet winters and cool, dry summers characterize the maritime climate in this region. Average annual precipitation is 240 cm, with 70 percent falling in prolonged periods between November and March. Precipitation type depends on elevation, with mostly rain below 400 m, transient snow at 400-1200 m, and seasonal snow above1200 m (Harr 1981, Perkins 1997). Summer is characterized by prolonged droughts, which, along with east wind events and lightning storms that periodically occur, lead to favorable conditions for fire in some years (Weisberg 1998).

Previous fire history studies revealed a complex natural historical fire regime in this region (Teensma 1987; Morrison and Swanson 1990; Weisberg 1998). Multiple fires of variable intensities over time produced a fine-scale mosaic of multi-aged stands. Interpretation of these events and patterns is further complicated by anthropogenic factors (e.g. European settlement, logging, grazing and fire suppression) in the late 19th and 20th centuries

3. Methods

3.1 Data sources and definitions

Data were collected and synthesized from four previous landscape-scale, overlapping, tree-ring based fire history studies (Morrison and Swanson unpublished; Teensma 1987; Morrison and Swanson 1990 Weisberg 1998) (Figure 2). In all studies, researchers inferred fire history in time and space primarily by utilizing field tree-ring counts of stumps in recent timber harvest units to estimate establishment and scar dates. Fieldwork was conducted in September 2002 and August 2003 to supplement existing data regarding locations and ages of SOG and to verify, to the extent possible, incomplete data.

Each researcher had somewhat different objectives, and each employed sampling designs and methodologies that, while similar, had unique components (Table 1). For descriptive and some statistical analyses, the study area was divided into eight, topographically heterogeneous “sub-areas,” defined using watershed boundaries (Figure 3). Sample site densities, quantified by researcher and by sub-area, were used as baselines against which to compare the frequency of SOG discovered.

Analyses of SOG were conducted by examining characteristics of SOG sites and SOG trees in the landscape. Site-level data were available for all studies. Tree-level data were available for all sites sampled by Weisberg (1998), but only for some sites sampled by Morrison and Swanson (unpublished), and no tree-level data were available for sites sampled by Teensma (1987). Spatial and temporal analyses of SOG sites could be conducted for the entire sample, but analyses of SOG trees within sites were possible in only ~50% of sample sites overall.

Table 1: Comparison of three previous fire history studies.

Researcher	Sampling Dates	Study Area (km^2)	# of sites	Sampling Density ($sites/km^2$)	Sampling Design	Site Size	Species	Samples Per site (mean)	# of trees sampled	# of origin dates	# of scars	Criteria for stump selection
Morrison & Swanson (unpub.)	1975-1976	490	408	0.8	Forest age cohort mapping	variable	Early seral	~ 4.4	~ 1800	1686	562	All age classes represented
Teensma (1987)	1982-1984	110	331	3.0	Fire history focus; representative of topographic variabilitity	variable	Early seral	6.5	2158	2022	708	1) All age classes represented 2) Oldest tree identified
Weisberg (1998)	1995-1996	450	137	0.3	Intensive sampling of fire history over extensive spatial area	~ 4 ha. within clearcuts, with more intensively sampled nested plots	Early seral & other species if fire scars present	33	4478	4478	unk.	Varied by sample site stratification – high priority for stumps w/fire scars

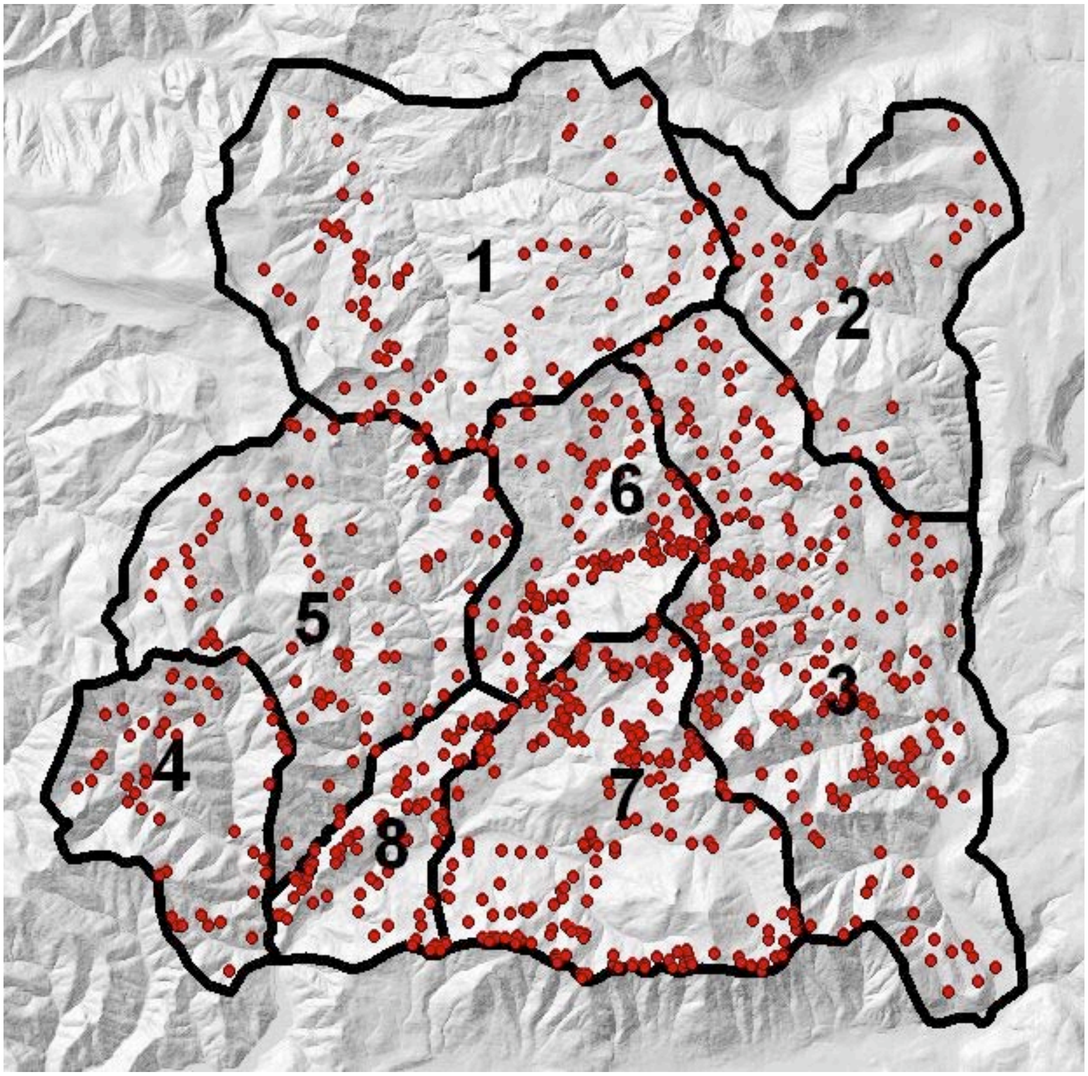


Figure 3: Map of study area showing sub-area boundaries. Points represent sample sites.

Origin dates of trees considered in this study span 9 centuries (1100s through 1900s). Teensma (1987) and Weisberg (1998) both reconstructed fire history chronologies that extend back to the late 1400s. The unpublished work of Morrison and Swanson consists of an extensive "reconnaissance study" of forest structure and fire history in the central western Cascades of Oregon conducted in 1975 and 1976. Data from this study were used to reconstruct a fire history chronology that dates back to 1150 A.D. (Morrison and Swanson 1990), (Figure 4).

In this study, fire history data from previous studies were grouped by century to account for errors in tree aging and lags in regeneration (see Weisberg and Swanson 2001), and to examine broad temporal patterns of fire occurrence over the past millennium. This classification system converted the number of fire episodes per century, which ranged from 1 to 31 individual fire episodes over the study area, depending on the century (Figure 5), into presence/absence data by site and century. Each sample site was then classified according to the presence/absence of fire and by fire severity for each of 9 centuries (1100s-1900s).

Century-scale fire severity classifications were derived from a reclassification of the fire evidence in chronologies created from previous fire history studies. In the Morrison and Swanson (unpub. and 1990) and Teensma (1987) fire chronologies, each fire episode at each site was classified by the type of evidence found (i.e. fire scar, regeneration cohort, or both). In the Weisberg (1998) fire chronology, each fire episode at each site was assigned one of 9 ordinal severity codes, based upon an algorithm that measured the ratio of the basal area of early-seral species trees regenerated within 40 years after a fire episode to the basal area of trees that predated

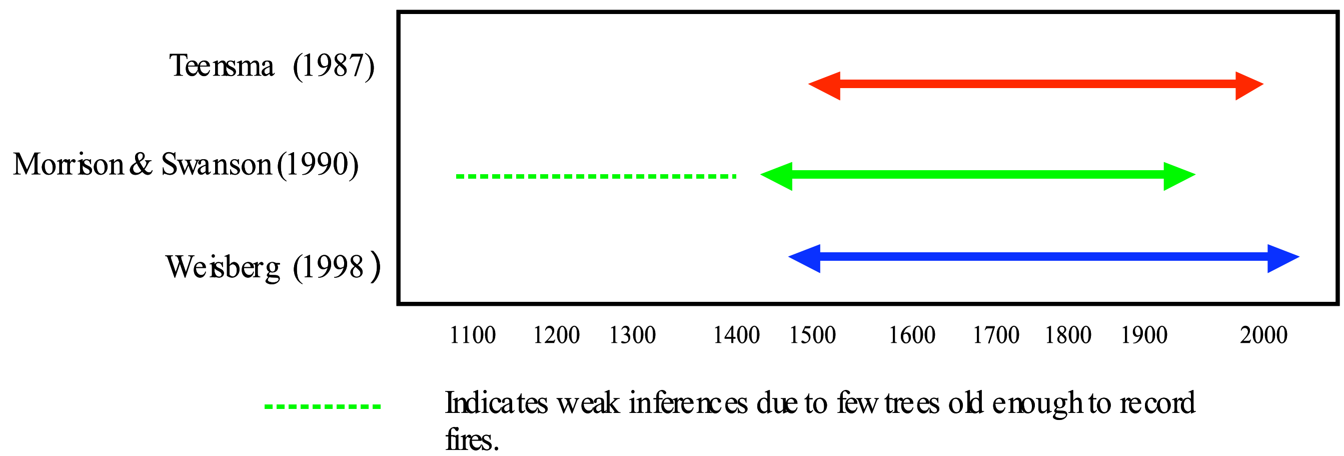


Figure 4: Time line of published fire history chronologies.

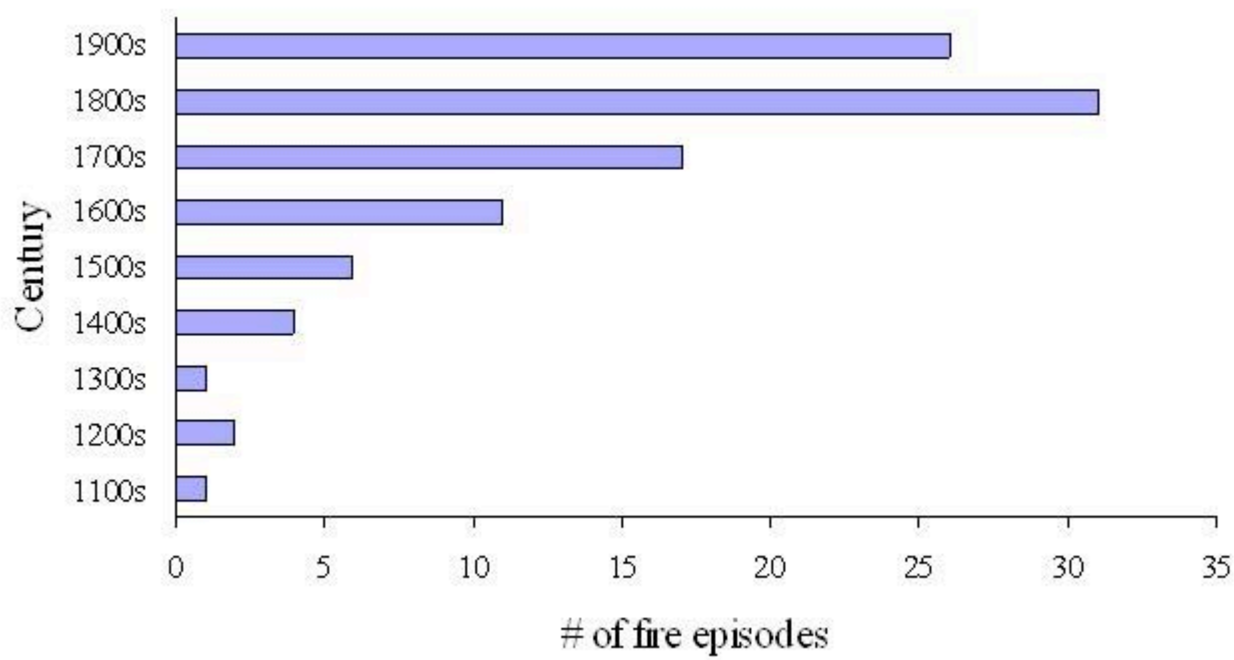


Figure 5: Number of fire episodes inferred in original fire chronology data prior to aggregation to century-scale fire occurrence and severity classes.

the fire episode. The century-scale fire chronology created for this study assigned a severity code (high-, or low-, or mixed-severity) to each site in these chronologies representing presence or absence of fires at each severity level for each century, based on a comprehensive classification scheme (Table 2)

Each site was also classified according to the presence or absence of SOG. Sites with one or more Douglas-fir trees with origin dates before 1450 A.D. were classified as SOG sites. I further classified SOG sites according to the presence of two other broad age classes: old-growth (OG) and mature-young (M-Y). "Old-growth" sites were defined as those with evidence of regeneration cohorts of Douglas-fir trees with origin dates between 1450 and 1799 A.D., and the "mature-young" classification was applied to sites with evidence of regeneration cohorts of trees with origin dates from 1800 A.D. to present. A regeneration cohort was defined as a grouping of Douglas-fir trees in the same age-class that colonized an area following high-severity fire.

3.2 GIS Methods

Spatial and temporal data were collected, edited, and combined to create a comprehensive database using ArcView versions 3.3 and 8.2 and Microsoft Excel (Figure 6). Step-by-step GIS procedures are provided in metadata for each GIS file created (see Appendix A).

Table 2: Scheme for classifying century-scale fire severity, based on evidence and severity classifications from annual-scale fire chronologies developed with data from previous fire history studies. The first three columns refer to the original fire chronologies; the last column shows classification codes used in century-scale fire chronology developed for this study.

Fire chronology[1]	Fire evidence code	Description	Reclassifed as[2]:
MS-T	1	Fire Scar date	L
MS-T	2	Pitch ring/resin crack, etc.	L
MS-T	3	Regeneration date	H
MS-T	4	Approximate regeneration date	H
MS-T	5	Fire scar and regeneration date	M
W	1	Underburn	L
W	2	Low/underburn	L
W	3	Low	L
W	4	Moderate	M
W	5	High	H
W	6	Unknown (not earliest date)	not used
W	7	Unknown (earliest date)	not used
W	8	Unknown - opportunistic site	not used
W	9	Erased (no trees old enough)	not used
W	0	No record of fire	not used

[1] MS-T = Chronology created from data from Morrison & Swanson (unpub. and 1990) and Teensma (1987); W = Chronology created from data from Weisberg (1998). Both chronologies were created by Peter Weisberg .

[2] L = low-severity fire; M = mixed-severity fire; H = high-severity fire. Each classification indicates that at least one fire of that severity class occurred in a given century at that site. Fires of other severities may or may not have occurred as well (i.e. each site could have multiple classifications for any given century).

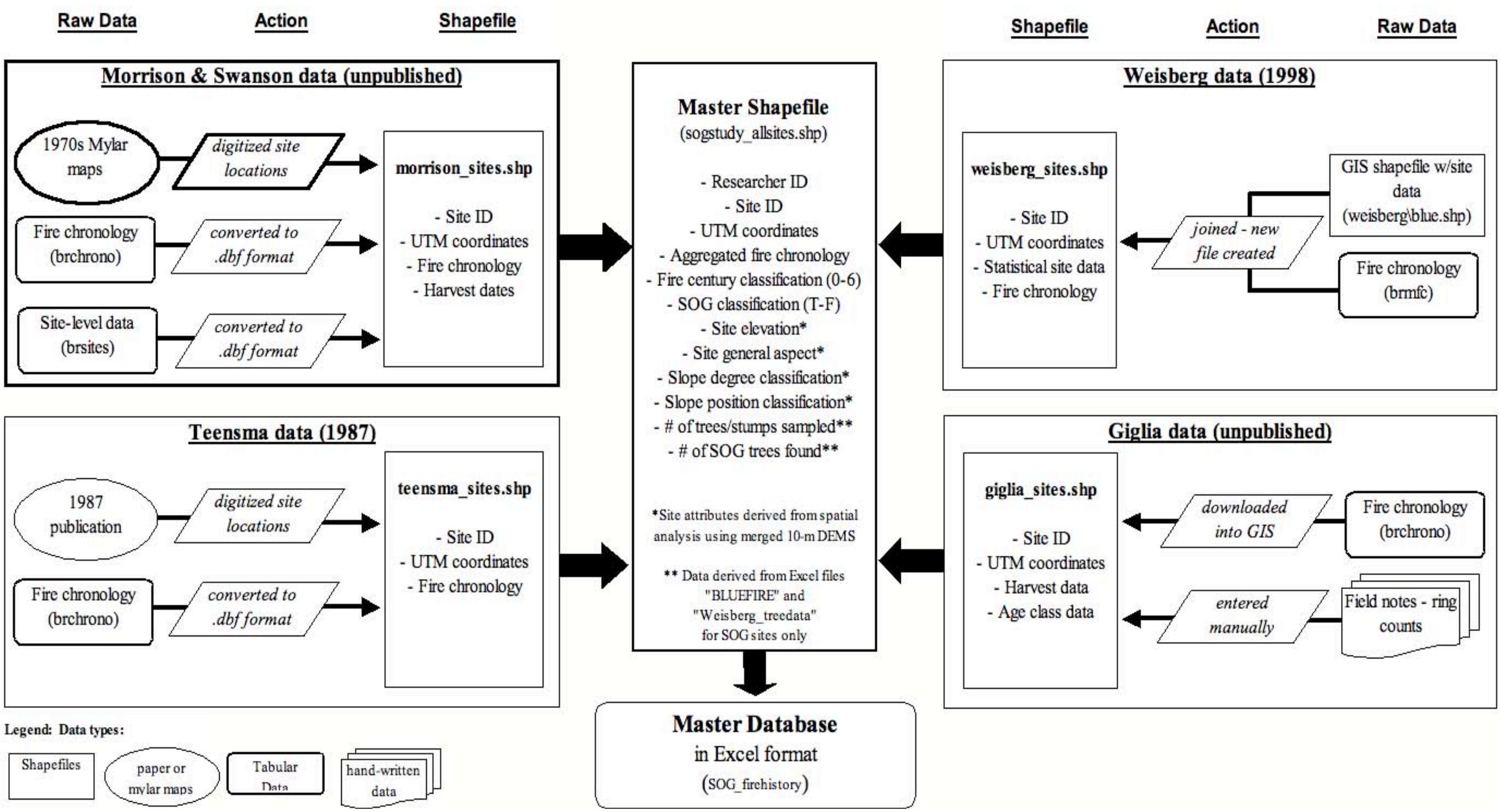


Figure 6: Flowchart of creation and structure of SOG master database.

3.2.1 Primary spatial and temporal data

Sampling site locations and study area boundaries were either obtained in digital format or scanned and/or digitized from hard copy maps using ArcEdit and ArcView software. Digitized maps were georeferenced, projected and converted to shapefile format. Each site was assigned an identification code and UTM coordinates. A separate shapefile was created for each fire history study ("researcher shapefiles"), containing sample site locations represented by points, and attribute data pertaining to sample sites within that study. Additional spatial data, including study area boundaries, digital elevation models (DEMs), aerial photos and landscape features were either digitized from primary sources or obtained in digital format, edited as needed, and utilized in GIS for mapping and spatial reference (Table 3).

To estimate the degree of spatial error in site locations from non-digital data sources, 30 sample sites for which harvest years were recorded were randomly selected from the Morrison and Swanson data (harvest dates were not recorded in the Teensma data, so these sites were not included). These digitized site locations were overlaid on a Willamette National Forest harvest data GIS layer obtained from the Regional Ecosystem Office Geospatial Center website. I found that 10 of these sampled points were within a harvest plot with a harvest year that matched the researcher site data. Fifteen sites were not located within an appropriate harvest plot, but were found to be an average of 89 meters (range from 16 to 186 meters; median 73 meters) from what was assumed to be the correct plot, based on harvest year recorded in the harvest data layer. The remaining 5 sites could not be reconciled to the harvest data layer.

Table 3: Primary spatial data used in GIS.

Datasource	**Data description**	**Data represented**
1. Morrison and Swanson (unpub.)	5 maps, hand-drawn on 1m x 1m mylar sheets, registered to USGS 7.5-min. topo quads	Location of sample sites
2. Morrison and Swanson (1990)	Paper map from publication	Study area boundary of Morrison and Swanson unpublished reconnaissance study
3. Teensma (1987)	Paper map from publication	Study area boundary and sample site locations
4. Weisberg (1998)	GIS shapefile used to create published map	Sample site locations
5. USFS PNW Research Station database	ArcInfo coverage of regional fire history studies	Study area boundary for Weisberg study
6. Giglia (unpub.)	GPS data obtained during fieldwork in Sept. 2002	Point locations of sampled sites and SOG
7. Regional Ecosystem Office Geospatial Center (www.reo.gov)	Nine 10-meter resolution digital elevation models (DEMs)	Elevation data for rectangular extent of study area
8. USFS PNW Research Station CDs	9 Digital Ortho Photos (DOQs); photos taken in 2000	Aerial photos of landscape for rectangular extent of study area
9. USFS PNW Research Station database	GIS hydrology shapefile for Willamette Natl. Forest	Rivers and streams in study area
10. USFS PNW Research Station database	GIS transportation shapefile for Willamette Natl. Forest	Roads and trails in study area

Annual fire chronology data from Excel spreadsheets created by Peter Weisberg were appended to the researcher shapefiles (Table 4). These data, along with the Willamette National Forest timber harvest data layer, were utilized in GIS to facilitate temporal and spatial analysis.

3.2.2 Master database creation

All researcher shapefiles were merged into a new master shapefile containing point locations for all sample sites and the following attributes: site ID, UTM coordinates, researcher ID, and a binary classification indicating the existence of SOG (true – false) (Figure 6). Additional data were appended to the master shapefile attribute table as follows: (1) available tree-level data for SOG sites only (i.e. number of trees/stumps sampled and number of SOG trees found per sample site), extracted from two supplemental Excel files, and (2) spatial and temporal site-level attribute data, extracted from primary data sources (Figure 6; Table 5).

3.3 Data analysis

I examined the composite database on fire history to answer my three main research questions.

3.3.1 What are the spatial patterns of SOG occurrence?

To examine general patterns of SOG across the study area, I compared the frequency and sampling density of SOG sites among sub-areas. I also compared the

Table 4: Primary temporal data used in GIS.

Data source	**Data description**	**Data represented**
11. Teensma (1987); Morrison & Swanson (unpub.)	Excel spreadsheet created by Peter Weisberg as a preliminary analysis for 1998 publication	Edited composite fire chronology for Teensma (1987) & Morrison & Swanson (unpub.) sample sites at annual time-scale.
12. Weisberg (unpub.)	Excel spreadsheet created for fire history analysis in 1998 publication	Fire chronology for Weisberg (1998) sample sites at annual time-scale.
13. USFS PNW Research Station database	ArcInfo coverage	Harvest unit boundaries, stand age and harvest year data

Table 5: Spatial and temporal site-level attribute data extracted from primary data sources and appended to master shapefile.

Attribute	Primary data source	Extraction methods	New data source
1. Century-scale fire activity (one attribute field for each century, 1100s – 1900s)	Fire chronologies from previous fire history studies at annual scale (#11 & 12 from Table 4.)	Fire occurrence was aggregated and coded by severity for each site and for each century	Excel spreadsheet, converted to dbf format
2. Fire centuries	Century-scale fire chronology (#1, above)	Each site was assigned a classification code from 0 to 6 representing the number of centuries with fire evidence[3]	None – attribute field added directly to master shapefile.
3. Elevation	Merged 10-meter DEM (#7 in Table 3)	Elevation contour lines were derived from DEM; GIS procedure assigned value of nearest line to each site	GIS shapefile with 20m contour lines
4. Aspect	Merged 10-meter DEM (#7 in Table 3)	Aspect quadrants (NE, NW, SE, SW) were derived from DEM and aggregated to ignore micro-topography; GIS procedure assigned an aspect code to each site	GIS shapefile with aspect polygons
5. Slope position	Aspect shapefile (#4 above)	Aspect polygons classified by slope position relative to proximal high ridges	None
6. Slope degree	Merged 10-meter DEM (#7 in Table 3)	Slope angle data (in degrees) were derived from DEM, classified as 0-15, 15-30 and >30 degrees; GIS procedure assigned a slope class code to each site.	GIS shapefile with 3 slope classifications

[3] The “0” classification was used for sites where age-class data was incomplete or where age classes were estimated by observation of live trees. These sites were used only to indicate presence or absence of SOG; they were not used for comparative temporal analysis.

frequency of SOG trees within stands to distinguish individual, remnant trees from possible cohorts of multiple SOG trees.

Spatial relationships of SOG to (1) elevation, (2) slope gradient (3) aspect, and (4) slope position relative to adjacent high ridges were tested using a chi-squared test of independence and odds ratios when appropriate (Ramsey and Schafer 2002). Slope position was defined as: (1) high ridge areas (above 1200 meters), (2) areas below 1200 meters and below high ridge areas, and (3) areas below 1200 meters, not below high ridge areas. Tests with cell counts of less than 5 were not considered to be statistically valid, but relationships were examined visually.

A predictive model for the location of SOG was created by identifying geographic locations within the study area that met the parameters of landscape variables most strongly associated with SOG. I then compared the proportion of the study area that met these criteria with (1) the proportion of total SOG sites, and (2) the proportion of sample sites by researcher, located within these areas.

3.3.2 How is SOG related to fire history?

I examined variability in fire frequency, extent and severity in the study area over time and space as follows: (1) The total number of centuries in which evidence of fire was recorded was compared among sub-areas; (2) The proportion of sites that had fire evidence was compared across sub-areas for each of 9 centuries (1100s through 1900s); and (3) The proportion of sites among sub-areas where high-severity fire had occurred was compared by century and on average for the periods 1100 to 1600 A.D., and 1600 A.D. through the 1900s.

Fire history at SOG sites was examined by comparing the age-class distribution among all SOG sites. Sites were compared based on the frequency of sites in four different "condition classes," defined as (1) sites where SOG was the only age class present; (2) sites where SOG co-occurred with OG; (3) sites where SOG co-occurred with M-Y; and (4) sites where SOG co-occurred with both OG and M-Y. Relationships between age class distribution and (1) aspect, and (2) researcher were tested using a chi-squared test of independence (Ramsey and Schafer 2002).

I also used available tree-level data from Morrison and Swanson (unpublished) and Weisberg (1998) to examine the relationship between age-class distributions and search intensity by comparing the number of trees sampled among condition classes.

Temporal relationships of SOG to fire occurrence in 4 time periods (mid-1400s through 1500s; 1600s; 1700s; 1800s) were tested using a chi-squared test of independence (Ramsey and Schafer 2002). The last half of the 1400s and the 1500s were combined in this analysis to establish statistically viable cell counts.

Finally, to examine the variability of fire history patterns at SOG sites throughout the study area, spatial and temporal patterns of fire history were compared between two sub-areas. Results from the comparison of SOG frequency among sub-areas (see section 3.3.1) were used to select the sub-areas compared in this analysis.

3.3.3 What factors affected the discovery of SOG by fire history researchers?

The following sets of relationships were tested using a chi-squared test of independence (Ramsey and Schafer 2002):

1. The frequency of SOG vs. researcher
2. The number of clearcuts sampled by harvest decade vs. researcher
3. The number of clearcuts sampled vs. not sampled by harvest decade for each researcher (3 tests)
4. The frequency of SOG vs. harvest decade

I also used available tree-level data to examine search intensity by comparing the number of trees/stumps sampled per site among SOG sites, and by researcher. These data were then compared to the number of SOG trees found by site and by researcher.

4. Results

4.1 Spatial patterns of SOG occurrence

SOG was found at ~12% (107/874) of all sample sites. The frequency of SOG was spatially variable, ranging from 0 to 29% of sites in the 8 sub-areas. The highest percentage of SOG sites occurred in the Latiwi-Sevenmile sub-area (29%), and the Browder-Bunchgrass sub-area (24%). Together, these two sub-areas contain ~31% of the SOG sites overall. The Mona-Tidbits sub-area, which contains ~6% of all sample sites, is the only sub-area where no SOG was found (Table 6; Figure 7).

SOG in the study area occurred both as single, remnant trees and as cohorts of multiple SOG trees. Field observation confirmed the existence of at least two stands of SOG, where more than 10 trees within a 50-year age range were found in one sample site. Both of these sites were located in the Browder-Bunchgrass sub-area. In both sites, the SOG trees represented the dominant age class by field count, with some younger, shade-tolerant species interspersed. Single SOG trees were found at about half of the additional 67 sites for which actual tree-ring counts were available, and more than one SOG tree was found at the other half (range 2 to10 trees). (Table 7; Figure 8).

SOG occurrence was independent of elevation (x^2 = 3.25; p = >0.25). Elevations of sample sites were representative of the distribution of elevation ranges in the study area (Figure 9). The range of elevations of SOG sites (540 – 1420 m) was narrower than the range of elevations for non-SOG sites (480 – 1540 m); however, the standard deviation and the mean elevation of SOG sites were not significantly different than those of non-SOG sites.

Table 6: Characteristics of sub-areas and entire study area ("all areas").

Subregion:	**Sampling Density ($sites/km^2$)**	**# of sample sites**	**# of SOG sites**	**% of sites with SOG**
1-Latiwi Cr* – Sevenmile Cr	1.0	85	25	29
2-Browder Cr – Bunchgrass Cr	0.8	38	9	24
3-Deer Creek	2.6	226	14	6
4-Mona Cr – Tidbits Cr	1.6	49	0	0
5-Cook Cr – Quentin Cr – Upper Canyon Cr	1.3	78	13	17
6-Wolf Rock	3.5	106	16	15
7-Mack Cr – McRae Cr – Upper Lookout Cr	4.1	217	16	7
8-Lower Lookout Cr – Blue River	4.0	75	14	19
ALL AREAS	2.1	874	107	12

* formerly Squaw Creek

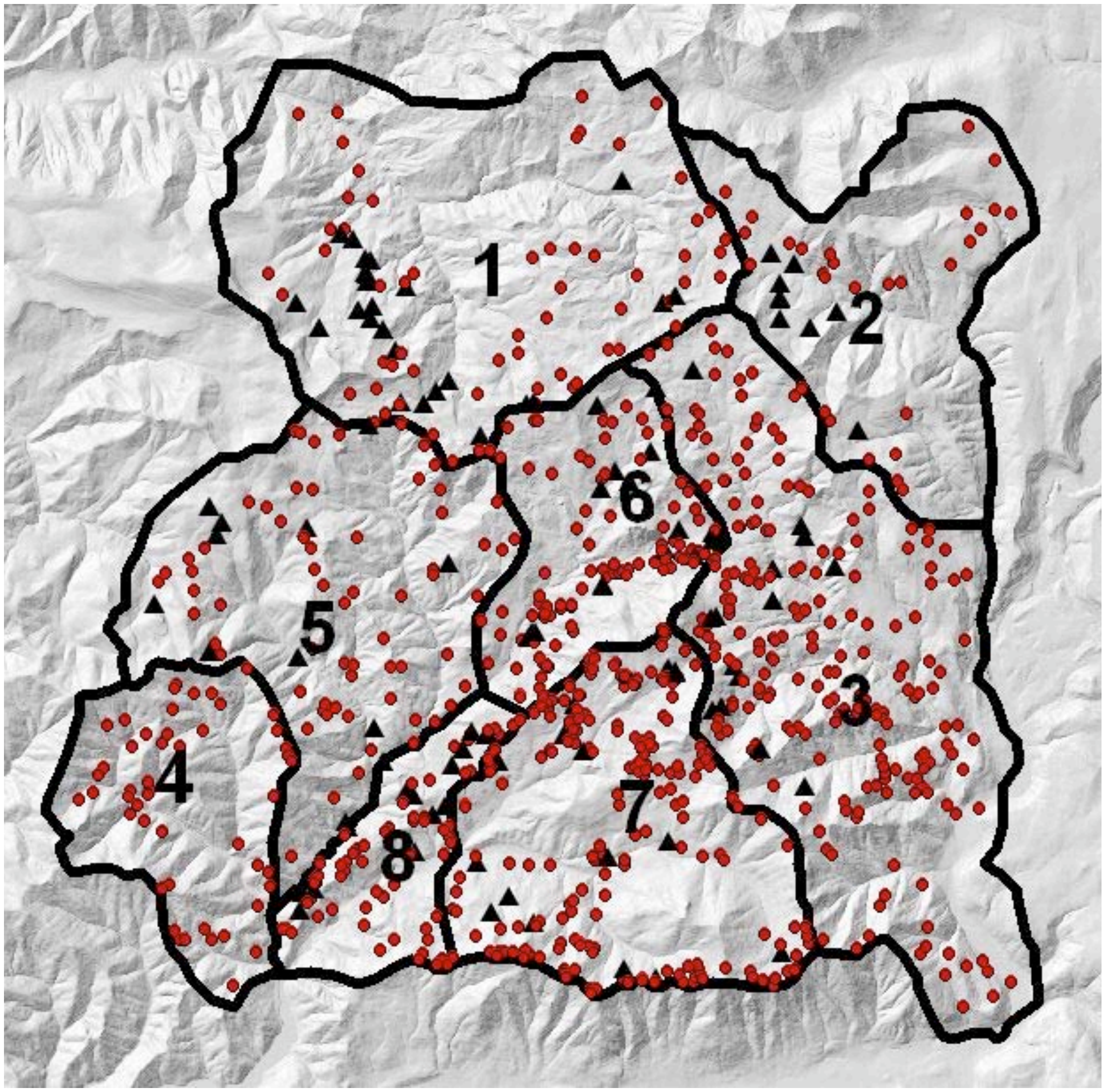


Figure 7: Study area map, showing sub-area boundaries and sample sites. Circles represent sites without SOG; triangles represent sites with SOG. Latiwi-Sevenmile sub-area (#1) and Browder-Bunchgrass sub-area (#2) had the highest proportions of SOG sites. Sub-area numbers correspond to Table 6.

Table 7: Frequency of sites with one or more than one SOG tree, and the relative likelihood of multiple SOG trees being part of a stand of SOG . Note: Some sites are included in more than one classification; e.g. 2 SOG trees within a 25-yr. age range, plus 1 individual SOG tree.

	Total SOG sites w/data	Sites with 1 SOG	Sites with possible stand[1]	Sites with likely stand[2]	Confirmed stand[3]
Morrison and Swanson (unpublished)	55	23	31	2	0
Weisberg (1998)	4	3	1	1	0
Giglia	10	8	0	0	2
Totals:	69	34	32	3	2

[1] 2-3 SOG tree with age range of <50 years, or ocular age estimate of live stand (note: this category includes13 Morrison & Swanson sites that had ocular estimates)

[2] 4-6 SOG trees with age range of <25 years

[3] >10 SOG trees in proximity to one another with age range <50 years

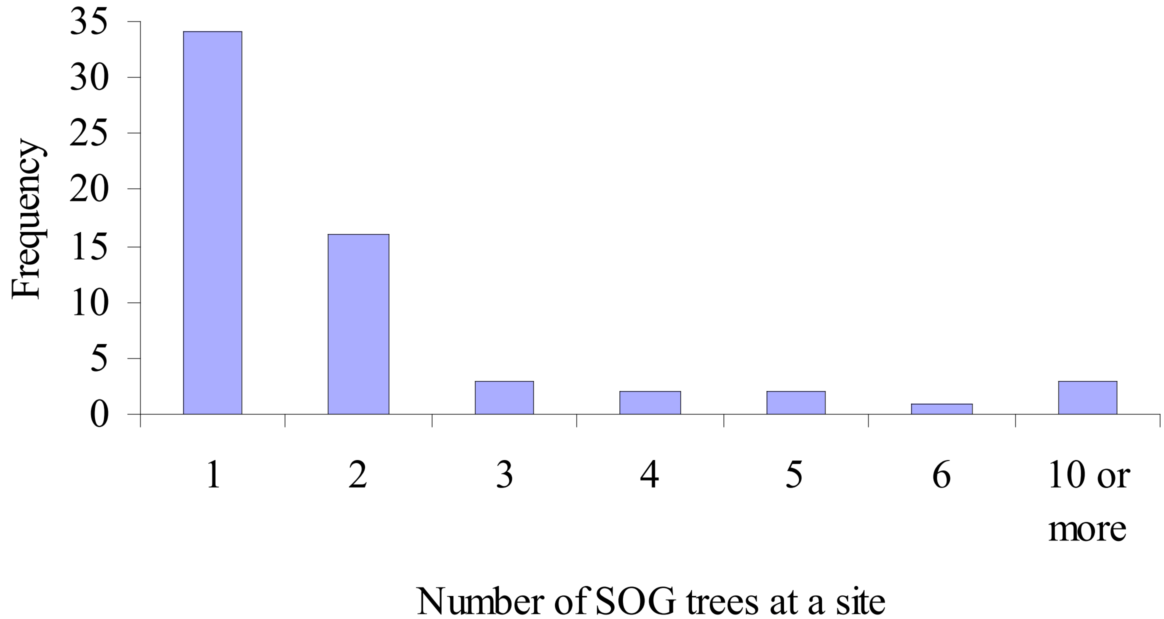


Figure 8: Frequency of single and multiple SOG trees at a site. (Sites with ocular estimates of live trees are not included).

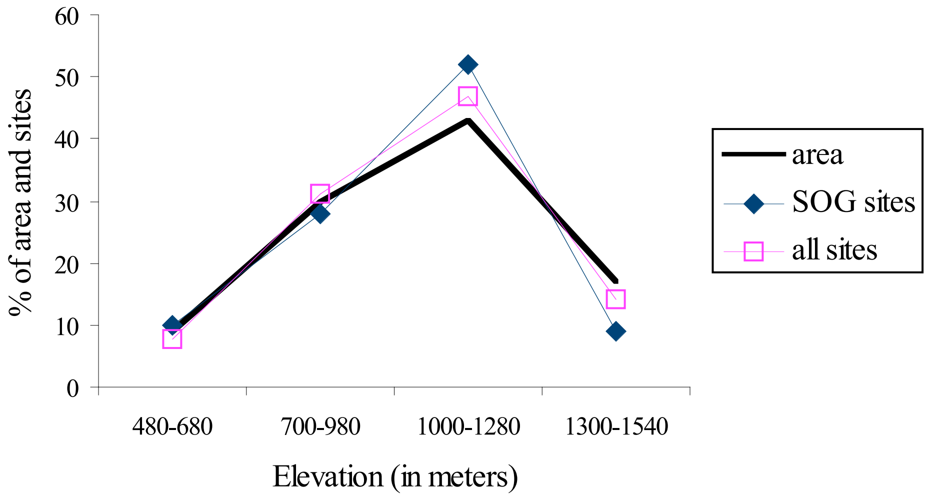


Figure 9: Proportion of study area, SOG sites and all sample sites at 4 elevation classes.

SOG was more likely to occur on gentle slopes than on steep slopes. Slope steepness of sample sites was fairly representative of the distribution of slope steepness in the study area. SOG was strongly associated with slope steepness (x^2= 14.69; p = 0.01). SOG was 2 to 2 ½ times more likely to occur on slopes of 0-15^o than on slopes of 15-30^o or on slopes >30^o, respectively (Figure 10).

SOG was slightly more likely to occur on NE and NW aspects in certain hillslope positions. Aspects of sample sites were fairly representative of the distribution of aspects in the study area. SOG was weakly associated with aspect (x^2 = 5.99; p = 0.13). A higher proportion of SOG sites occurred on northeast and northwest aspects than on southeast and southwest aspects (Figure 11). SOG was independent of slope position (x^2 = 1.92; p > 0.25). However, SOG was slightly more likely to occur on NE aspects below high ridges than in other parts of the landscape (Figure 12). This pattern is particularly evident in the two sub-areas with the highest proportion of SOG (Latiwi-Sevenmile and Browder-Bunchgrass) (Figure 13, 14).

Two spatial variables were identified as the most strongly associated with SOG across the study area: north aspect and 0-15^o slope gradient. Approximately 12% of the study area met the criteria of this predictive model; 20% of all sample sites and 34% of SOG sites were located within these areas (Figure 15).

The proportion of sites sampled by Weisberg (1998) was most representative of the proportion of the study area that met the criteria of the predictive model. Morrison and Swanson (unpublished), Teensma (1987), and Giglia (unpublished fieldwork) sampled a higher proportion of sites located in areas that met the model criteria (Figure 16).

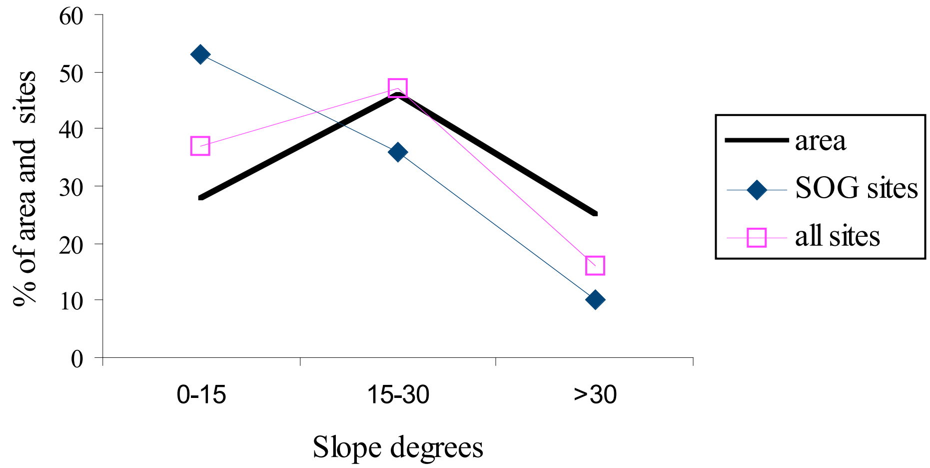


Figure 10: Proportion of study area, SOG sites and all sample sites in 3 slope steepness classes.

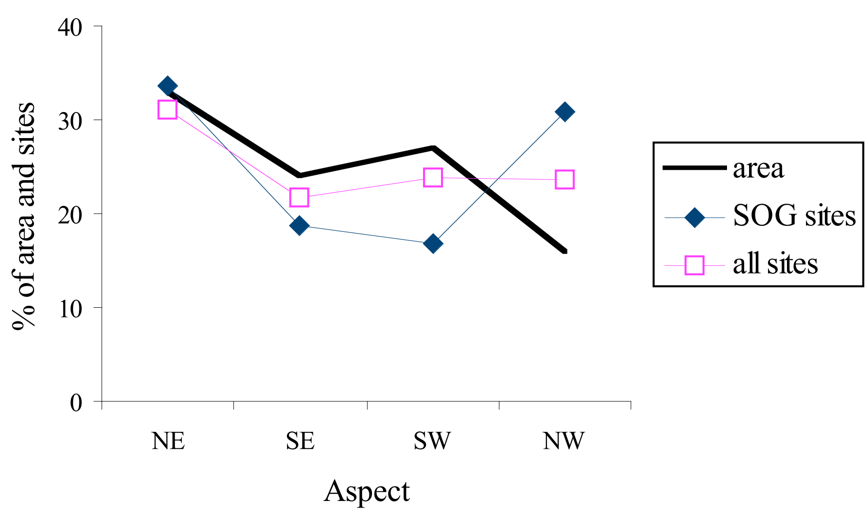


Figure 11: Proportion of study area, SOG sites and all sample sites in 4 aspect classes.

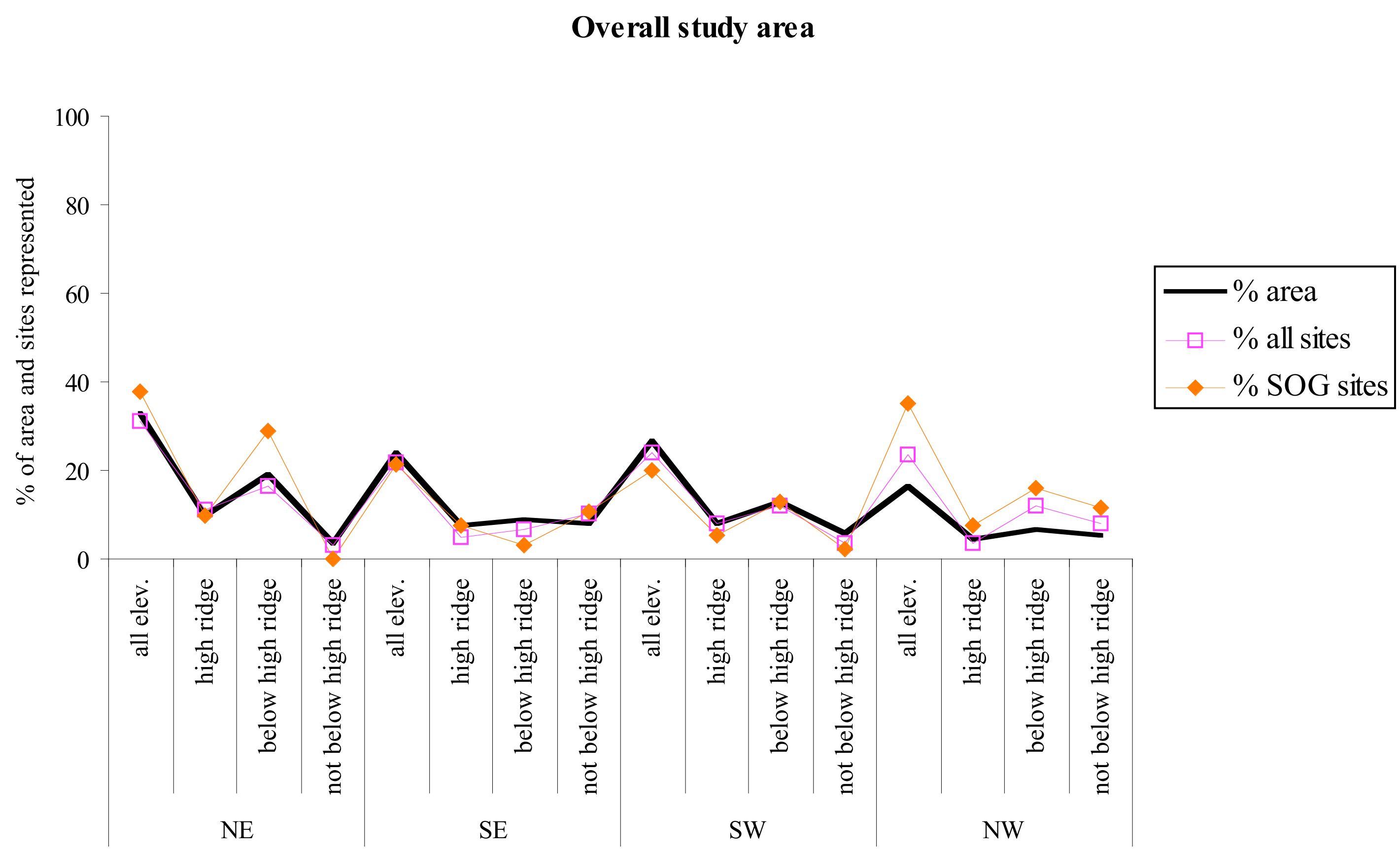


Figure 12: Proportion of study area, SOG sites and all sample sites in each of 12 aspect/slope position classes.

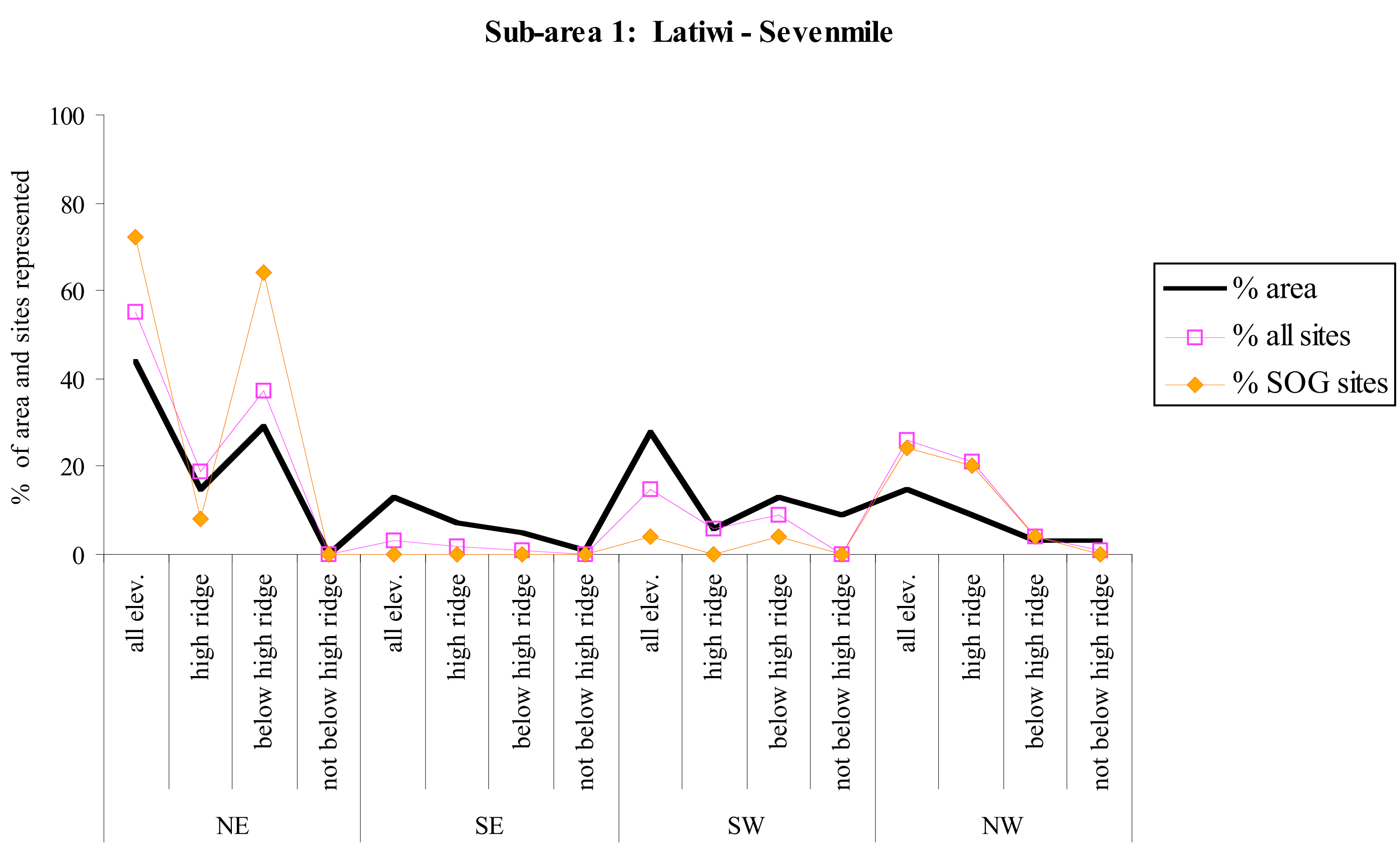


Figure 13: Proportion of landscape, SOG sites and all sample sites, within sub-area 1, in each of 12 aspect/slope position classes.

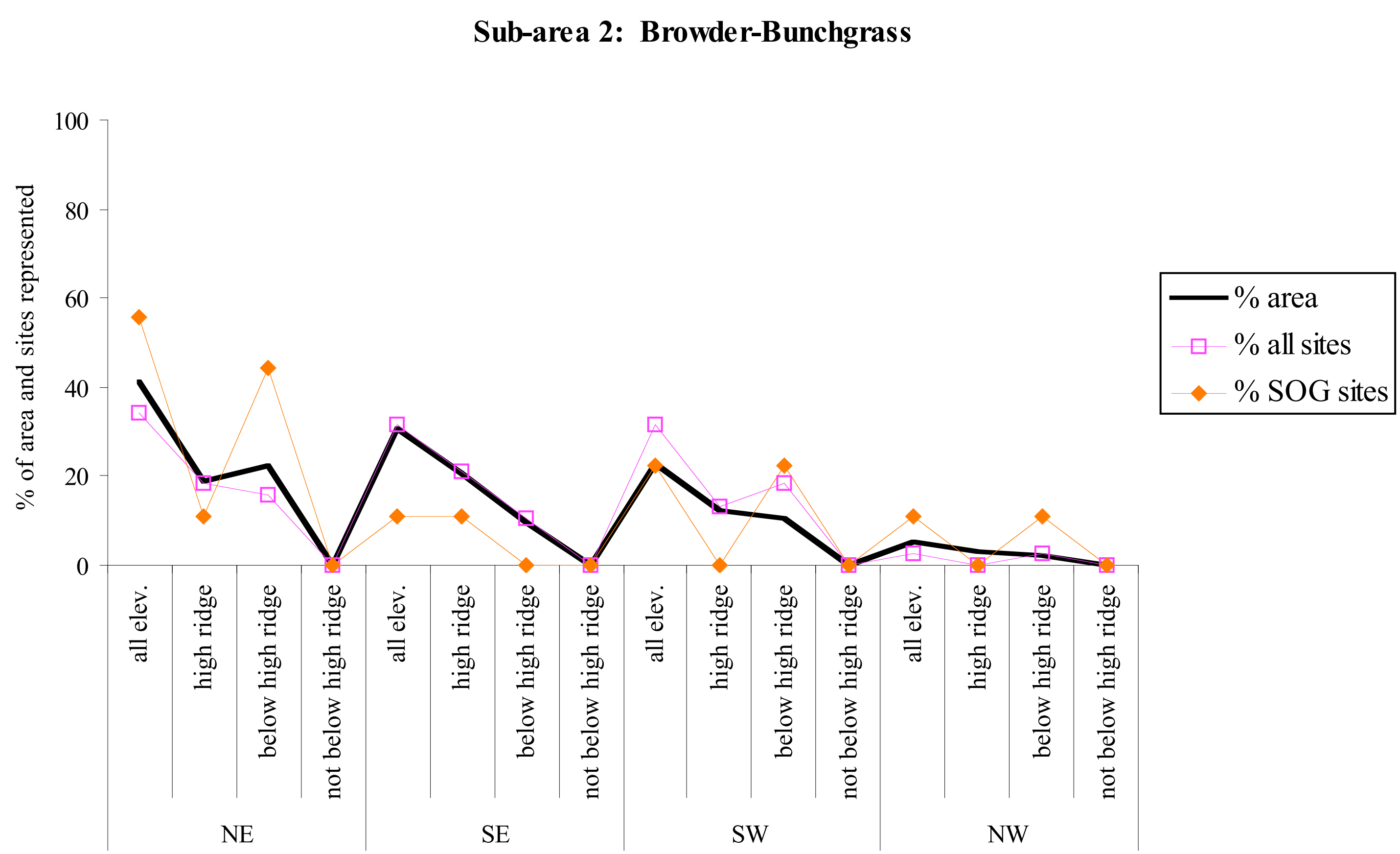


Figure 14: Proportion of landscape, SOG sites and all sample sites, within sub-area 2, in each of 12 aspect/slope position classes.

Figure 15: SOG predictive model. Shaded polygons represent areas with north aspect and 0-15 degree slope gradient. These areas represent 12% of the study area, contain 20% of all sample sites, and 34% of the SOG sites found. Only SOG sites are shown, represented by points.

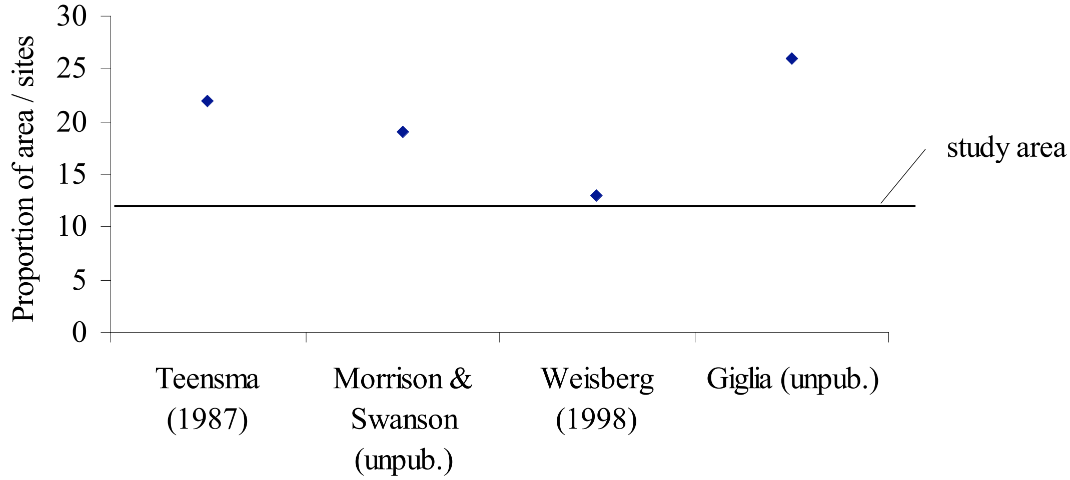


Figure 16: Proportion of the study area (horizontal line) and proportion of sample sites for each researcher (points) located in areas that fit the criteria for the SOG predictive model.

4.2 Patterns of fire history

4.2.1 General patterns in the study area

Fire frequency, extent and severity were variable over time and space. Three of 8 sub-areas had evidence of fire in all 9 centuries (1100s through 1900s). The other 5 sub-areas lacked evidence of fire in at least one century in the "super-old" time period (1100s through 1300s) (Table 8).

Fire was most widespread in the 1500s and in the 1800s (fire evidence at 47% and 59% of all sample sites, respectively) (Table 8). However, in the Browder – Bunchgrass sub-area, fire was most extensive in the 1300s and the 1700s (fire evidence at 21% and 37% of sample sites, respectively) (Figure 17).

Over the whole study area, fire occurrence in any given century during the time period from 1100 to 1600 was highly likely to be classified as high-severity fire (Table 8)[1]. From 1600 forward, however, an average of 38% of fire activity was classified as high-severity by century throughout most of the study area. The one exception was the Browder-Bunchgrass sub-area, where 83% of century-scale fire activity was classified as high-severity from 1600 to the present (Table 8).

4.2.2 Fire history in SOG sites

SOG age classes occurred in mixed-age stands with old-growth and/or mature-to-young age classes in 79 of 107 SOG sites (73% of sites) (Figure 18). In 11 sites

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[1] A sample site was classified as having experienced high-severity fire for any given century if at least one high-severity fire was inferred to have occurred in that century; mixed and/or low severity fires may or may not have also been inferred.

Table 8: (2 pgs.) Century-scale fire frequency, extent and severity data for 8 sub-areas and for the whole study area (all areas, pg. 2)

		Century									Avg. 1100s-	Avg. 1600s-
Fire Occurrence by site		**1100s**	**1200s**	**1300s**	**1400s**	**1500s**	**1600s**	**1700s**	**1800s**	**1900s**	**1500s**	**1900s**
1 - Latiwi - Sevenmile (85 ttl sites)												
a. # of sites w/at least 1 fire		4	16	5	12	44	18	15	31	6		
b. % of total sites w/fire	%	5	19	6	14	52	21	18	37	7		
c. # of sites w/at least 1 high-severity fire		4	16	5	10	41	4	6	14	0		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	100	83	93	22	40	45	0	95	27
2 - Browder - Bunchgrass (38 ttl sites)												
a. # of sites w/at least 1 fire		0	3	8	1	5	4	14	5	1		
b. % of total sites w/fire	%	0	8	21	3	13	11	37	13	3		
c. # of sites w/at least 1 high-severity fire		0	3	8	1	5	4	13	3	0		
d. % of sites w/high-severity fire ("c" / "a")	%	0	100	100	100	100	100	93	60	0	100	83
3 - Deer Creek (226 ttl sites)												
a. # of sites w/at least 1 fire		1	4	0	30	94	28	118	147	12		
b. % of total sites w/fire	%	0	2	0	13	42	12	52	65	5		
c. # of sites w/at least 1 high-severity fire		1	4	0	28	91	10	93	71	3		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	0	93	97	36	79	48	25	98	47
4 - Mona - Tidbits (49 ttl sites)												
a. # of sites w/at least 1 fire		0	0	0	9	30	9	12	23	19		
b. % of total sites w/fire	%	0	0	0	18	61	18	25	47	39		
c. # of sites w/at least 1 high-severity fire		0	0	0	9	30	2	0	13	3		
d. % of sites w/high-severity fire ("c" / "a")	%	0	0	0	100	100	22	0	57	16	100	24

(continued on next page)

Table 8: (continued)

		Century									Avg. 1100s-1500s	Avg. 1600s-1900s
Fire Occurrence by site		**1100s**	**1200s**	**1300s**	**1400s**	**1500s**	**1600s**	**1700s**	**1800s**	**1900s**		
5 - Cook - Quentin - Upper Canyon (78 ttl sites)												
a. # of sites w/at least 1 fire		5	5	1	11	30	16	28	47	18		
b. % of total sites w/fire	%	6	6	1	14	39	21	36	60	23		
c. # of sites w/at least 1 high-severity fire		5	5	1	10	30	8	14	20	3		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	100	91	100	50	50	43	17	98	40
6 - Wolf Rock (106 ttl sites)												
a. # of sites w/at least 1 fire		4	1	2	52	43	16	32	73	26		
b. % of total sites w/fire	%	4	1	2	49	40	15	30	69	25		
c. # of sites w/at least 1 high-severity fire		4	1	2	48	36	6	11	30	8		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	100	98	84	38	34	41	31	96	36
7 - Mack - McRae - Upper Lookout (217 ttl sites)												
a. # of sites w/at least 1 fire		3	1	0	91	113	60	97	134	26		
b. % of total sites w/fire	%	1	0	0	42	52	28	45	62	12		
c. # of sites w/at least 1 high-severity fire		3	1	0	90	107	21	32	59	5		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	0	99	95	35	33	44	19	99	33
8 - Lower Lookout - Blue River (75 ttl sites)												
a. # of sites w/at least 1 fire		1	1	0	40	55	27	17	58	10		
b. % of total sites w/fire	%	1	1	0	53	73	36	23	77	13		
c. # of sites w/at least 1 high-severity fire		1	1	0	39	44	9	3	26	2		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	0	98	80	33	18	45	20	95	29
ALL AREAS (874 ttl sites)												
a. # of sites w/at least 1 fire		18	31	16	247	547	239	327	402	109		
b. % of total sites w/fire	%	2	4	2	28	47	20	38	59	13		
c. # of sites w/at least 1 high-severity fire		18	31	16	235	384	64	172	236	24		
d. % of sites w/high-severity fire ("c" / "a")	%	100	100	100	97	92	35	51	45	20	98	38

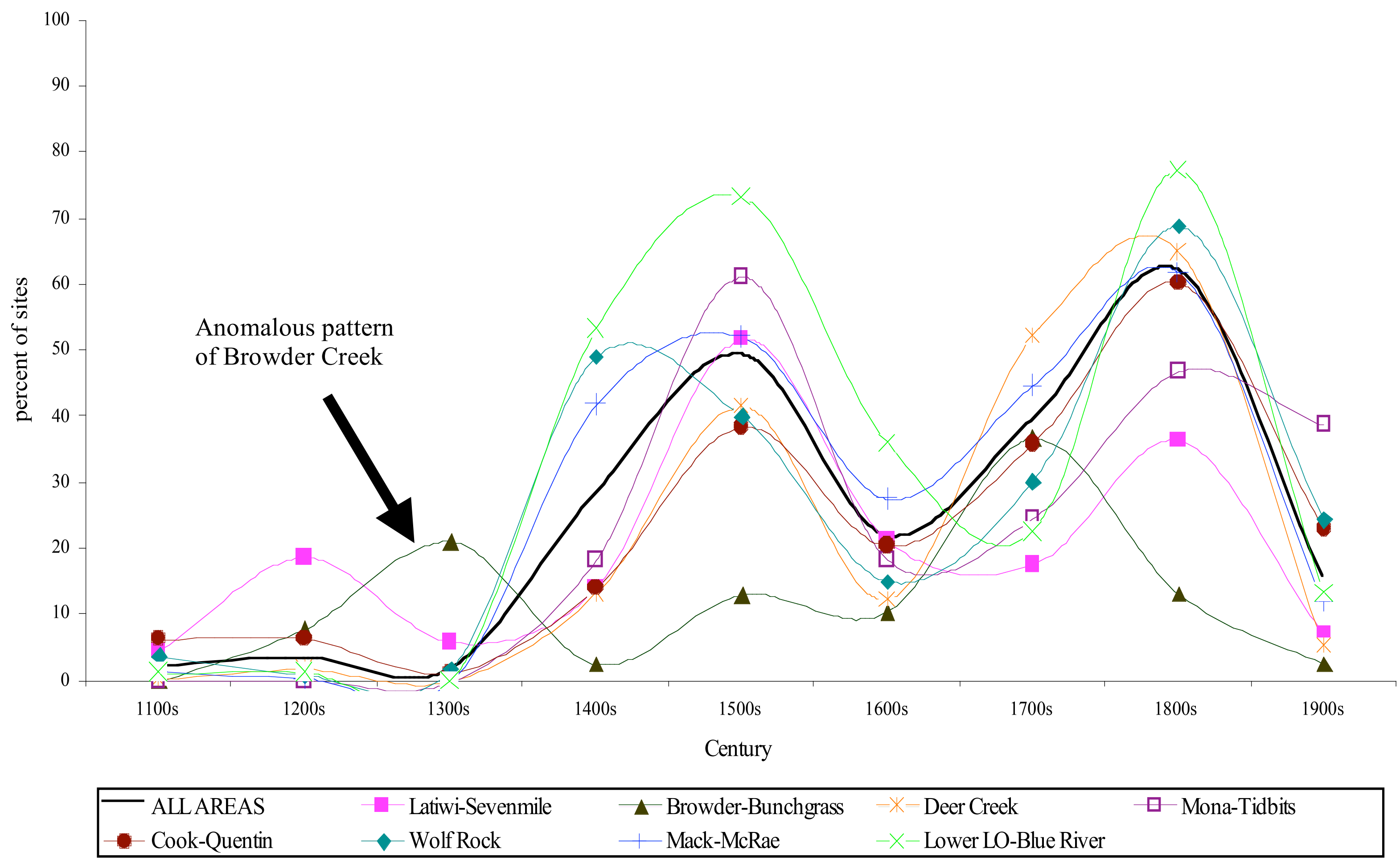

Figure 17: Proportion of sample sites with fire evidence at century-scale, by sub-area and for the whole study area.

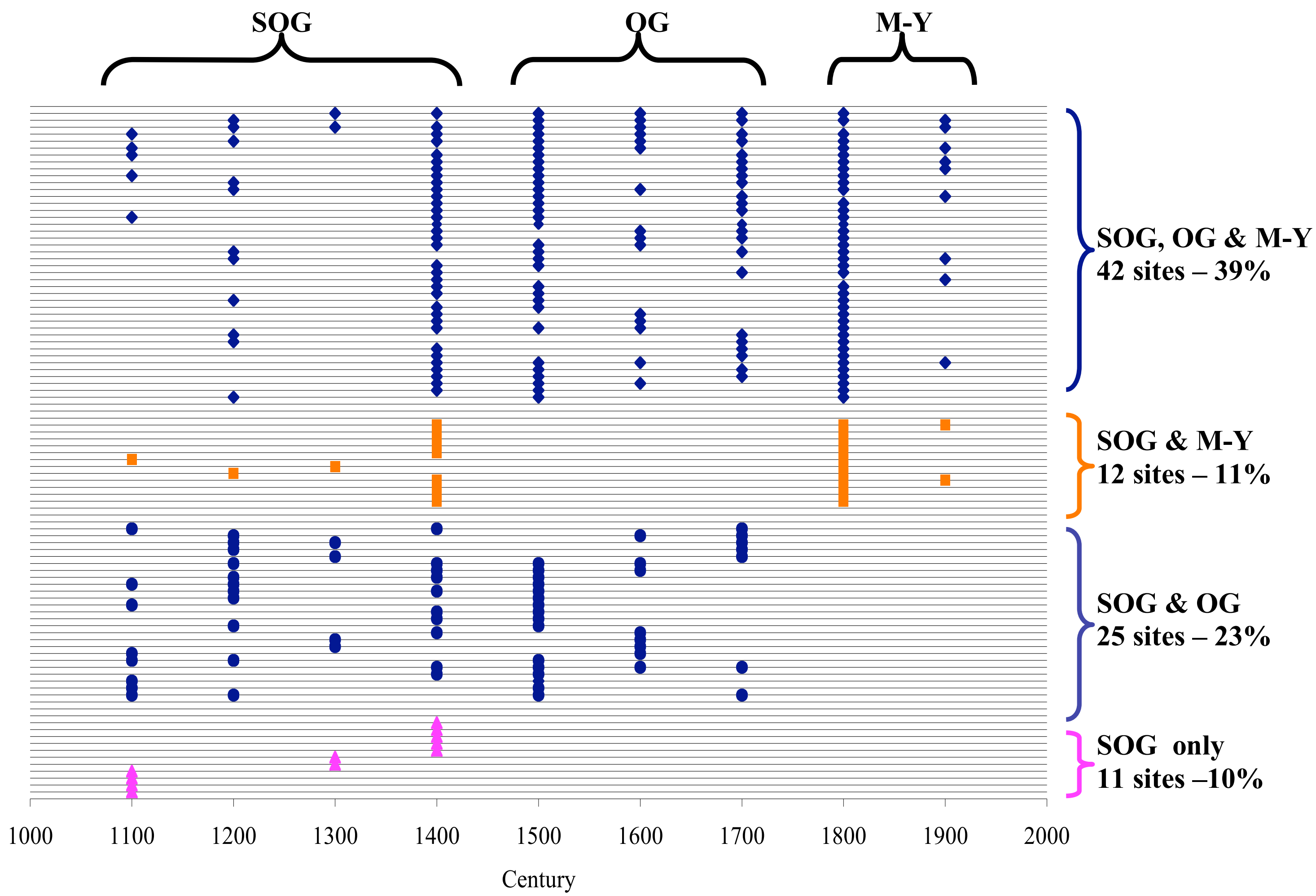

Figure 18: Age class distribution in SOG sites. Each horizontal line represents one SOG site. Each point represents the existence of tree(s) with origin dates in a given century. Sites with incomplete age class data (17 sites – 16% of SOG sites) were excluded from this analysis.

(10% of sites), SOG was the only age class recorded. Seventeen sites (16%) were excluded from this analysis because all age-classes were not recorded for these sites.

The age-class distribution of SOG sites was not related to aspect for sites with mixed age classes ($x^2 = 0.31$; $p > 0.25$), but it was related to researcher ($x^2 = 9.70$; $p = 0.03$). Although sample size was too small for statistical analysis, sites with SOG only occurred on NW and SE aspects more frequently, and on NE and SW aspects less frequently than expected (Figure 19). The number of age classes present also varied by researcher, however. All of the SOG sites sampled by Weisberg had all 3 age classes present. SOG sites sampled by Morrison and Swanson had fewer age classes present, and SOG sites sampled by Teensma had more age classes present than expected. (Figure 20).

The mean number of trees sampled was lowest for sites where only SOG occurred and highest for sites where SOG co-occurred with OG and M-Y (Table 9; Figure 21). These findings are based on only 50 of 107 SOG sites; the remaining SOG sites had insufficient tree-level and/or site-level data for this analysis.

There is suggestive, but inconclusive evidence that SOG was related to fire occurrence in two specific centuries. SOG was slightly more frequent than expected in sites that did not experience fire in the 1700s ($x^2 = 3.18$; $p = 0.08$) and in the 1800s ($x^2 = 2.85$; $p = 0.08$). SOG was independent of fire occurrence in the mid-1400s through the 1500s ($x^2 = .72$; $p > 0.25$) and in the 1600s ($x^2 = .44$; $p > 0.25$).

The fire history of SOG sites was spatially variable across the study area; this was most evident when comparing characteristics of the two sub-areas where the highest densities of SOG were found. While the Latiwi-Sevenmile sub-area and the

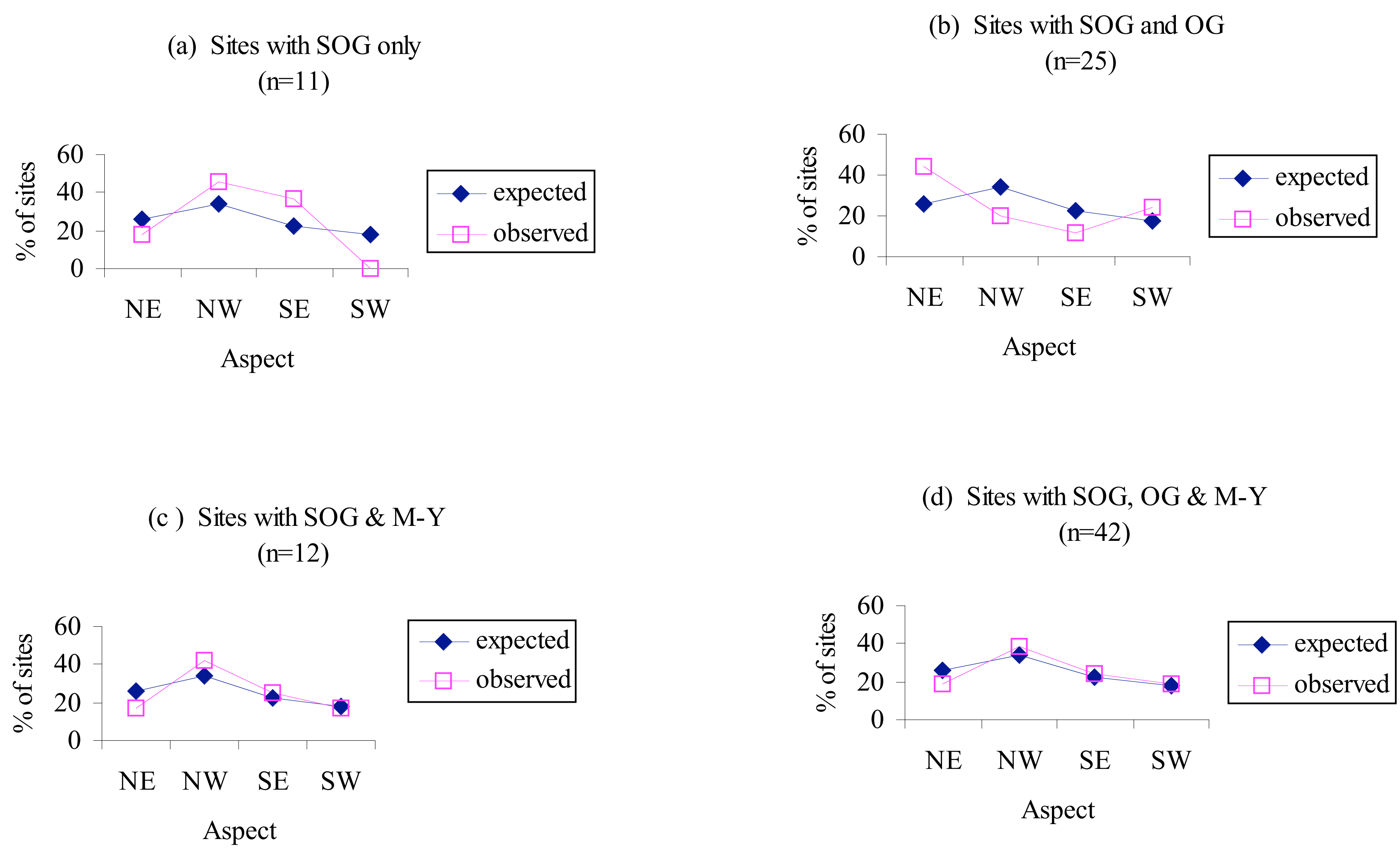

Figure 19: Proportion of all SOG sites (expected) compared to proportion of sites with (a) SOG only; (b) SOG and OG; (c) SOG & M-Y; and (d) SOG, OG and M-Y age classes (observed).

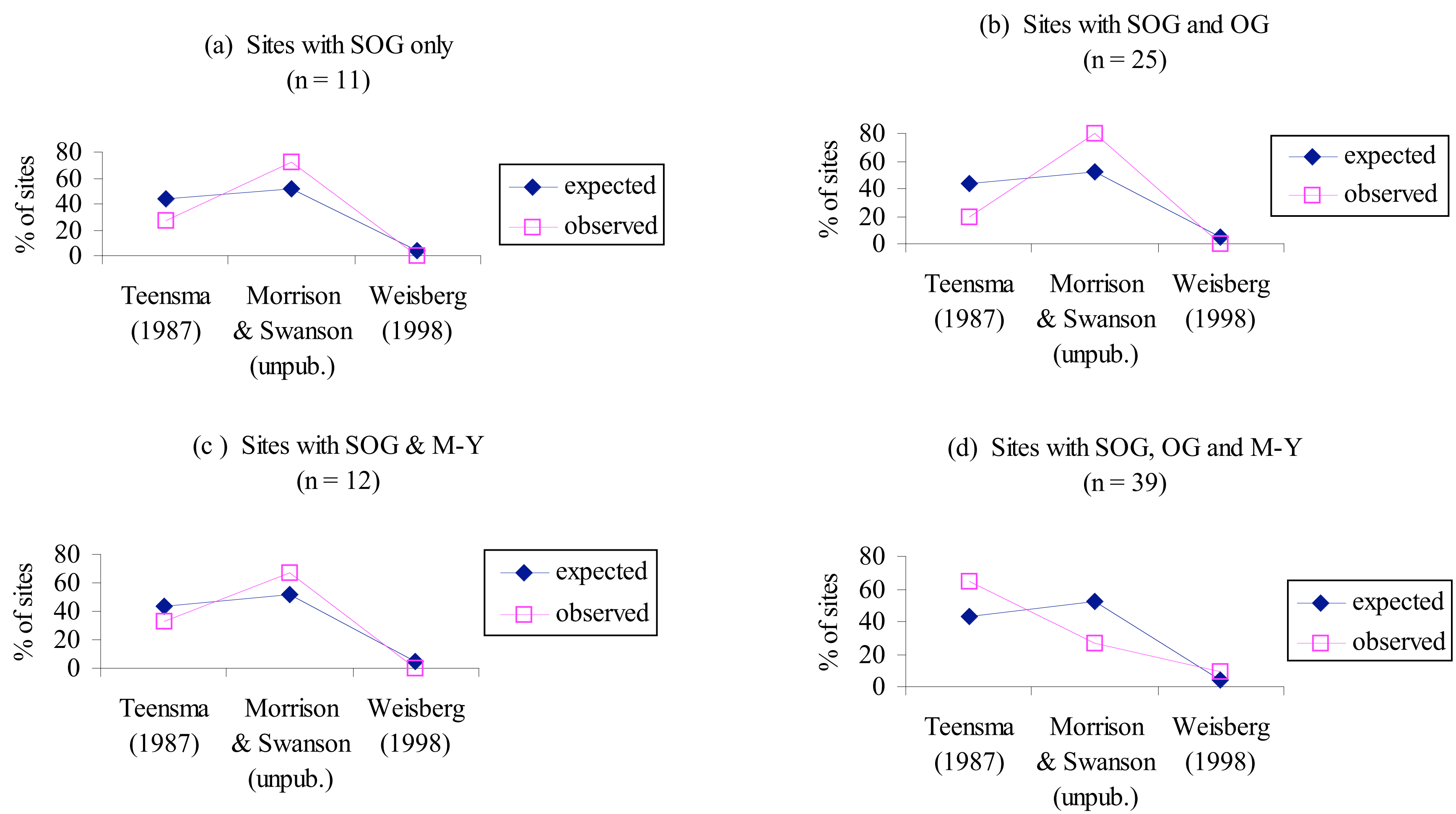

Figure 20: Proportion of all SOG sites (expected) vs. proportion of SOG sites recorded by each researcher (observed) with age-class compositions of (a) SOG only); (b) SOG & OG; (c) SOG & M-Y; and (d) SOG with OG & MY.

Table 9: Mean number of trees sampled for sites in each of four age-class distribution condition classes. Based on 51 of 107 SOG sites with sufficient data for this analysis.

Condition class	**Mean # of trees sampled**
1 - SOG only	1.5
2 - SOG & OG	3.4
3 - SOG & M-Y	4.8
4 - SOG, OG & M-Y	5.5

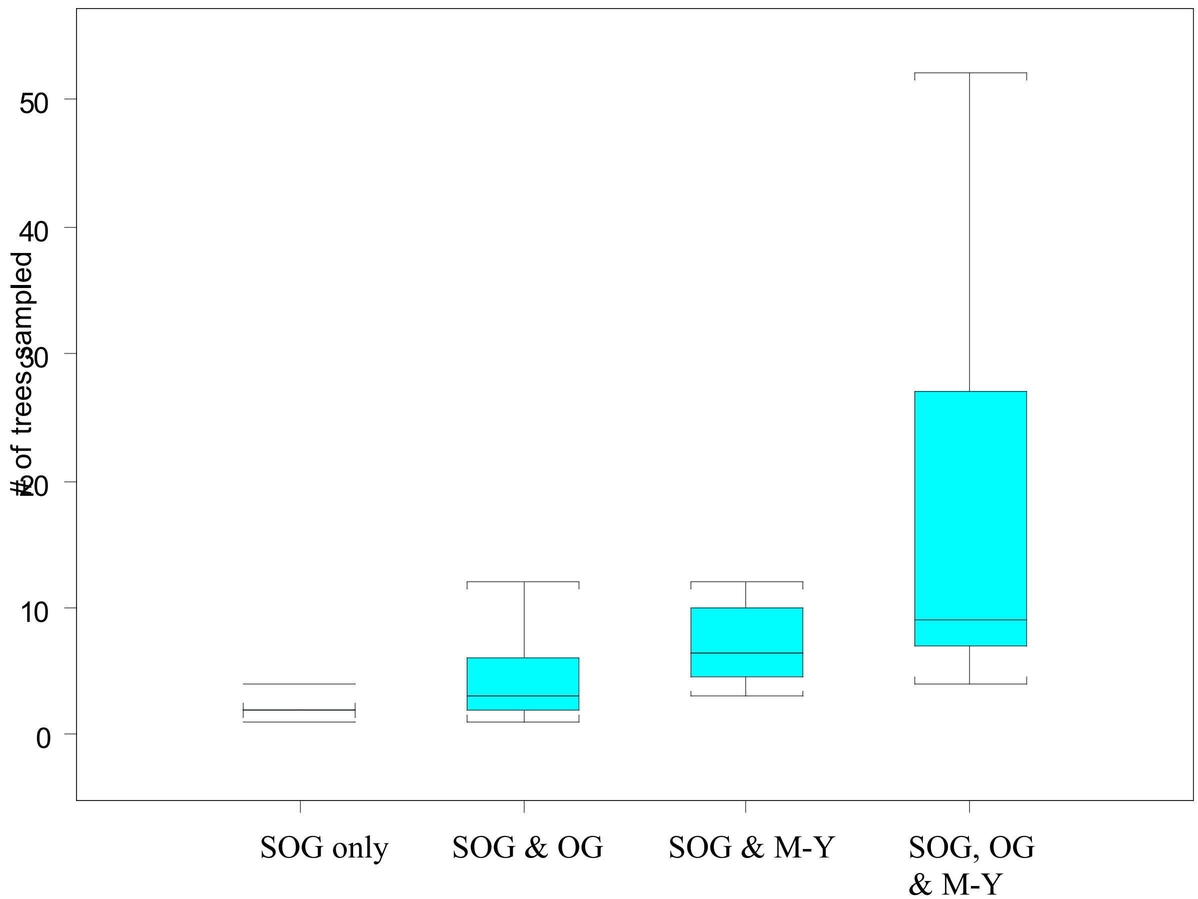

Figure 21: Box and whiskers plot showing the frequency, median and range of stumps (trees) sampled in 4 age class distribution condition classes.

Browder-Bunchgrass sub-area both had high proportions of SOG, evidence suggests notable differences in fire frequency, fire severity, and spatial patterns of SOG occurrence between the two sub-areas (Table 10). In the Latiwi-Sevenmile sub-area, areas burned in multiple centuries were super-imposed on one another, whereas patterns of areas burned over time in the Browder-Bunchgrass sub-area showed much less overlap. (Figure 22).

4.3 Factors affecting the discovery of SOG by fire history researchers

The discovery of SOG was dependent on researcher (x^2 = 8.5, p = 0.02). Weisberg (1998) found significantly fewer SOG sites than average for the three studies. On the other hand, Morrison and Swanson (unpublished) and Teensma (1987) both found slightly more SOG sites than average (Figure 23).

Researchers sampled significantly different proportions of clearcuts that had been harvested over the period 1950-1993 (x^2 = 368.66; p <0.0005). Morrison and Swanson (unpublished) and Teensma (1987) conducted most of their sampling in clearcuts harvested in the 1960s and 1970s, whereas Weisberg conducted most of his sampling in clearcuts harvested in the 1980s (Figure 24). Much of the difference among studies was due to differences in the timing of the sampling; field research was conducted by Morrison and Swanson (unpublished) in the 1970s, by Teensma (1987) in the 1980s and by Weisberg (1998) in the 1990s. Field sampling in each study was largely restricted to clearcuts that had been harvested 0-20 years prior to sampling because stumps were too decomposed to be legible for tree-ring counts in sites that had been harvested earlier.

Table 10: Comparison of fire history and forest structure characteristics of Latiwi-Sevenmile and Browder-Bunchgrass sub-areas.

	Latiwi-Sevenmile	Browder-Bunchgrass
Proportion of sites with SOG	29%	24%
Proportion of sites with fire in multiple centuries	74%	38%
Proportion of sites with fire in consecutive centuries	27%	11%
Fire severity	mostly mixed-severity	mostly high-severity
Configuration of SOG	Individual trees	Cohorts of multiple SOG trees found

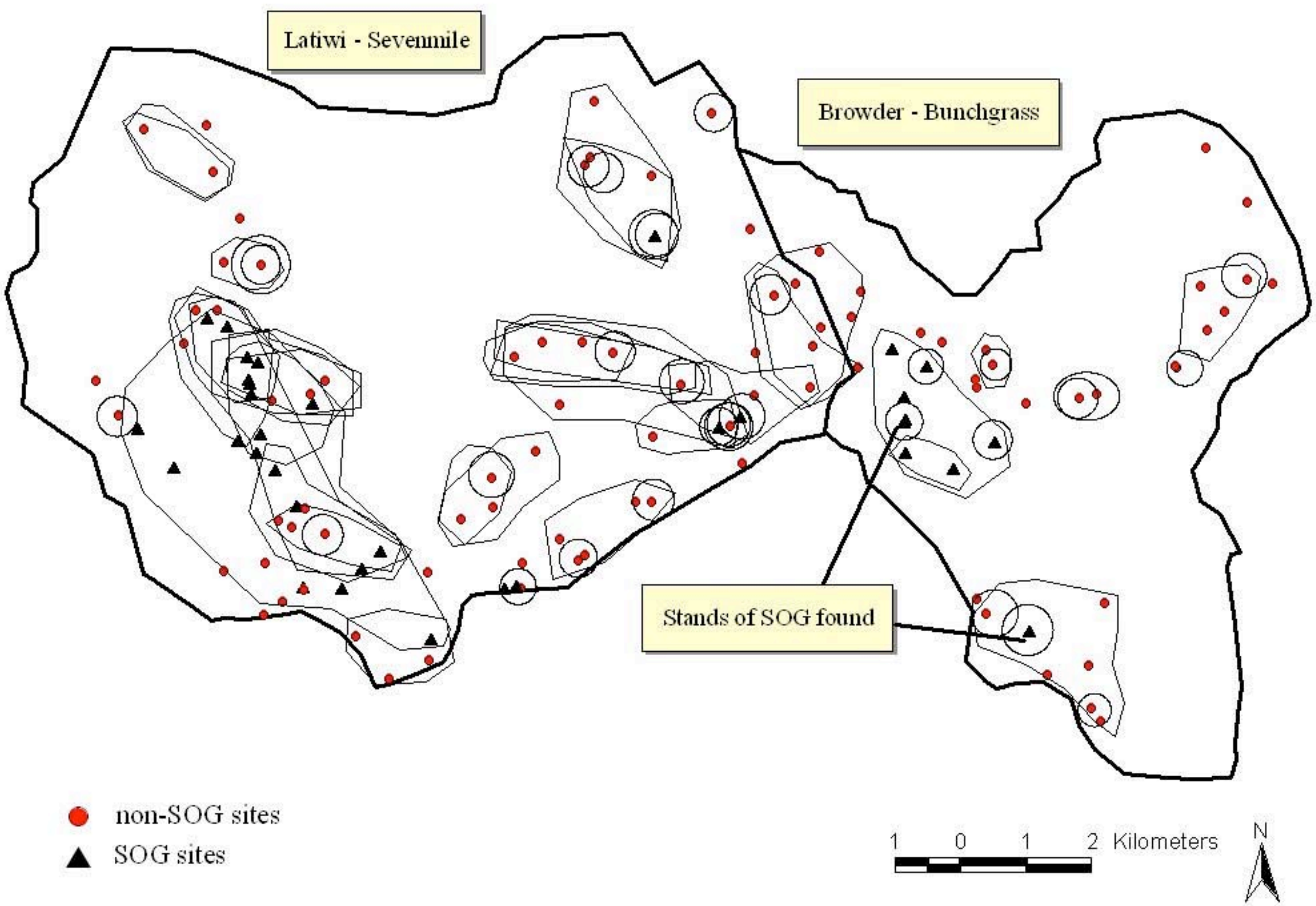

Figure 22: Spatial patterns of fire occurrence over 9 centuries in Latiwi-Sevenmile sub-area and Browder-Bunchgrass sub-area. Polygons represent groupings of sample sites where fire evidence was found in a single century.

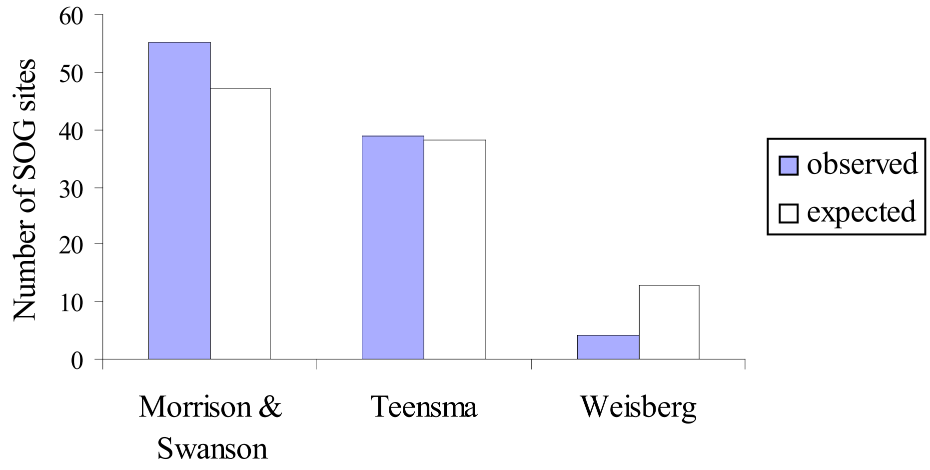

Figure 23: Number of SOG sites found by each researcher (observed) vs. expected if SOG discovery was independent of researcher.

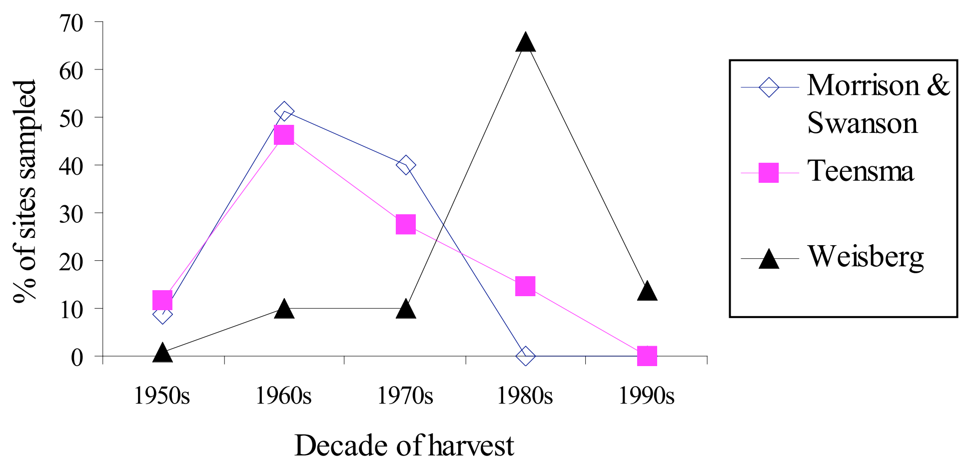

Figure 24: Proportion of total sites by harvest decade sampled by each researcher.

The sample sites selected by two researchers were not representative of the proportions of clearcuts by harvest date that were present in their study areas at the time of sampling. Morrison and Swanson (unpublished) sampled significantly more clearcuts harvested in the 1960s and significantly fewer clearcuts harvested in the early 1970s compared to the proportions of clearcuts in the landscape at the time (x^2 = 28.29, p <0.0005) (Figure 25a). Weisberg (1998) sampled significantly more clearcuts harvested in the 1980s, and correspondingly fewer clearcuts harvested in earlier decades, compared to the proportions of clearcuts in the landscape at the time of sampling (x^2 = 53.04, p < 0.0005) (Figure 25b). Sampling by Teensma (1987), however, was fairly representative of the proportion of clearcuts by harvest decade that were present on the landscape at the time of the study (x^2 = 4.43, p = 0.20) (Figure 25c).

Despite differences among researchers in sampling intensity by decade, the frequency of SOG was independent of the timing of harvest (x^2 = 1.53; p > 0.25). The proportion of SOG found in sites harvested in each decade (1950s through 1990s) was very close to the proportion expected. SOG was found slightly, but not significantly more frequently in sites that had been harvested in the 1960s, and less frequently in sites harvested in the 1980s (Figure 26).

There was no apparent relationship between the number of trees sampled at a site and the number of SOG trees found (Figure 27). Weisberg (1998) found the least SOG, but sampled 7.5 times more trees per site than Morrison and Swanson (unpublished) and 5 times more trees per site than Teensma (1987) (see Table 1, section 3.1). All but one of the 15 SOG trees that Weisberg found were identified at

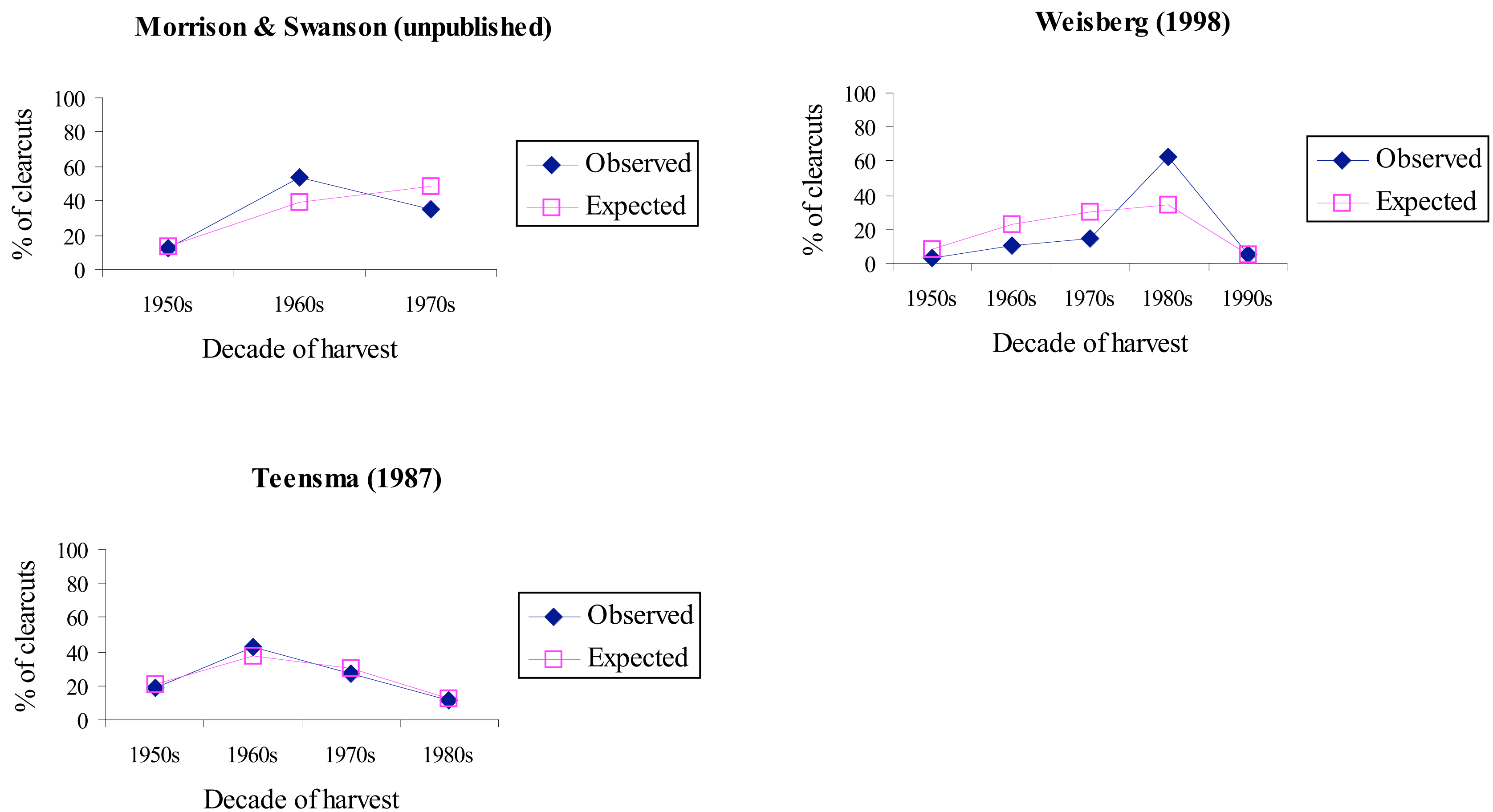

Figure 25: Proportion of clearcuts by harvest decade on the landscape at time of study (expected) and proportion of clearcuts by harvest decade sampled (observed) by (a) Morrison & Swanson (unpublished), (b) Weisberg (1998), and (c) Teensma (1987).

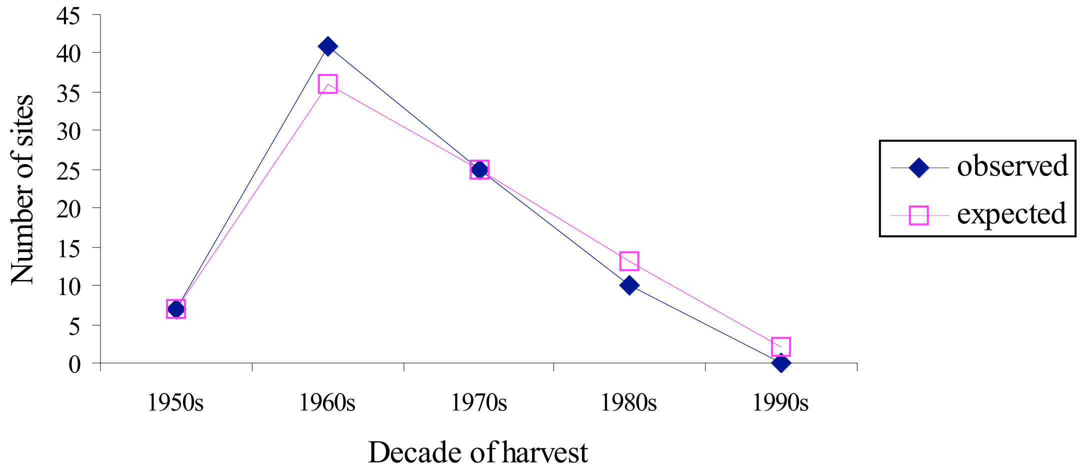

Figure 26: Number of SOG sites found by harvest decade in all fire history studies (observed), vs. expected if SOG was independent of harvest decade.

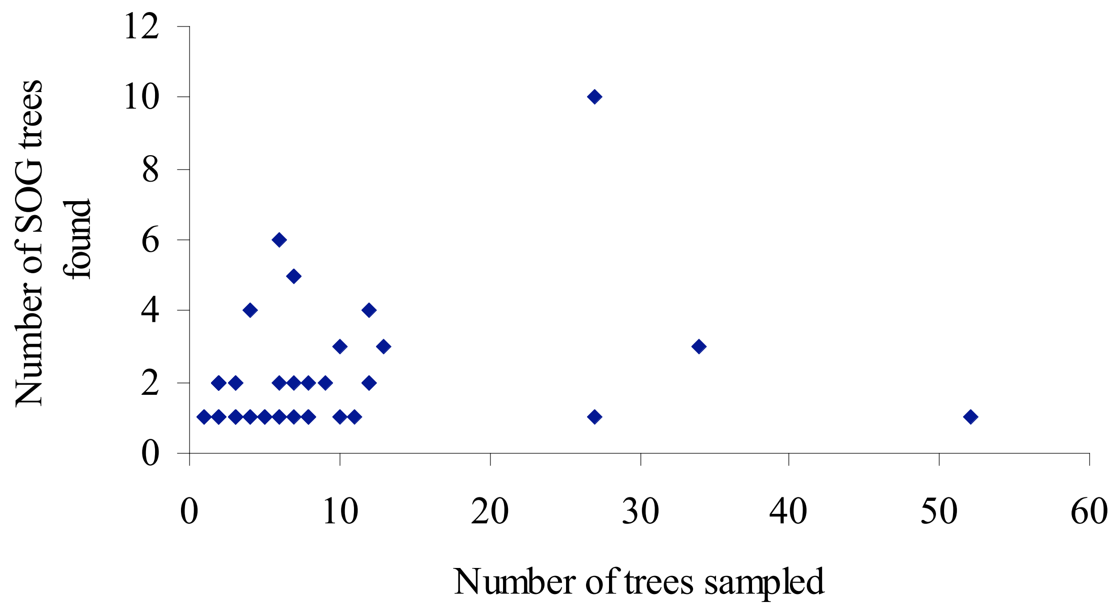

Figure 27: Scatter plot of number of SOG trees found vs. number of trees sampled. (Includes all of Weisberg samples sites and ~50% of Morrison & Swanson (unpub.) sample sites).

sites where search intensity (i.e. trees sampled per site) was at or below the mean search intensity for his study (Figure 28).

Overall, Weisberg (1998) found 1 SOG tree for every 300 trees sampled; Morrison and Swanson (unpublished) found at least 1 SOG tree for every 20 trees sampled (this is a low estimate, as Morrison and Swanson did not identify all individual SOG trees found). The number of SOG trees found by Teensma (1987) is unknown.

Figure 28: Diagram showing minimum and maximum number of trees sampled per site by Weisberg (1998), and sampling frequencies at which SOG trees were recorded. Each shaded rectangle represents one site; the size of the rectangle is relative to the number of SOG trees found. Overall, Weisberg (1998) found 1 SOG tree for every ~300 trees sampled.

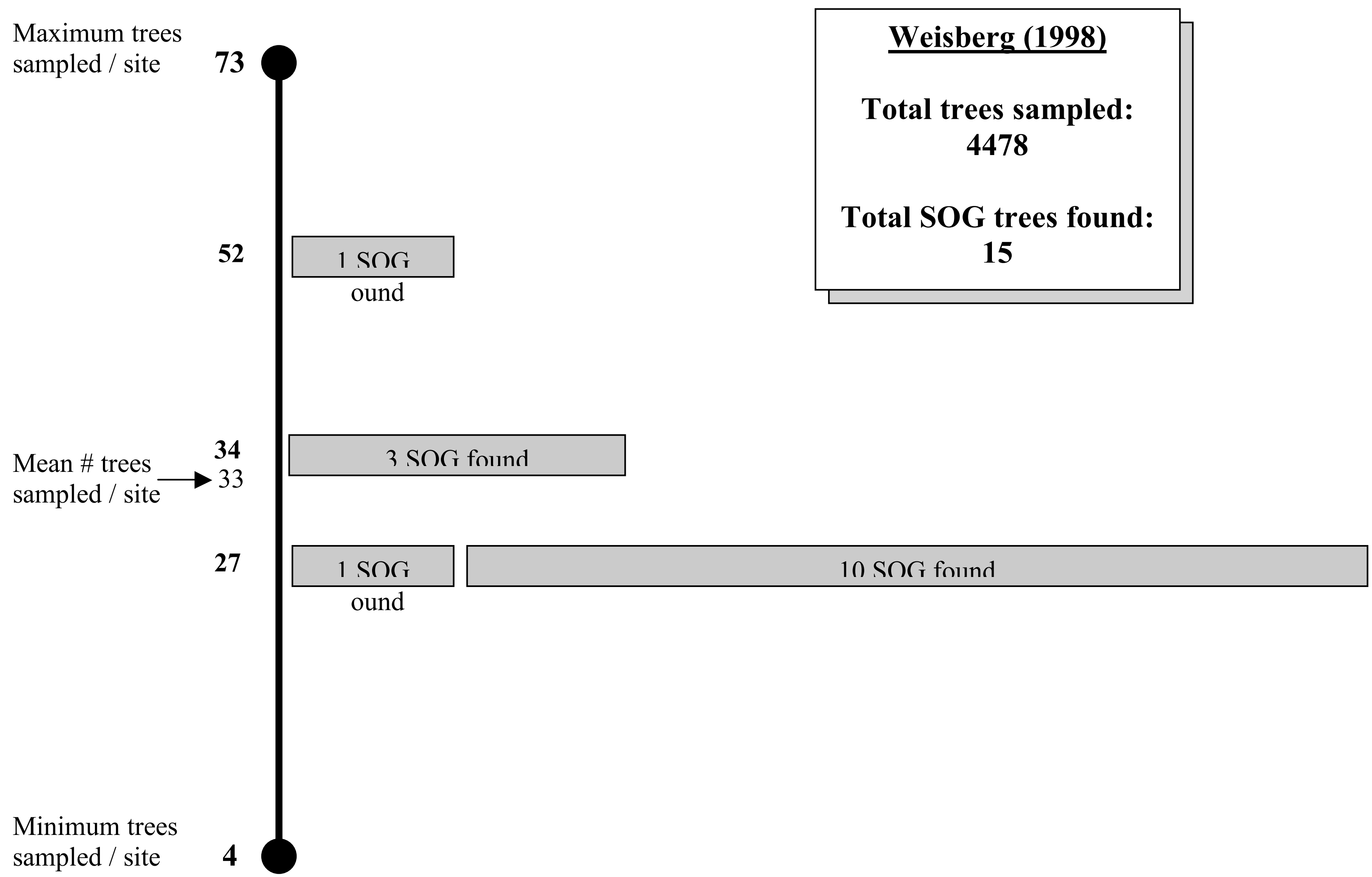
Maximum trees
sampled / site
73
52
1 SOG
ound
Mean # trees
sampled / site
34
33
3 SOG found
27
1 SOG
ound
10 SOG found
Minimum trees
sampled / site
4
Weisberg (1998)
Total trees sampled:
4478
Total SOG trees found:
15

Figure 28

5. <u>Discussion</u>

5.1 Novel aspects of this study

Past fire history studies provided valuable insight regarding the interaction of disturbance regimes with forest structure and function at the landscape scale in a broad region of the Pacific Northwest. Subsequent meta-analyses of these studies (Berkley 2000; Weisberg and Swanson 2003) elucidated the spatial and temporal variability of fire over time and identified regional temporal patterns of fire, possibly linked to patterns of climate change. In fire history studies, however, the attenuation of evidence over time increasingly limits the ability of researchers to make inferences about ancient forest history and fire regimes (Lertzman and Fall 1998; Whitlock *et. al.* in press), a phenomenon that affected all of these studies.

In order to strengthen inferences regarding forest and fire history based on the oldest, most attenuated part of the record, it was first necessary to extract new information from the limited data that existed. Therefore, this study was designed as a meta-analysis of a sub-set of 4 fire history studies, focused on the oldest surviving trees on the landscape (SOG). The distinction of SOG as a unique entity at multiple scales allowed us to link topography and fire history to the persistence of these ancient trees on the landscape over time. Results from this novel approach not only uncovered new information from existing data, but also suggested that more SOG could, perhaps, be found in the study landscape.

To facilitate this meta-analysis, a master database was assembled that includes new site-level data in addition to a synthesis of the original data from previous studies.

All new and pre-existing data were geographically referenced and organized to facilitate spatial analysis and display. This database is a valuable contribution to the existing body of forest history knowledge for this region that can be utilized in future forest history studies.

5.2 Limitations of this study

Five types of error contributed to uncertainty in this study: those associated with (1) spatial analysis; (2) tree and scar dating; (3) detection of fire episodes, (4) detection of SOG, and (5) the properties of fire episodes, especially fire severity. Because each researcher had unique objectives, sampling designs and methods, the source and magnitude of error were unique to each study as well.

Two factors contributed to uncertainty associated with spatial analysis: (a) errors in the location of sample sites, and (b) uncertainty about the size of sample sites. Possible sources of error in sample site locations include the manual placement of sample site locations on hand-drawn maps and errors introduced during the digitizing process. Spatial data from Weisberg (1998), obtained in digital format, were not subject to these types of errors. Overall, errors in the location of sample sites ranged from 0 to 186 meters (mean of 89 meters), based on a sample of 30 sites (see section 3.2.1).

The size of sample sites was unknown for all but the Weisberg (1998) data (see Table 1, section 3.1). Because it was not possible to quantify the degree of uncertainty in sample site size, it was difficult to determine the appropriate spatial resolution at which to perform spatial analyses. To compensate for spatial uncertainty, I used a coarse resolution for spatial analyses whenever possible. Landscape attributes, i.e. elevation, aspect and slope gradient, were generalized, ignoring fine-scale patterns such as microtopography. By summarizing the values of landscape attributes over fairly broad geographic areas, these measures likely compensated for much of the uncertainty associated with the location and size of sample sites.

Additional data from Morrion and Swanson (1990) were left out of this study; inclusion of these data may have contributed to the strength of our inferences from spatial analysis in certain parts of the study area. These data were from two 1940-ha areas that lie within the boundaries of the Morrison and Swanson unpublished reconnaissance study, and consisted of 58 additional sampling sites, 9 of which contained SOG. These sites were initially assumed to be duplicates of existing sites and were therefore not included in analyses. Inclusion of these additional sites would have increased the overall sampling density by 0.15%, and the proportion of SOG found by 0.3%. Detailed data on these sites are available (see Appendix A and B) and should be utilized in future SOG studies.

Three factors contributed to error in tree ages and scar dates: (a) the use of tree ring counts obtained in the field on minimally prepared surfaces, (b) the lack of matching lab ring counts, and (c) the lack of cross-dating of origin and scar dates. Weisberg and Swanson (2001) found that field counting generally underestimated ages of fire scar and tree origin dates, and that the magnitude of error from unchecked field counts ranged from -13 to +78 years, with 75% of counts within 10 years of their true value, and 87% of counts within 20 years of their true value.

Sources of error regarding the detection of fire episodes were (a) the uncertainty in scar and tree origin dates, (b) the lack of evidence for early fires, and (c) the range of regeneration dates that can occur following a major fire event (Hemstrom and Franklin 1982). In all three studies, researchers identified fire episodes by clusters of tree establishment and scar data within a particular time period, which may have indicated one or multiple fires.

The fire chronology data used in this study were aggregated to the century-scale (see section 3.1) to compensate for these temporal uncertainties. However, the aggregation removed the within-century variability that exists in the original data and increased the likelihood of incorrectly classifying fire episodes that occurred near the beginning or end of centuries.

The detection of SOG was inconsistent among researchers due to (a) different research objectives and (b) the use of different criteria to define fire episodes. Teensma (1987) required the existence of both fire scar and regeneration evidence to infer a fire episode for a particular time period. However, Teensma also stated the detection of the oldest tree on a site as one of his objectives. This suggests that he actively looked for SOG, even though he did not use the existence of SOG alone to infer fire activity in early centuries.

The criteria used by Morrison and Swanson (unpublished and 1990) to detect fire episodes did not require scar data for early fires. Regeneration alone was considered evidence for the oldest fires. These detection rules would be apt to include

SOG sites in an effort to identify early fires and to meet the objective of representing all age classes that existed on the landscape.

Weisberg (1998) considered regeneration of an early-seral species at a particular site as fire evidence only if fire scars that predated the regeneration were found within 3 km of the regeneration cohort. Therefore, Weisberg used SOG to date fires only if the SOG trees contained fire scars or existed as part of an apparent regeneration cohort. Since evidence suggests that both scenarios were rare in the study area, these detection rules would be more apt to exclude SOG.

Sources of uncertainty regarding the properties of fire include (a) the uncertainty of fire dates (affecting inferences about the extent and frequency of fire) and (b) erasure of the record over time (affecting inferences about the extent, frequency and severity of fire). Inferences regarding the severity of historical fires in particular contributed to uncertainty in this study. The existence of fire scars on surviving trees is evidence of low- to moderate-intensity fire at the local scale. Due to erasure of the record by subsequent fires and land use over time, little fire scar evidence existed from the period prior to 1475 A.D. The majority of fires were classified as high-severity in the early centuries in this study because of this erasure factor (see Table 8, section 4.2.1). To effectively control for this phenomenon, comparisons were made across sites for a given century or group of centuries, but comparisons were not made across centuries for single sites or groups of sites.

Finally, our study faced the same challenges as any other study that deals with patterns that occur over extensive time scales. It is an inherently challenging task to elucidate patterns that occur at temporal scales spanning multiple centuries, perhaps even millennia, while working with data that may or may not capture these long-term patterns.

5.3 Interpretation of findings

No clear distinction has previously been made in the literature between the 400-500 year-old age class that is still fairly widespread in the central western Cascades, and the 500-1000 year old, senescent, “super-old” growth trees. Such a distinction may be warranted and desirable. SOG trees are remnants of the oldest surviving age classes on the landscape. Even-aged stands of SOG trees, which appear to be even more rare than individual SOG trees, represent pockets of ecosystems that have not experienced high-severity disturbance for many centuries. These biological legacies embody significant information about forest and climate history extending nearly a millennium into the past.

The sampling methods of Morrison and Swanson (unpublished and 1990) and Teensma (1987) may have overestimated the proportion of the landscape that would be likely to have SOG, while the sampling methods of Weisberg (1998) may have underestimated the true proportion of SOG. Weisberg sampled a more representative portion of the landscape that fit the criteria of our predictive model than other researchers (see Figure 16, section 4.1). This would suggest that the lower frequency of SOG he recorded may be closer to what actually existed on the landscape than indicated by the studies of Teensma (1987) and Morrison and Swanson (unpublished and 1990). On the other hand, his sampling methods may have been more likely to exclude SOG than the other studies, which both may have been more likely to include SOG (see section 5.2). The true proportion of sites where SOG may exist in a randomly sampled central western Cascades landscape likely lies somewhere between 3% (as indicated by the Weisberg study) and 12% (as indicated by the Teensma and Morrison and Swanson studies).

The primary conclusion drawn from this study is that SOG is not a random phenomenon in the central western Cascades. It occurs in certain landscape positions and may be associated with particular fire disturbance histories.

The locations where SOG was found have attributes that are consistent with the preservation of old trees. In this study, SOG was more likely to occur on northern aspects, at mid- to lower-slope positions, and on gentle terrain. Northern aspects are generally more mesic than southern aspects, and less susceptible to solar desiccation that can result in fast-spreading, high-intensity fire (Swanson 1981; Agee 1993). Northern aspects are also mostly protected from southwest winds, which are the dominant cause of windthrow in Pacific Northwest forests (Powers *et al*., 1999). Fires do not generally burn as intensely on gentle slopes, allowing thick-barked Douglas-fir trees to survive on gentle compared to steep slopes, where stand-replacing crown fires are more likely (Swanson 1981; Agee 1993). The results of this study suggest that these local effects of topography on disturbance consequently impact the longevity of trees and stands on the landscape.

I was not able to identify a significant relationship between SOG and specific characteristics of fire history due to dating uncertainties and small sample size; however, findings from this study provide some information relevant to the interpretation of fire history. Evidence suggests that the configuration of SOG (remnant trees as opposed to intact cohorts of SOG) may have been related to fire history. Although missing tree-level data and differences in search intensity among researchers limited our ability to distinguish remnant trees from cohorts of SOG over much of the study area, some unambiguous patterns emerged. Fire history was spatially and temporally variable across the study area, with anomalous patterns in the Browder Creek-Bunchgrass sub-area of higher-severity, lower-frequency fire and peaks of fire occurrence in different centuries than other sub-areas (see Table 8 and Figure 17, section 4.2.1). This sub-area had the second highest proportion of SOG sites, and it is the only sub-area where I observed cohorts of SOG trees in the field. A comparison of Browder-Bunchgrass with the Latiwi-Sevenmile sub-area, where the highest proportions of SOG sites were found, suggested that SOG can survive in different fire history contexts: (1) in areas subject to relatively frequent, mixed-severity fires as remnant trees that survived multiple low- to moderate-severity fires and (2) in areas subject to infrequent, high severity fire on sites as cohorts of trees on sites that have not burned since their establishment.

Tree-level data from researchers as well as field observation support the inferred relationship between SOG configuration and fire history. While the Browder-Bunchgrass sub-area was sampled only by Morrison and Swanson, the Latiwi-Sevenmile sub-area was sampled by Morrison and Swanson and also sampled intensively by Weisberg. Fifty percent of the SOG sites, and 73% of the SOG trees found by Weisberg were located in the Latiwi-Sevenmile area, including 10 SOG trees at one sample site with origin dates spanning two centuries (i.e., not representative of a single regeneration cohort). Additionally, field investigation of both sub-areas confirmed the existence of intact cohorts of SOG in the Browder-Bunchgrass sub-area and identified only individual, remnant SOG trees in the Latiwi-Sevenmile sub-area.

The findings of this study regarding the location, configuration and fire history context in which SOG occurs are consistent with information derived from fire history studies conducted in the western Cascades both north and south of the area examined in this study (Hemstrom and Franklin 1982; Agee and Krusemark 2001; VanNorman 1998). However, SOG was not found in a fire history study conducted in the Coast Range of Oregon (Impara 1997).

In Mount Rainier National Park, located in the western Cascades of Washington, SOG, defined as the oldest surviving age classes found on the landscape, was found as stands that had never experienced fire (Hemstrom and Franklin 1982). The fire regime in this area is characterized by very infrequent, large, high-severity fires. The majority of forests are around 350 years old, regenerated following a large fire ca. 1628. Two distinct age classes of SOG were noted: (1) sites with trees exceeding 1000 years in age that showed no evidence of past fire and (2) sites with trees around 750 years of age that regenerated following a large fire ca. 1230, but did not burn in the 1628 fire. Locations where SOG was found were described as "well-protected," mostly in valley bottoms throughout the park.

SOG trees found in northwestern Oregon were also noted as stands that had not previously burned (Agee and Krusemark 2001). This area is also characterized by large, infrequent, stand-replacing fires. The dominant age class of Douglas-fir, as in the central western Cascades, was 450-500 years old, regenerated from the widespread fires of the late 15th and 16th centuries. Remnant 750-year old stands (covering ~130 of 26,000 ha in the study area) were identified as the only areas that did not burn during that time. Low and moderate-severity fire was noted in areas defined as the edges of high-severity fires or in drainages and rocky areas. "Occasional residuals" were noted in these locations and in other "protected microsites."

In fire studies conducted in the the central western Cascades (Morrison and Swanson unpub. and 1990; Teensma 1987; Weisberg 1998), and in the southern western Cascades (VanNorman 1998), SOG was found mostly as individual, remnant trees on sites that had experienced mixed-severity fire. In areas with this type of fire regime, SOG can be found, not because it exists in stands that have never burned, but because fires did not completely erase the record.

In this study, I found that the existence of SOG was independent of the occurrence of fire during the period of widespread fire in the early 15th and 16th centuries (see section 4.2.2). In other words, SOG was found proportionately both in sites that did and did not burn during that time. Most of the SOG trees were also found in sites with multiple age classes (see section 4.2.2). In the western Cascades of southern Oregon, where a complex, mixed-severity fire regime is present, SOG was rare, and noted only as individual, remnant trees (VanNorman 1998).

In the Oregon Coast Range, only 8% of sampled trees or stumps exceeded 400 years of age; the oldest tree found was 516 years old (Impara 1997). The 450-500 year age class, though distinguishable, was not nearly as widespread as in the western Cascades. Most Coast Range stands originated from a large, high-severity fire in 1852. The high-severity fire regime and high fuel loads (due to rapid plant growth and long fire intervals) of the Coast Range tend to result in catastrophic fires that effectively erase evidence of previous fires, and leave few remnant survivors. This scenario is more similar to the fire regimes of the northern western Cascades than to the adjacent central western Cascades. The Coast Range, however, has experienced widespread, high-severity fire more recently than the forests to the north. Remnant trees that survived the 1852 fire are 300 to 400 years old. The previous generation (SOG) has been completely destroyed. Although the author noted that the oldest trees were found on lower hillslopes, he found no significant relationship between spatial factors such as aspect or hillslope position and fire patterns. It seems likely that the lower relief of the Coast Range relative to the western Cascades provided fewer refuges for trees to survive.

Land use history, not addressed in this study, might also explain patterns of SOG. Historical land uses in this study area include Native American burning, mining, sheep grazing, and transportation corridors, any of which may have resulted in erasure of the early fire record. We know that areas that were highly utilized by humans and areas adjacent to high human activity were more likely to experience fire due to increased ignition source (Burke 1979). Whitlock and Knox (2002) argued that the alterations caused by the activities of prehistoric peoples, including burning, occurred only at local scales. Others (Pyne 1982; Denevan 1992) have argued that the effects of Native American activities were more widespread. Because the longevity of trees is related to the interaction of pattern and process (topography and fire) at local scales, even the conservative estimate of impact proposed by Whitlock and Knox

(2002) suggests that it is likely that Native American activities had some affect on patterns of SOG.

5.4 Future research – management and policy implications

Interest in the oldest trees in the forest is not unique to the Pacific Northwest. Recent research on forests of the eastern United States has focused on the discovery of "ancient forests" that are both older and more abundant than previously documented (Stahle and Chaney 1994; Orwig *et. al.* 2001; Horton 2003). As recently as 10 years ago, ancient forests in the east were believed to be extremely rare, existing as conifers in a few protected areas such as the Great Smoky Mountains National Park and the Adirondacks of New York, where ancient trees are survivors of natural disturbances such as windthrow and hurricanes. Researchers have discovered, however, that ancient forests are much more widespread, in areas that were unsuitable for timber harvest or conversion to agricultural lands because of poor soils and/or rugged, inaccessible terrain. Most were not previously recognized because the site characteristics and small stature of the trees did not fit the "established old-growth stereotype" (Orwig *et. al.* 2001). Many of these forests are composed of northern hardwood species that are at or near the maximum longevity known for their species. Due to the discovery of these ancient forests, estimates of ancient eastern forests are four times higher than the acreage previously estimated (Orwig *et.al.* 2001; Horton 2003).

The information that can be derived from SOG, wherever it is found, is relevant to forest management, climate change research, and efforts to maintain biodiversity in forested ecosystems. A search for additional SOG in the central western Cascades could be useful for the purpose of archiving wood samples from SOG trees. These samples could then be cross-dated in the laboratory to establish a temporally extensive master chronology[1] for the area to facilitate climate reconstructions, further fire history work, and other tree-ring based studies.

Over 350 hectares were identified within the study area as previously unsampled clearcuts where SOG might be found. Using GIS, I intersected polygons representing areas that fit the predictive model (see section 4.1) with polygons representing unsampled clearcuts that have been harvested in the past 27 years (since the time of the Morrison and Swanson unpublished study). The mapped results show patches with a total area of 383 hectares within the study area where it is likely that additional SOG stumps could be found (Figure 29). The window of opportunity for collecting such samples is rapidly closing, due to the drastic reduction in timber harvesting in the past 15 years. Accessible areas with SOG stumps that are still legible are rare and becoming more so with each passing season. In fact, it is likely that some of these areas were not sampled due to the unfavorable condition of the stumps. It is possible that some stumps in older clearcuts could be utilized for wood samples, however, if several inches of the decomposed stump surface were removed to reveal a fresh, legible surface (J. Mayo, US Forest Service, personal communication).

A recognition of SOG as a unique entity could be beneficial in land use planning and management. SOG provides a special learning opportunity to examine

[1] A master chronology is a dated composite chronology, created by computing yearly averages of mathematical indices derived from tree-ring width measurements. It is then used as a reference for cross-dating new wood specimens from the same geographic area.

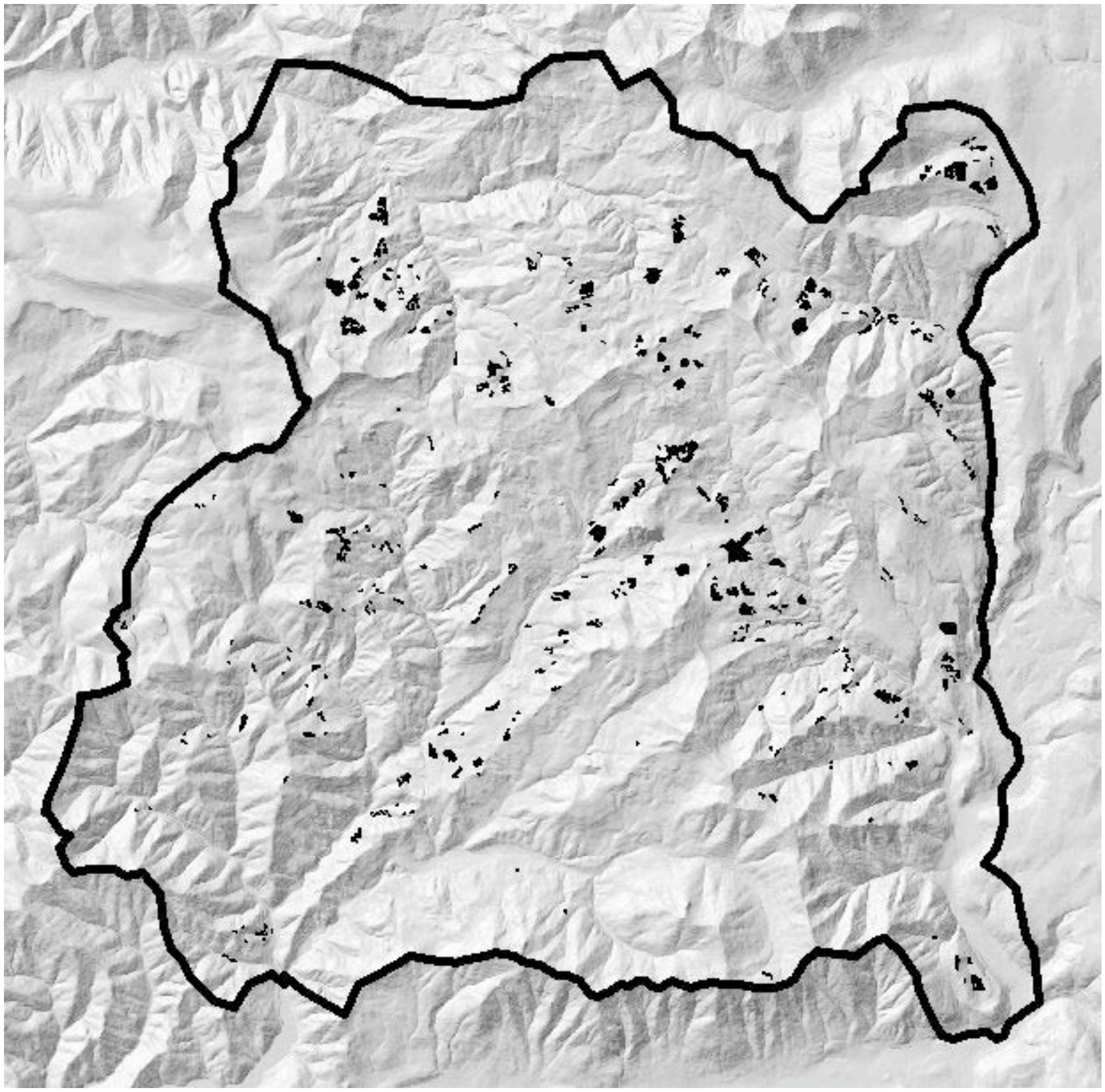

Figure 29: Study area showing patches that: (1) fit the predictive model criteria (i.e. north-facing aspect, slope gradient 0-15 degrees), (2) have been harvested in the past 27 years, and (3) have not been previously sampled.

the composition and perhaps the ecological function of stands where it is found. The distinction of SOG from “garden variety” old-growth could also be beneficial to old-growth conservation efforts. If we know where trees are likely to attain maximum longevity (and become SOG) under natural conditions, it seems logical to utilize this information when developing old-growth conservation strategies.

6. Conclusions

The oldest Douglas-fir trees on the landscape in the central western Cascades of Oregon persist in locations and in configurations that appear to be related to topography and fire history. In particular, protected areas on north-facing aspects and on gentle slope gradients provide a refuge where Douglas-fir trees can live up to 800 years or longer. Cohorts of SOG may be more likely to exist in areas on the landscape that are prone to long fire intervals and high-severity, stand-replacing fires, whereas singular or dispersed SOG trees may be more likely to exist in areas that are prone to lower-severity fires and shorter fire frequency intervals. These findings are consistent with what is known about the occurrence of the oldest trees on the landscape from fire history studies conducted in the western Cascades both north and south of the area examined in this study.

An unbiased, randomly sampled field investigation in the central western Cascades of Oregon would probably identify SOG in 4% to 11% of sites sampled. Super-old growth trees were found in approximately 12% of sites sampled overall by three previous fire history researchers, but this proportion is likely higher than what a random study would reveal, due to different objectives in sampling design and methods.

Future efforts to locate more SOG in this landscape would be prudent for the purposes of climate reconstruction and other tree-ring based studies. Through spatial analysis, patches in our study area were identified representing a total of 383 hectares that (1) fit the criteria of a predictive model for the existence of SOG (i.e. north-facing aspects and slope gradient of 0-15^{o}), (2) have been harvested in the past 27 years, and

(3) have not been previously sampled. These patches represent locations where more SOG would be most likely to be found.

Rare super-old growth trees and stands provide a window into the distant past, a valuable historical record of forest ecosystem processes and variability in climate and fire regimes. An enhanced understanding of forest history may contribute to our understanding of and preparation for future challenges we face as a result of widespread climatic and environmental changes, both natural and human-induced, which are currently taking place.

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APPENDICES

Appendix A

GIS Data

The following spatial data are archived in the Forest Science Data Bank (FSDB) at the USDA Forest Service Forestry Sciences Laboratory in Corvallis, Oregon. Unless otherwise noted, shapefiles created by the author contain metadata in accordance with federal digital geospatial metadata standards. These data are also available online through the HJ Andrews Experimental Forest website: www.fsl.orst.edu/lter

Name	Description
sogstudy_allsites	Master shapefile derived by merging and editing four researcher shapefiles. Includes points representing sample sites coded by researcher, attribute data for sample sites, and fire chronology data by century and by sample site.
sogstudy_sogsites	Sub-set of master shapefile (“sogstudy_allsites”) with locations only of sites where SOG was found. All attribute data from master shapefile was carried forward, and additional data added, including available age-class data and tree-level data.
sog_studyarea	SOG study area boundary.
weisberg_sites	Original GIS shapefile obtained from Peter Weisberg, edited to include a “site ID” field that matched site identification codes used in “Weisberg_treedata” Excel file (see Appendix B). Contains all sample site locations and attribute data used in PhD dissertation.
weisberg_firechron	GIS shapefile obtained from Peter Weisberg, containing all sample site locations and original, annual-scale fire chronology data for each sample site. This shapefile was also edited to include a “site ID” field as indicated for “weisberg_sites” (above). Note: Fire chronology data also available in “brmfc” (See Appendix B).
weisberg_studyarea	Study area boundary for Weisberg (1998).

Name	Description
teensma_allsites	Researcher shapefile created by digitizing sample site locations from published paper map (Teensma 1987). Includes annual-scale fire chronology data for each site. Fire chronology data was extracted from "BRCHRONO" (see Appendix B).
teensma_studyarea	Study area boundary for Teensma (1987).
m&s_unpub_allsites	Researcher shapefile created by digitizing sample site locations from hand-drawn mylar maps (Morrion & Swanson unpublished). Includes annual-scale fire chronology data for each site. Fire chronology data was extracted from "BRCHRONO" (see Appendix B).
morrison_studyarea	Study area boundary for Morrison & Swanson (unpublished).
mands1990	Study area boundary for Morrison & Swanson (1990).
giglia_allsites	Researcher shapefile created by downloading GPS locations of sample sites examined during fieldwork in September 2002, with site attributes manually appended.
el_class	Shapefile created from reclassified grid with four elevation classes used in SOG study.
gen_aspect	Shapefile created from reclassified grid with four quadrant aspect classes, and three slope position classes used in SOG study.
slope_class	Shapefile created from reclassified grid with three slope gradient classes used in SOG study.
dem10m	Grid file composed of 9 merged 10m digital elevation models (DEMs) covering the rectangular extent of the SOG study area.
clip_wnfveg6	Shapefile converted from ArcInfo coverage "wnfveg6" (available from www.reo.gov/gis/gisdata.htm) and clipped to fit rectangular extent of study area. Contains timber harvest and forest data for Willamette National Forest. Note – updated version of this coverage is in progress.

naspect_slope1	Shapefile derived from intersection of NW and NE aspects from gen_aspect shapefile, and slope class "1" from slope_class shapefile. Predictive model for SOG study.
model_cc_not_samp	Shapefile derived from intersection of naspect_slope1 shapefile with clip_wnfveg6 shapefile. Contains locations of patches of terrain that fit the predictive model (naspect_slope1), have been harvested since 1977, and have not been previously sampled.

* These files have only limited metadata available. Contact Peter Weisberg at pweisberg@cabnr.unr.edu for more information.

Appendix B

Data files

The following data are archived in the Forest Science Data Bank (FSDB) at the USDA Forest Service Forestry Sciences Laboratory in Corvallis, Oregon. These data are also available online through the HJ Andrews Experimental Forest website: www.fsl.orst.edu/lter

Name	Description
BLUEFIRE	Excel file created by Peter Weisberg, containing tree-level data for Morrison & Swanson (unpublished) and Morrison & Swanson (1990) sample sites.
Weisberg_treedata	Excel file created by Peter Weisberg, containing tree-level data for Weisberg (1998) sample sites.
BRCHRONO	Excel file created by Peter Weisberg, containing edited fire chronology for Morrison & Swanson (unpublished), Morrison & Swanson (1990) and Teensma (1987). This data is also spatially referenced in "m&s_unpubsites" and "teensma_sites2". (see Appendix A).
brmfc	Excel file created by Peter Weisberg, containing fire chronology from Weisberg (1998). This data is also spatially referenced in "weisberg_firechron" (see Appendix A).
brmfc_scarRegenSev	Excel file created by Peter Weisberg, containing fire chronology data from "brmfc," reclassified with fire severity criteria used for "BRCHRONO". These data not used in SOG study.