Fire and Climatic Variability in the Inland Pacific Northwest: Integrating Science and Management

Final report to the Joint Fire Science Program on Project #01-1-6-01

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Key Science Findings

- A broad-scale quantitative relationship exists between fire extent and drought in eastern Washington.
- A quasi-periodic relationship exists between fire occurrence and the El Niño Southern Oscillation (ENSO, 3-7 year periodicity) and Pacific Decadal Oscillation (PDO, 20-30 year periodicity).
- Fire frequency and temporal patterns of fire hazard vary considerably as a function of spatial scale.
- Topography exerts stronger controls on fire regimes than biophysical or environmental variation at medium to small spatial scales.
- The spatial and temporal complexity of fire occurrence across a broad region can be communicated effectively through a new Web-based method of GIS-based data delivery and visualization.
- The quantitative influence of (top-down) climatic controls, (bottom-up) topographic controls, and spatial scale dependencies of fire regimes are less evident in the 20th century.

Key Applications in Management and Science Delivery

- Understanding and quantifying the spatial variability of fire regimes within vegetation or ecosystem types is a key to appropriate management and restoration approaches.
- The effect of topographic constraints on fire regimes and fuels is a strong consideration in fuels management and fuel treatments within forest districts, watersheds, or other local management units.
- Data on historical fuel dynamics are needed to address historical range of variation and fuel-based restoration targets.
- Appropriate restoration practices need to be as site-specific as possible, because historical "reference conditions" vary so much spatially and temporally.
- Forecasting the responses of forest ecosystems to climatic variability will be confounded by the history of fire exclusion for many decades to come.
- The fire history record for eastern Washington provides no analogues to expected greenhouse warming, so we can expect surprises in the future.
- User friendly Web-based GIS tools provide the level of detail needed to represent and visualize historical conditions and potential management alternatives.

Summary

We proposed and developed a multi-scale analysis of the relationships between climate and topography and spatio-temporal patterns in historical fire regimes in the inland Pacific Northwest, using existing fire history data from six watersheds on the Okanogan-Wenatchee and Colville National Forests. We investigated current year, lagged, and low frequency relationships between composite fire histories and Palmer Drought Severity Index (PDSI), Pacific Decadal Oscillation (PDO), and the Southern Oscillation Index (SOI) using superposed epoch analysis and cross-spectral analysis. We identified smaller scale controls on fire exerted by fuel limitations by comparing patterns of fire hazard over time on simulated landscapes without controls to landscapes in the six watersheds. We used spatial autocorrelation, geostatistics, and multivariate methods to quantify the spatial structures of fire regimes and how they depended on local topography. We documented clear differences in fire regimes between the historical period (ca. 1650-1900) and the period after initiation of fire suppression in the region (ca.1900). We developed a unique geo-spatial database that takes advantage of both the spatially explicit nature of the fire-history data and new paradigms in geographic information science.

Major findings include:

- The El Niño/Southern Oscillation (ENSO) was only a weak driver of fire occurrence in the past three centuries, but fires tended to occur during dry summers and during the positive phase of the PDO. In the Pacific Northwest, attention should be paid to summer moisture conditions the year of the fire. Long-term fire planning using the PDO may be possible in the Pacific Northwest, potentially allowing decadal-scale management of fire regimes and vegetation dynamics.
- The relationship between drought and fire occurrence was disrupted during the 20th century as a result of land use changes.
- At small scales (20 ha or less), likelihood of fire clearly increased over time on fire-history sites that experienced short fire-return intervals, suggesting that fuels build-up was the primary local control on fire.
- In watersheds with longer fire-return intervals, this pattern did not hold. Fire occurrence displayed spatially heterogeneous temporal patterns in watersheds in which the sample area was dissected by topographic boundaries, whereas this was not the case where topography was gentle or where all recorder trees were in a single basin. Thus, spatial variation in historical fire regimes was clearly a function of topographic structure.

In some of the watersheds, fires virtually disappeared in the 20th century; in all watersheds, 20th century fire regimes departed from their historical patterns, suggesting that to a large degree human influences have disrupted historical controls. This process may not be reversible. Given projected climatic changes and documented relationships between fire and climate, reference conditions from pre-1900 may not be achievable.

The GIS database is being placed on a dedicated web server, on CD-ROMs, making it available not only to fire managers in eastern Washington, but also to those around the country and the world for whom this extraordinary spatially explicit record of fire would be of use. It will also be linked to the Paleofire Database (http://www.ngdc.noaa.gov/paleo/impd/paleofire.html). Project scientists based in Seattle (McKenzie, Kellogg) will provide ongoing support to local users (Okanogan-Wenatchee and Colville national forests) of the database.

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1 Introduction

In order to manage fire regimes based on scientific information, it is critical to quantify the spatial and temporal variation in historical fire regimes, link this variation to climatic variability, and develop tools to identify fire hazard based on these linkages. This project addressed the Joint Fire Science Program request for proposals 2001-1 by linking climate to fire regime characteristics and by developing spatially explicit, empirically based models for predicting the response of fire regimes to climatic conditions, topographic variation, and changes in management, particularly fire suppression. We proposed a multi-scale analysis of the relationships between climate and topography and spatio-temporal patterns in historical fire regimes in the inland Pacific Northwest, using existing fire history data from the Okanogan-Wenatchee and Colville national forests. This analysis had the following broad objectives:

- Quantify the relationships between fire regimes, climate and topography in the inland Pacific Northwest at multiple spatial scales.
- Determine how fire exclusion has altered relationships between climate and fire by comparing pre- and post-20th century fire regimes.
- Integrate the results of this research with decision support systems used by federal land managers to help plan fuel reduction efforts, anticipate future extreme fire years, and manage broad-scale patterns of fire effects.

We proposed to answer two key questions at each scale.

<u>Small Scale</u>

- Which drivers (e.g., topography, climate, fire exclusion) influence the temporal pattern of fire at each point and within topographic units?
- How do these drivers affect the synchrony of fire between points?

<u>Medium Scale</u>

- How do temporal and spatial patterns of fire vary between watersheds and what are the primary drivers (e.g., topography, climate, fire exclusion) of this variability?
- How do relationships between climate and fire change over time, and how do these changes vary among watersheds?

<u>Large Scale</u>

- What is the relationship between temporal patterns of fire occurrence and climatic variability?
- How do these relationships change along biophysical gradients associated with seasonal precipitation and temporal gradients associated with fire exclusion?

Answers to the key questions were provided in scientific publications and conference presentations. Decision support and technology transfer were originally to be implemented in an existing system, but the uniqueness of the fire-history data and advances in GIS science over the past 5 years called for a more customized approach to disseminating the data and results (see Section 6).

1.1 Fire history study sites

Everett *et al.* (2000) selected the study sites to capture the heterogeneity of the eastern Cascade landscape and the limited range of ponderosa pine-dominated ecosystems (fig. 1). The six sites and their locations from north to south are: South Deep and Quartzite located in the Colville National Forest, and Frosty Creek, Entiat, Swauk and Nile Creek located in the Okanogan-Wenatchee National Forest. The area of the study sites and sampling intensity varied at each site (table 1).

The South Deep and Quartzite study areas are in the Colville National Forest (CNF) within the Okanogan Highlands. South Deep is within the southernmost range of the Selkirk Mountains. The mountainous environment is cool (mean annual temperature 7.2 degrees C, at 500 m elevation in Colville, WA, 48° 33' N, 117° 54' W, 1946-2001, Western Regional Climate Center 2003) and wet (75-100 cm yr -1, 1969-1990, Spatial Data Analysis Center 2000) where ponderosa pine occurs in association with Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) in South Deep, and Douglas-fir and grand fir in Quartzite (Williams *et al.* 1995). Landform in both sites was heavily influenced by continental ice sheet glaciations producing rounded summits (elevations 500-2200 m), with relatively gentle mountain slopes (<20 deg.) separated by broad, U-shaped valleys. Both areas are covered with a mantle of till and outwash deposited over medium-to-coarse grain granitic bedrock (Schellhaas *et al.* 2000a and 2000b).

The Frosty Creek, Entiat, Swauk and Nile study areas are located on the Okanogan-Wenatchee National Forest (OWNF). The OWNF spans three major ecological regions (Lillybridge *et al.* 1995). Frosty Creek and Entiat are located in Chelan Terrane (Alt and Hyndman 1984) that is comparatively warmer (8.3 degrees C at 265 m in Republic, WA, 48° 39' N, 118° 44' W, 1946-2001, Western Regional Climate Center 2003) than the Okanogan Highlands and drier (<30 cm yr -1, 1969-1990, Spatial Climate Analysis Service 2000) than the other four sites. Both study areas are dominated by forests of ponderosa pine and Douglas-fir (Lillybridge *et al*. 1995), are mountainous, and were shaped by continental and mountain glaciations. Elevations in Frosty Creek range from 1000-1700 m, with summits that are barely discernable from the undulating U-shaped valleys. In contrast, topography in the Entiat is more complex and incised with deep (elevations 360-2000 m) V-shaped valleys (slopes 30-50 deg.). Geologically, both study areas are predominately granitic and metamorphic bedrock overlain with deposits of coarse volcanic ash and glacial till (Lillybridge *et al.* 1995, Schellhaas *et al.* 2002).

The Swauk is located south of the Chelan Terrane, and extends from the Entiat fault to Ellensburg, Washington. This region is part of the old North Cascades subcontinent (Lillybridge *et al.* 1995); the Cascade mountains are narrower than average for the rest of the range and the climate is slightly warmer (9.8 degrees C at 323m in Yakima, WA, 46° 34' N, 120° 32' W, 1946-2001, Western Regional Climate Center 2003) and drier (100-150cm yr -1, 1969-1990, Spatial Climate Analysis Service 2000). Study areas are comprised of dry forest types, dominated by ponderosa pine, Douglas-fir, and grand fir (Lillybridge *et al.* 1995). The Swauk was outside of the limits of the continental ice sheet, but experienced extensive mountain glaciations. Consequently, the topography is rugged with deeply incised mountains, and rocky ridges (elevations 400-3000 m) separated by V-shaped valleys with steep (30-60%) long slopes. The area has complex geological parent materials ranging from highly acidic granitic rock types to ultrabasic serpentine material, with extensive areas of marine sandstones (Williams and Lillybridge 1983, Lillybridge *et al.* 1995, Williams *et al.* 1995).

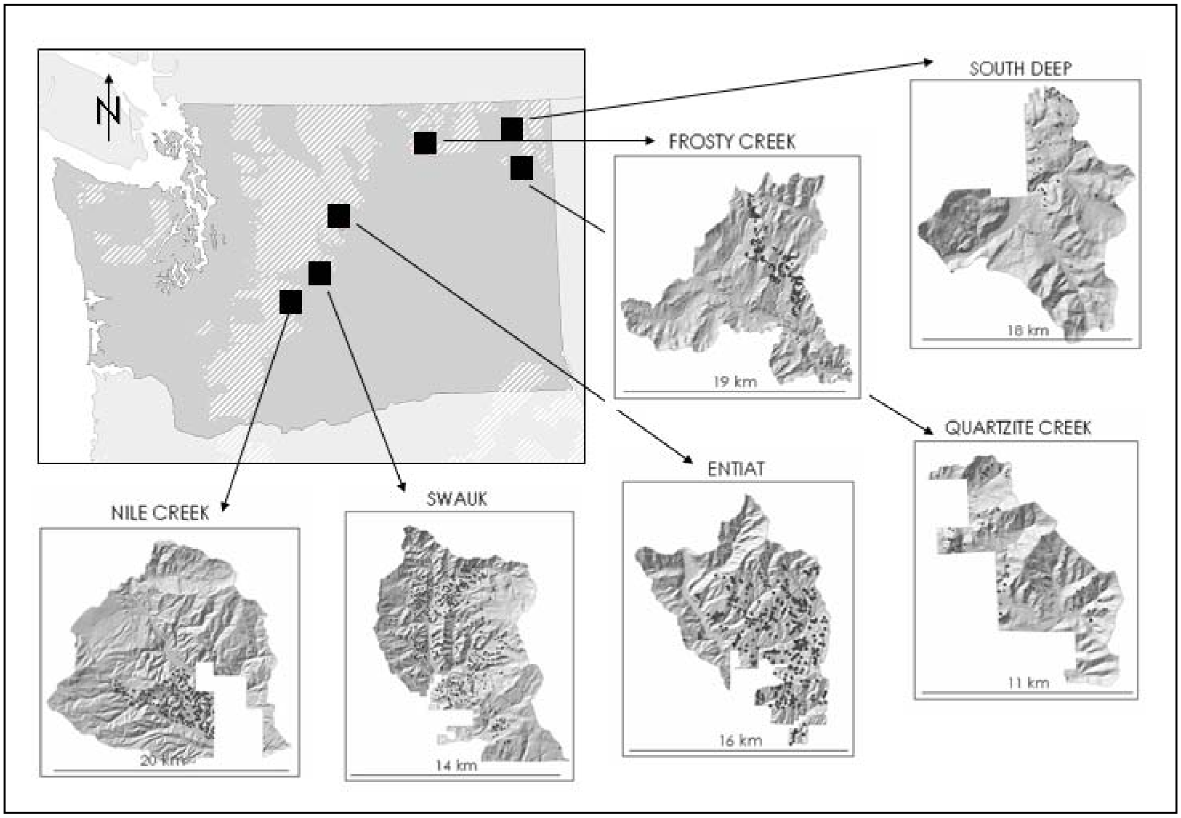

Figure 1 — The six study sites (watersheds) in eastern Washington.

Table 1. Location, area, sample sizes and analysis time frame of fire scarred trees at each of the six study sites from south to north.

Site	**Location**		**Area sampled (ha)**	**Trees (n)**	**Fire scars**		
	Lat. (N)	**Lon. (W)**			**Number of fire scars**	**First scar (year)**	**Last scar (year)**
Nile	46° 52’	121° 05’	3237	234	2314	1367	1970
Swauk	47° 15’	120° 38’	11088	665	7048	1257	1942
Entiat	47° 48’	120° 20’	12747	490	3904	1530	1988
Frosty Creek	48° 34’	119° 00'	2300	420	4461	1343	1994
Quartzite	48° 17’	117° 37’	3116	142	1300	1384	1989
South Deep	48° 45’	117° 40’	12019	168	680	1399	1986
Total	---	---	44507	2119	19707	---	---

The Nile is the most southerly of the study areas and is located south of Ellensburg and north of the Yakima Reservation. Elevations are lower, but the climate and forest types in the Nile are comparable to those of the Swauk. Parent material is primarily comprised of basalt and andesite flows that have been subjected to extensive mountain glaciations. Topography in the Nile is reflective of these events and its mountainous terrain (600-2000 m) is characterized by long, gently sloping (10-30 deg.) ridges with steep dissected side slopes (20-50 deg).

1.2 Fire-scar data

Everett *et al.* (2000) generated an extensive, spatially distributed network of geo-referenced and crossdated fire scar chronologies that are ideal for spatial and temporal analysis of regional surface-fire history. Within each study site, aerial photographs and topographic maps were used to identify and map aspect polygons, delineated by aspect (northerly or southerly) and slope (flat, moderate, or steep). Sizes of aspect polygons ranged from 32 to 1700 ha, and the number within each site ranged from 2 to 21. Polygons were internally stratified into four to five sub-polygons to ensure that fire scar samples were spatially segregated in the polygon. All fire-scarred trees within each sub-polygon were mapped, and between 2 and 23 "high quality" trees (with a large number of scars) were sampled. Sections were cut from live trees (Arno and Sneck 1977), and cross-sections were collected from stumps, snags and logs.

Fire scars were collected from both living and dead trees and prepared using standard procedures (Arno and Sneck 1977). Live sections were planed and both live and dead sections were sanded with 80-600 grit sandpaper to identify individual tree rings. All samples were then crossdated (Stokes and Smiley 1968) against an independent master tree-ring chronology developed from 20-50 climatically sensitive trees (without fire scars) within each sampling area. The year of each fire scar was determined by the position of the scar relative to the dated sequence of annual rings in the cross-section (Dieterich and Swetnam 1984). Dates were checked by at least two technicians before being archived and summarized using FHX2 fire history software (Grissino-Mayer *et al.* 1995). Samples that could not be conclusively dated with annual resolution were excluded from the analysis. Based on the pattern of late season fires (July-October) in the modern record, dormant season fires were always assigned to the calendar year of the previous ring (representing a fall fire), rather than the following ring (representing a spring fire).

We developed a master database of fire history records for all points (fire-scarred trees), study sites and the entire region. Trees that are scarred by fire lose protective bark and are therefore more likely to record fires again. As a result, trees are only considered "recorder trees" from the time of initial scarring until either the death of the tree or the sampling date (Romme 1980). Because a single tree can record many fire events and many of these events were likely quite small (recorded by only 1-2 trees), we created composite fire histories for each study site (Grissino-Mayer *et al.* 1995). These composites include only those years during which ≥10% of the recorder trees in a study site recorded fire, a minimum sample depth of two recorder trees were present, and at least two trees recorded fire. To identify regional fire years, defined as those representing large fire events that span more than one study site, we calculated the percentage scarred from each site and weighted (divided) it by the size of the study area. This prevented large study areas from having an exaggerated influence on our determination of regional fires. We then identified those years during which ≥10% of all recorder trees (weighted by study area size) in all study sites recorded fires (with a minimum sample depth of two recorder trees and two scars). Large regional fire years were identified using the same method, but with a minimum of 25% of recorder trees recording fire.

We created collector's curves to graphically display the number of fire years recorded given different numbers of recorder trees sampled. We used these curves to evaluate the adequacy of the sample size in each study site and to identify the time period with an adequate sample size for analysis of the fire regime. As the collector's curve flattens, additional samples add fewer and fewer new fire years to the history of fire at that site, indicating that additional samples will yield little new information.

To describe the basic fire history of our study sites and to understand changes in fire history with Euro-American settlement, we calculated fire return intervals for each point both prior to and following Euro-American influence (1700-1900 and 1901-1990, respectively). Point intervals, or the time between fires affecting a single point, are longer than composite intervals, but are not subject to the variation associated with varying sample size or sample area (Agee 1993; Baker and Ehle 2001).

Point fire intervals suggest that prior to Euro-American settlement, fire intervals at individual trees were highly variable. Between 1700 and 1900, mean point fire intervals for each study site range from 11 years for Entiat to 37 years for South Deep. Interestingly, the mean point fire interval for South Deep actually decreases from the pre-settlement to the post-settlement period, from 37 years to 27 years. At all other sites during the 20th century mean point fire intervals increase from two to six times their length between 1700 and 1900. For all sites, the total number of intervals (and number of trees recording fire) sharply declined after 1900.

Between 1700 and 1900, the longest fire intervals were in South Deep (table 2). Although Quartzite is also located in the northeastern portion of the study area and is adjacent to South Deep, this site experienced shorter fire-free intervals during that same period. South Deep is also unique among sites in its response to climatic variability (see section 2).

Regionally, major fires (≥25% scarred) occurred 3 times between 1700 and 1900 (1776, 1834 and 1886), but only the 1776 event was extensive in all watersheds. Fire frequency increased between 1771 and 1795, then decreased between 1796 and 1811, a pattern also observed in the southwestern United States and northern Patagonia (Kitzberger *et al.* 2001). Fire frequency and extent then increased between 1812 and 1900 with a short gap between 1870-1886. Following 1895, no fires were recorded in ≥10% of the recorder trees, signaling a major change in the fire regime.

Table 2. Fire interval statistics (in years) for the period 1701-1900 defined as years in which 10% of trees recorded scars (minimum of 2 trees).

Site	Number of fire intervals	Mean interval	Standard deviation	Minimum interval	Maximum interval
Nile Creek	30	6	4	1	18
Swauk Creek	25	8	7	1	33
Entiat River	32	6	4	1	16
Frosty Creek	33	6	5	1	17
Quartzite	41	5	4	1	17
South Deep	20	10	9	1	31

2 Climatic Variability and Fire

2.1 Summary

We quantified the relationship between fire occurrence and interannual to decadal climatic variability (Palmer Drought Severity Index [PDSI], El Niño/Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO]). Using five of the study sites in central and eastern Washington (excluding Frosty Creek), we investigated current year, lagged, and low frequency relationships between composite fire histories and PDSI, PDO, and ENSO (using the Southern Oscillation Index [SOI] as a measure of ENSO variability) using superposed epoch analysis and cross-spectral analysis. Fires tended to occur during dry summers and during the positive phase of the PDO. Cross-spectral analysis indicates that percentage of trees scarred by fire and the PDO are spectrally coherent at 47 years, the approximate cycle of the PDO. Similarly, percentage scarred and ENSO are spectrally coherent at 6 years, the approximate cycle of ENSO. However, other results suggest that ENSO was only a weak driver of fire occurrence in the past three centuries. Whereas drought and fire appear to be tightly linked between 1700-1900, the relationship between drought and fire occurrence was disrupted during the 20th century as a result of land use changes. We suggest that long-term fire planning using the PDO may be possible in the PNW, potentially allowing decadal-scale management of fire regimes, prescribed fire and vegetation dynamics.

2.2 Introduction

For decades, fire ecologists have appreciated the effect of weather on fuel conditions (Schroeder and Buck 1970, Anderson 1981) on hourly to daily time scales, and the effect of climate on fuel accumulation, on seasonal to annual time scales. However, not until the last decade have ecologists investigated the relationship between multi-year climatic signals, such as El Niño/Southern Oscillation (ENSO), and fire occurrence and extent (e.g. Swetnam and Betancourt 1990, Johnson and Larsen 1991, Swetnam 1993, Veblen *et al.* 2000, Heyerdahl *et al.* 2002). From an ecological perspective, connections between fire and climate at interannual (and longer) timescales suggest the possibility that other ecosystem processes, such as nutrient cycling, regeneration and mortality may also be linked to interannual to decadal variability in climate, through fire effects. From a management perspective, the connections between fire and interannual climatic variability allow managers to predict wildfire severity at a broad range of temporal scales, from daily and seasonal predictions of fire hazard to annual and multi-annual predictions of fire occurrence and extent, where climatic controls like ENSO are important. If climatic phenomena operating on decadal time scales, such as the Pacific Decadal Oscillation (PDO), also affect fire occurrence and spread, then our perspective on ecosystem processes as well as our ability to predict fire hazard will be significantly broadened. Unlike centennial to millennial scale fluctuations in fire activity linked to climate via lake charcoal sediment reconstructions (Clark 1990, Millspaugh and Whitlock 1995), decadal scale fluctuations are still within the temporal scale at which human institutions operate and could fill a gap between interannual and centennial scale studies.

Atmospheric processes operating at different spatial and temporal scales, reflected in climate indices such as the Palmer Drought Severity Index (PDSI), El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are known to be associated with local climate in the Pacific Northwest (PNW). PDSI is a composite monthly index of regional climatic conditions calculated from precipitation and temperature changes (Palmer 1965, Alley 1984, Heddinghaus and Sabol 1991), and incorporates both immediate (same-month) and cumulative (multi-month) effects of drought. Two synoptic scale patterns centered over the Pacific Ocean (ENSO and PDO) are known to affect local level climate in the PNW. ENSO originates with anomalies in tropical sea-surface temperatures, but affects climate across western North America, especially winter conditions. El Niño conditions tend to produce warmer drier winters and La Niña conditions tend to produce cooler wetter winters in the PNW (Redmond and Koch 1991, McCabe and Dettinger 1999, Mote *et al.* 1999a). Like ENSO, the PDO is an index of variability in climate of the Pacific Ocean, in this case the northern Pacific. The PDO also affects local climate in the PNW, but at lower frequencies (20-40 years) than ENSO. The positive phase of the PDO is associated with warmer drier winters, whereas the negative phase is associated with cooler wetter winters (Mantua *et al.* 1997). Interestingly, the phase of the PDO may affect the strength of El Niño and La Niña events (Gershunov and Barnett 1998). During the cold phase of the PDO, the effects of El Niño on U.S. climate may be weakened, but the effects of La Nina may be enhanced.

Continental-scale oscillations associated with ENSO have inverse effects in the Pacific Northwest versus the Southwest (Cayan 1996, Kunkel and Angel 1999). For example, El Niño years are typically associated with warmer, drier winters in the Northwest but cooler, wetter winters in the Southwest. Given observed relationships between ENSO and fire in the Southwest and Rocky Mountains, we may expect that in the Pacific Northwest the warm phase of ENSO (El Niño) may be associated with severe fire years. Also, in the Pacific Northwest, other climatic patterns besides ENSO may be important for fire regimes. For example, the Pacific Decadal Oscillation (PDO) is associated with decadal-scale patterns in precipitation (Mantua *et al.* 1997), productivity in high-elevation forests (Peterson and Peterson 2001) and possibly with large fire occurrence in the 20th century (Mote *et al.* 1999b). Given the relationship between fire occurrence and climatic variability in the Southwest and the Rocky Mountains, it is possible that decadal scale, quasi-periodic climatic variability in the Pacific Northwest and associated dry conditions over several years could predictably affect the occurrence of fires in a given year, particularly in arid ecosystems through either fine fuel development prior to the fire season or through fuel moisture condition during the fire season. Alternatively, wholly different climatic patterns, unassociated with ENSO or PDO, may affect fire occurrence in the Pacific Northwest.

2.3 Methods

Three reconstructed climatic variables were used in this analysis. We used a reconstruction of summer PDSI based on a gridded network of tree-ring chronologies from the United States (Cook *et al.* 1999, gridpoint #9) to evaluate the effect of drought on fire occurrence. We also used a tree-ring reconstruction of the winter SOI (Southern Oscillation Index, an ENSO index) based on regionally averaged tree-ring data from Mexico and Oklahoma (Stahle *et al.* 1998) to compare fire history to ENSO. When SOI is positive, La Niña conditions (cool, wet) dominate and when SOI is negative, El Niño conditions (warm, dry) dominate. We used a tree-ring reconstruction of PDO based on Pacific Northwest trees (Gedalof and Smith 2001) to compare fire occurrence to the PDO. Although PDO and ENSO are synoptic scale indices of climate, they are both correlated with local climate conditions in the study area. Consistent with regional relationships, SOI is negatively correlated with spring temperatures and positively correlated with winter precipitation in our study area. Also consistent with regional relationships, the PDO is positively correlated with spring temperature and negatively correlated with winter precipitation in our study area.

We investigated current year, lagged, and decadal frequency relationships between fire and PDSI, PDO, and SOI using graphical analysis, correlation, superposed epoch analysis (SEA) (Haurwitz and Brier 1981, Prager and Hoenig 1989, Baisan and Swetnam 1990) and cross-spectral analysis

(Bloomfield 2000). Correlation was used to identify relationships between PDSI and fire occurrence prior to and following Euro-American land-use changes. SEA identifies statistical, non-linear relationships between climate variables and fire years. Mean values of reconstructed PDSI and SOI were calculated for 6-year windows (3 years preceding, 2 years following and each composite fire year [when ≥10% of the trees in each watershed were scarred]) for each watershed. We chose 6-year windows to allow us to evaluate conditions preceding fire that may be linked to multi-annual climatic variability and/or fuel buildup. These values were compared with the complete climatic record during the period of analysis for PDSI and SOI, and tested for significance using Monte Carlo simulations that randomly pick years, identify 6-year windows, calculate expected means, and provide 95% bootstrap confidence intervals (Grissino-Mayer *et al.* 1995). We did not perform SEA on fire occurrence and PDO because the frequency of PDO is too low (20-40 years) to be captured by the SEA window. Instead we used cross-spectral analysis to identify associations between both the PDO and SOI indices and the percentage of recorder trees scarred. This technique is more appropriate for examining low-frequency variability in time series.

2.4 Results and discussion

Regional fire years (≥10% scarred) have occurred when PDSI is both low and high; however, 17 out of 26 fire years occurred when reconstructed PDSI was below the mean (fig. 2). Large regional fire years (≥25% scarred) occurred when PDSI is below the mean (4 fire years) or following a multi-year period with below average PDSI (1 fire year). In summary, not every dry year produced a fire, but most fire years were associated with dry years.

Regional and large regional fire events occurred during both El Niño and La Niña events (fig. 3). SEA of SOI at both the site level and the regional level indicate that there is no significant difference between ENSO during fire years versus non-fire years. However, the coherence spectrum of SOI with percentage scarred shows a strong peak, significant at $\alpha = 0.05$, at approximately 6.3 yr, with a phase shift (SOI leading percentage scarred) of approximately 3.3 years. With a lag of approximately half the frequency (at maximum coherence), the two series are almost exactly out of phase so when SOI is positive (negative) and La Niña (El Niño) conditions predominate, percentage scarred is low (high). Thus fires tend to occur during El Niño events when winter and early spring conditions are warm and dry rather than during La Niña events when winter and early spring conditions are cool and wet.

Regional and large regional fire events have occurred more frequently during the positive phase of PDO than during the negative phase. Five out of five large regional fire years (≥25% scarred) and 16 out of 27 regional fire years (≥10% scarred) occurred during the positive phase. The correlation between (annual) PDO and (annual) PDSI is 0.125 ($p = 0.03$) indicating that any relationship between PDO and fire is only weakly associated with interannual drought and instead may represent a long-term influence on fuels through soil moisture, foliar moisture and needle mortality.

The coherence of PDO with percentage scarred for all five watersheds during the period 1700-1900 had one significant peak (lower 95% confidence limit > 0). The time series were coherent with a period of approximately 47 years, with a phase-spectrum value at that frequency of 5.62, corresponding to a 5-year lag between PDO and regional fires (Bloomfield 2000). Because each of the two phases of PDO normally lasts for 20-30 years, 47 years approximates one full cycle.

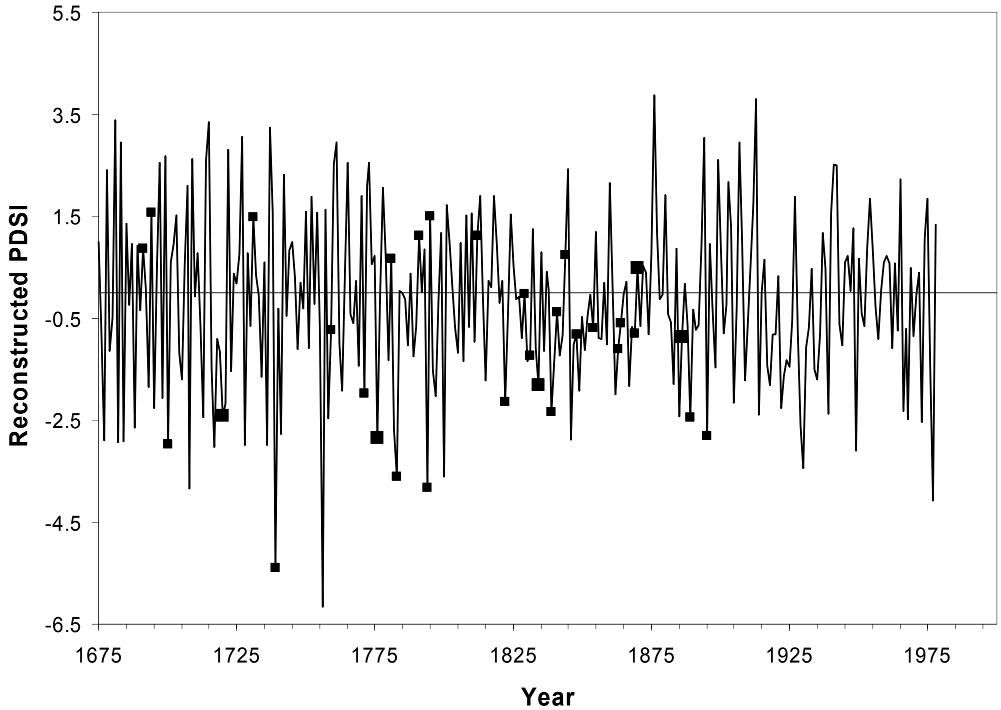

Figure 2—Palmer Drought Severity Index (PDSI) reconstructed from tree-rings (Cook *et al.* 1999) (1675-1978) plotted with large squares for large regional fire years (≥ 25% of all recorder trees in all watersheds recording fire, n = 5) and with small squares for smaller regional fires (≥ 10% of all recorder trees in all watersheds recording fire, n = 26). Note the large number of fires that occurred between ~1820 and 1895 when PDSI was consistently low, whereas the drought period between 1915 and 1935 did not produce regional fires, presumably because of effective fire suppression.

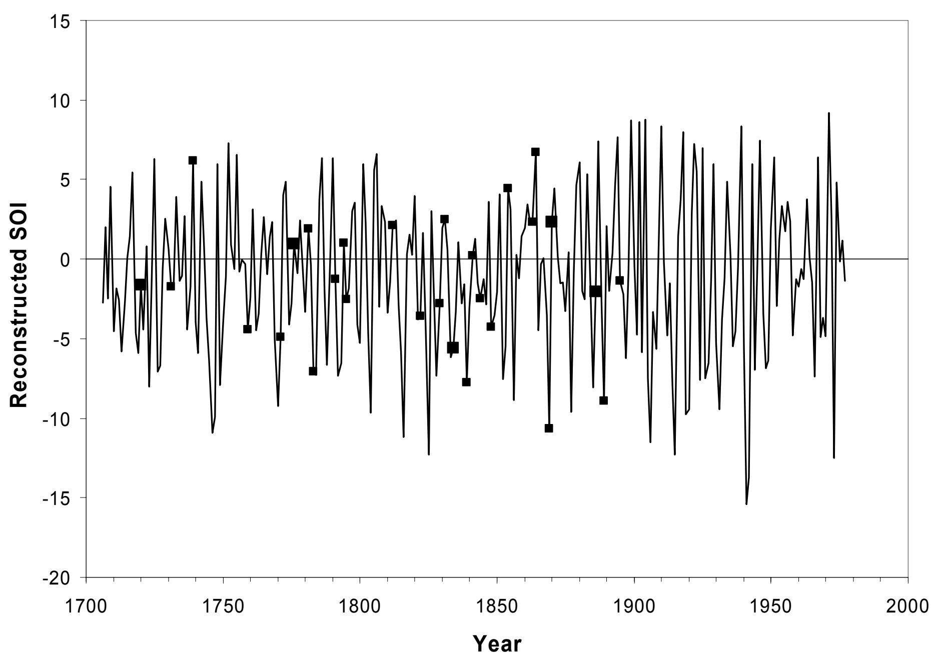

Figure 3—Southern Oscillation Index (Stahle *et al.* 1998) (1706-1977) plotted with large squares for regional fire years (≥25% of all recorder trees in all watersheds recording fire, n = 5) and with small squares for smaller regional fires (≥10% of all recorder trees in all watersheds recording fire, n = 23).

SEA of PDSI and fire indicated that for all sites, drought is associated with fire occurrence (fig. 4). Reconstructed PDSI during the year of the fire was negative (representing warm, dry conditions) and was statistically significant in all sites except South Deep. In South Deep, fire years appear to be centered on multi-year warm, dry periods, but the pattern was not statistically significant. The pattern of reconstructed PDSI in the three years leading up to the fire year varied between sites. For Entiat, two years prior to fire events were significantly wet and cool ($p < 0.05$, $n = 30$) but the year before the fire was approximately average. Although this pattern of increased moisture leading up to fire years has been observed in southwestern ponderosa pine forests, it was only evident in one (Entiat) of the five areas studied here. In both Quartzite and Nile, the year before the fire year was also warm and dry, with reconstructed PDSI values significantly drier ($p < 0.05$) than average conditions. In the SEA for all sites combined (≥10% recorders scarred, minimum of two recorder trees, minimum of two scars, weighted by sample area), PDSI the year of the fire is below the 99.9% lower confidence limit, suggesting that regional fires occurred during years of extreme drought. But fire years were not necessarily preceded by any consistent climatic conditions, either dry or wet, in contrast to the Southwest.

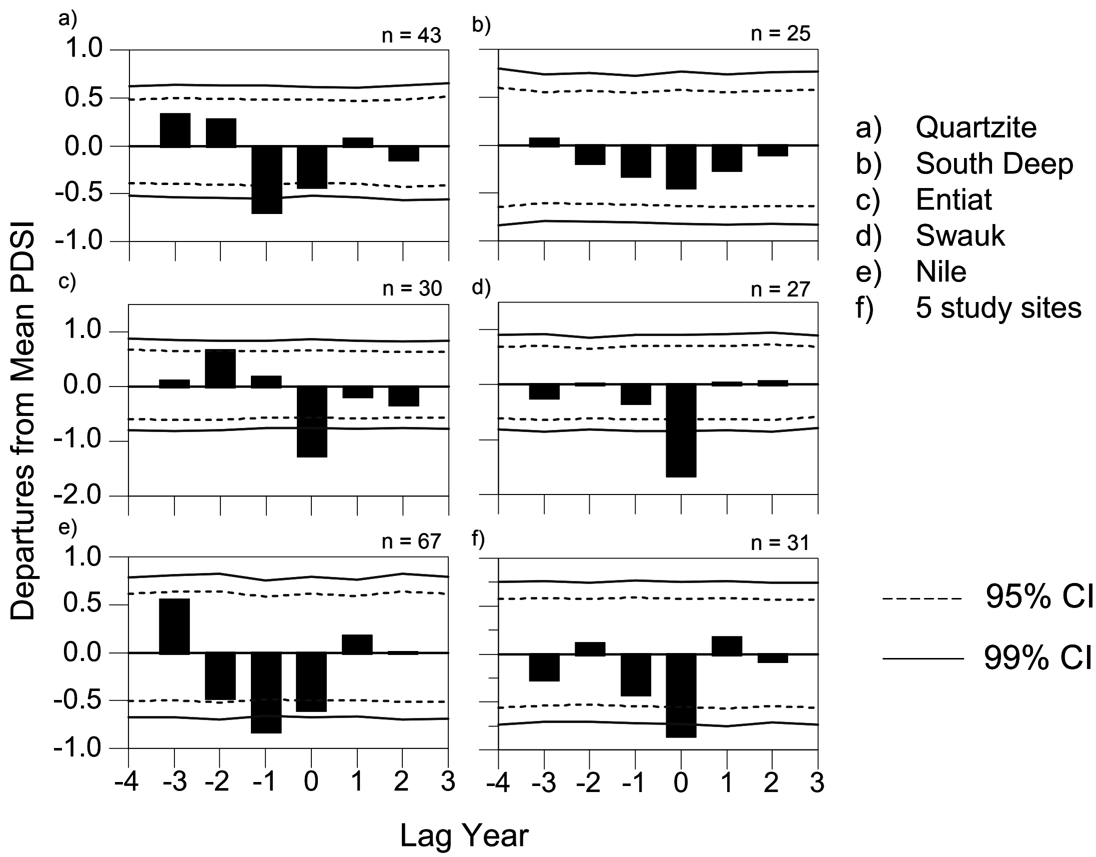

Figure 4—Superposed epoch analysis for each watershed showing departures from mean annual Palmer Drought Severity Index (PDSI) during fires that affected ≥10% of the recorder trees in Quartzite (a), South Deep (b), Entiat (c), Swauk (d), Nile (e) and all sites combined (f). PDSI is shown during the fire year (lag year 0), prior to the fire year (lags –3 to –1) and following the fire year (lags 1 to 2). The horizontal solid and dashed lines are the 95 and 99 percent confidence intervals derived from 1000 Monte Carlo simulations performed on the entire PDSI dataset (1675-1978).

Ten-year running means of percentage scarred and summer PDSI indicate a strong relationship between fire occurrence and summer drought prior to 1900, and a much weaker relationship in the 20th century (fig. 5). Years with low fire occurrence happened during periods of cool, moist climate throughout the period of record (1684-1978). Major fires followed abrupt changes in PDSI from positive to negative in the 1700s. During the 1800s, decadal frequency variability and a long (~50 year) drought were reflected in increased frequency of fire events. Between ~1890 and 1910 cool, wet conditions dominated and regional fire events were rare. However, minor, less frequent fires occurred throughout the exceptionally droughty conditions of the 1920s and 1930s, a pattern inconsistent with the previous two centuries of inverse relations between drought and fire. The 10-yr running means of PDSI and percentage scarred are correlated ($r = -0.375$, $p < 0.001$) during the period of record (1684-1978). Prior to 1901, the 10-yr running means of PDSI and percentage scarred are more strongly correlated ($r = -0.577$, $p < 0.001$), indicating that the relationship between fire and climate in the 20th century is weaker than in the previous two centuries. Although temporal autocorrelation introduced by the running means may elevate these r-values, visually there is a clear relationship between the two variables prior to 1901, which is also supported by the results of the SEA.

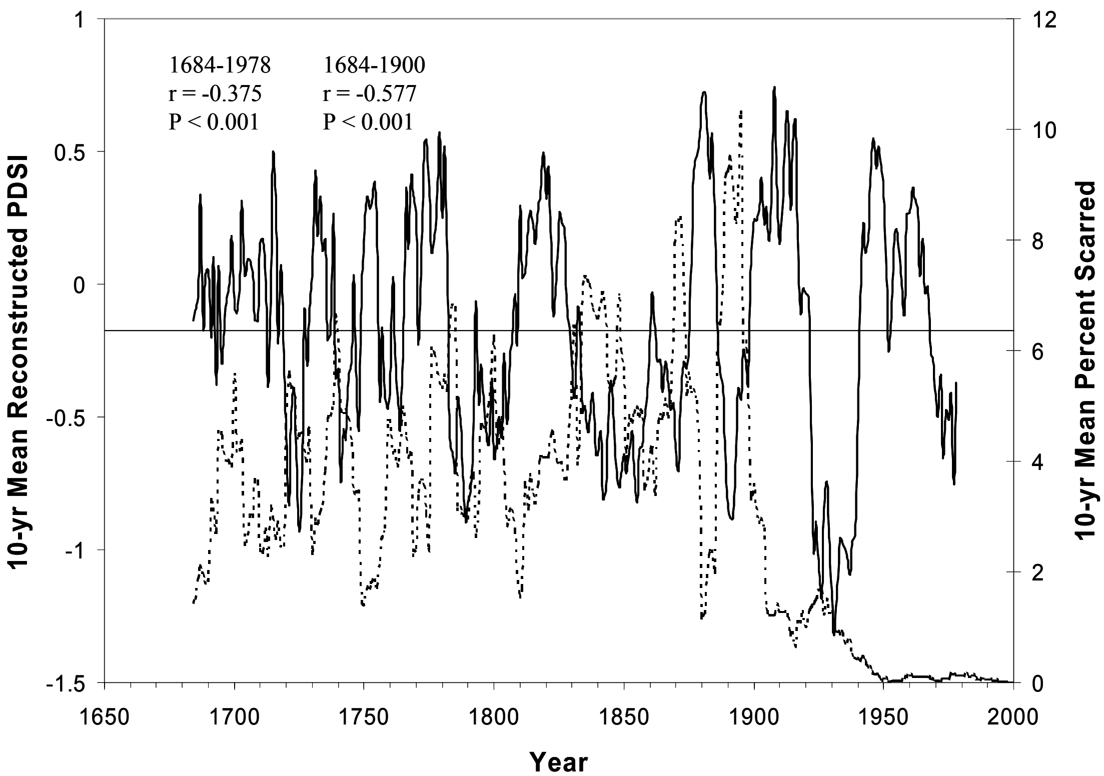

Figure 5—Ten-year average of Palmer Drought Severity Index (PDSI) reconstructed from tree-rings (Cook *et al.* 1999) (1684-1978) (solid line) and ten-year average of percentage scarred over time (dotted line).

3 Topographic Constraints on Fire

3.1 Summary

Fire regimes are complex systems that represent an aggregate of spatial and temporal events whose statistical properties are scale-dependent. Despite the breadth of research regarding the spatial controls on fire regime variability, ours is the first dataset with sufficient spatial resolution to test spatially explicit hypotheses. We decomposed the spatial relationships within each of the six sites in eastern Washington, using spatial autocorrelation in fire history data to derive empirical and theoretical parameter estimates of semivariance that enabled us to infer mechanisms that generate spatial patterns of fire in ecosystems. We used the Mantel's test on temporal patterns of fire occurrence to differentiate the spatial component of their variability from the influences of environmental conditions.

The spatial dependence of historical fire regimes varied within and among sites. Spatial controls on low-severity fire regimes within similar dry forest ecosystem types operate at varying spatial scales, reflecting topographic properties of local landscapes. However, only portions of the spatial variability in fire events can be attributed to topography, with controls diminishing from complex, rugged terrain to more open and rolling terrain. Results illustrate that the statistical spatial characteristics of fire regimes change with landform characteristics within a forest type, suggesting that a simple relationship between fire frequency and forest or vegetation type does not exist. Quantifying the spatial structures in fire occurrence associated with topographic variation demonstrated that fire regime variability is scale and location dependent. By identifying the scale dependencies associated with specific fire regimes we can match the regime to the scales of the controlling factors with greater precision, thus increasing our abilities to evaluate their relationship.

3.2 Introduction

Topographic gradients impose physical constraints on how ecological and physical processes interact to generate spatial patterns in dry forests of the western North America (Swanson *et al.* 1988). Topography contributes to direct and indirect controls on fire behavior (Rothermel 1972, 1983), controlling fire spread directly and interacting with fuels and weather (Agee 1993, Lertzman and Fall 1998). Topographic effects on historical fire regimes vary with spatial scale: local (tens of ha), intermediate (200 – 15,000 ha), and regional scales or greater (0.5 – 1.0 million ha, or greater) (Hemstrom and Franklin 1982, Swetnam and Baisan 1994, Taylor and Skinner 1998, Heyerdahl *et al.* 2001).

Topographic position exerts a bottom-up control on fire through variation in microclimates, thereby influencing the type, availability, abundance, continuity, and moisture of fuels (Romme and Knight 1981, 1982; Beatty and Taylor 2001; Bekker and Taylor 2001; Taylor and Skinner 2003). Local topography directly and indirectly mediates the variability of fire regimes at intermediate scales, by modifying vegetation structure and composition, fuel continuity, and fuel moisture (Hemstrom and Franklin 1982, Taylor and Skinner 1998, Bekker and Taylor 2001, Heyerdahl *et al.* 2001, Taylor and Skinner 2003). Mesoscale topographic features may isolate patches of forest from major disturbance, potentially creating fire refugia (Camp *et al.* 1997, Agee 2000). For example, sub-drainages oriented perpendicular to prevailing winds may not burn even during large, high-intensity fires (Johnson and Larsen 1991).

At regional scales, climatic variability appears to drive fire behavior and frequency (Swetnam and Betancourt 1990, Agee 1993, Swetnam 1993, Veblen *et al.* 2000, Hessl *et al.* 2004, Gedalof *et al.* in press), although orographic controls are certainly important in mountainous regions. Regional-scale landforms may also affect fire extent directly by facilitating the spread of fire. For example, fire extent may be limited in regions with complex topography, which alters prevailing wind direction, and may be enabled in regions with gentle topography, which provides fewer barriers to fire spread (Swanson *et al.* 1988, Agee 1993, Swetnam and Baisan 1994).

Topographic variables are frequently mentioned as contributing to fire regime variability but are rarely identified uniquely or quantified as mechanisms that influence spatial patterns of fire occurrence. The inability to identify the extent to which topography is acting solely as a control on fire regime variability is confounded because topographic variables are often used as proxies for environmental variables. Issues of spatial-autocorrelation further confound our ability to make inferences regarding topography's contributions to fire regime variability (Legendre and Fortin 1989, Legendre and Legendre 1998). Fire history research typically begins in the field with measurements that are made at fine scales. From a statistical perspective, the sample data become increasingly spatially autocorrelated with finer-grained observations, meaning that the evidence of fires for one recorder tree is dependent upon the evidence of fire measured for nearby recorder trees (Dutilleul 1998). These data are often treated with standard parametric statistics, but violate the assumptions of independence (Dorner *et al.* 2002).

Statistical analysis of random processes allows us to model the spatial dependence associated with fire regimes. Several spatial and geo-statistical methods (spatial autocorrelation and the correlogram, semivariance and the variogram, and the Mantel's and partial Mantel's tests) have been applied to spatially explicit, autocorrelated data for the purpose of quantifying spatial dependence in ecology (Legendre and Troussellier 1988, Stephenson 1990, Wagner 2003), epidemiology (Cliff and Ord 1981), soil sciences (Isaaks and Srivastava 1989; Rossi *et al.* 1992), and genetics (Smouse *et al.* 1986, Oden and Sokal *et al.* 1992). Before our study, however, there had been no such analyses used to quantify the spatial structures associated with fire regimes.

3.3 Methods

We used cluster analysis, Mantel's tests, and structure functions (Moran's I and variograms) to examine both global and local spatial dependence of fire occurrence. Spatial autocorrelation of both mean fire intervals and temporal patterns was interpreted as a measure of topographic control on the variability of fire occurrence.

Topographic variance maps (figs. 6 and 7) identified dominant topographic features and located areas where the environment was homogeneous vs. heterogeneous. A "moving window" method was used to calculate focal descriptive statistics of the environment (terrain and physiography) on a variable-by-variable basis and built into single gridded data layers to identify each cell with a specific variance value. The final maps of variance were overlain on fire-scar records to compare patterns of topographic heterogeneity and the spatial extent of historically synchronous fire occurrence.

Following Taylor and Skinner (2001), we used cluster analysis to identify clusters of recorder trees displaying similar temporal patterns of fire occurrence. Cluster analysis is a heuristic, statistical

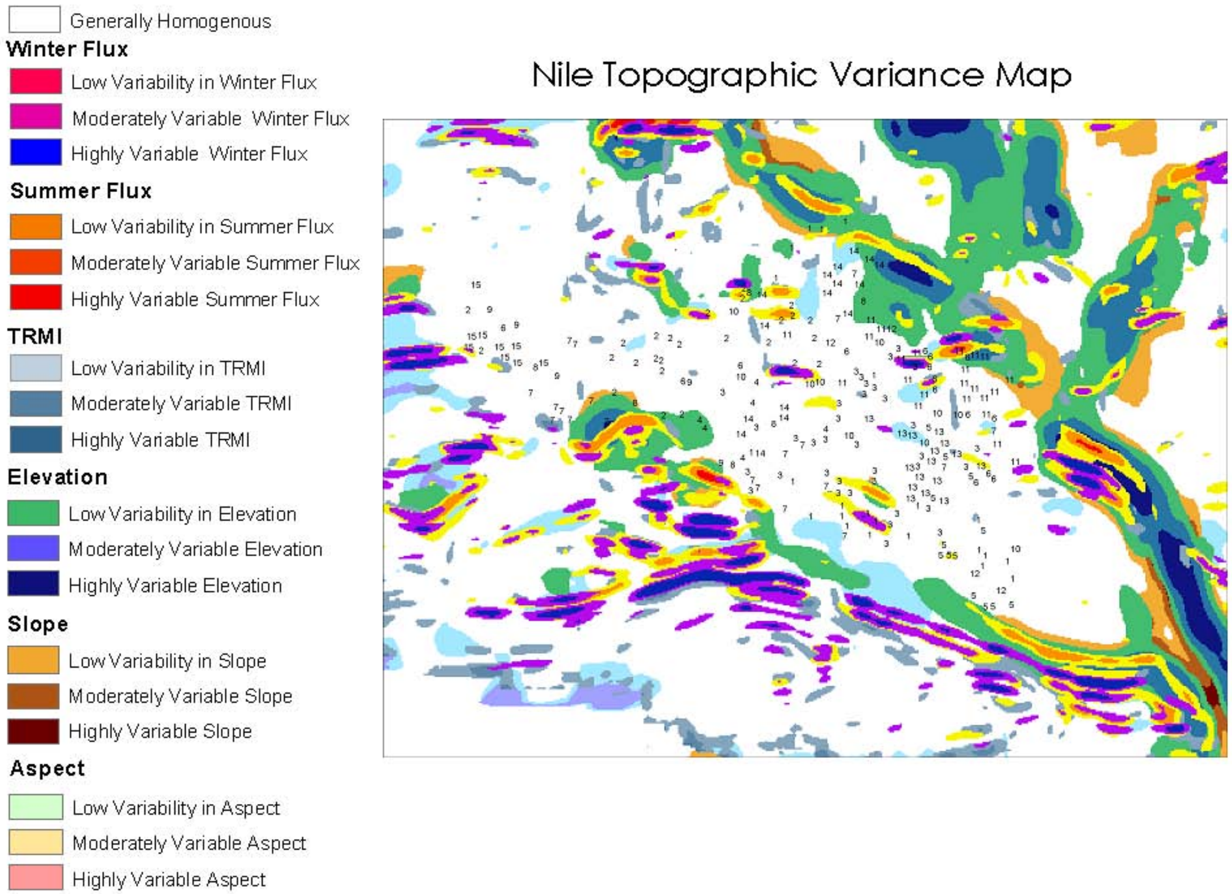

Figure 6—Topographic and physiographic variability for Nile Creek.

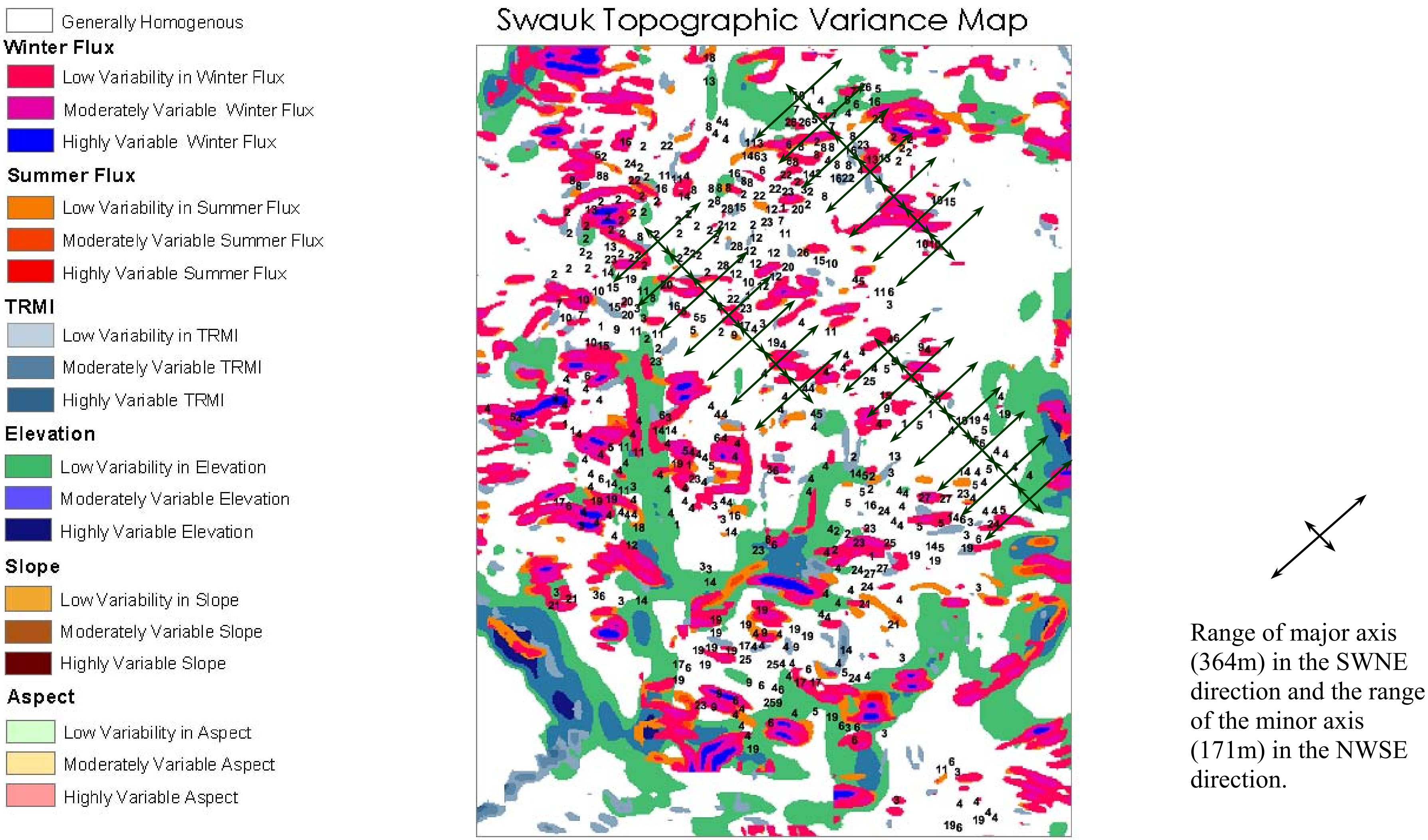

Figure 7—Topographic and physiographic variability for Swauk Creek with semivariogram model measurements of anisotropy for mean fire return interval overlain. Longer arrows indicate a greater variogram range. TMRI = topographic relative moisture index.

approach to identify homogeneous groups of observations, using a distance measure, but not appropriate for hypothesis testing (Sokal and Rolf 1995). Mantel's tests were used to test the null hypothesis that temporal patterns of fire occurrence were spatially random in each study area. When able to reject the null hypothesis that fire occurrence was spatially random in each study area, the partial Mantel's test was used to test if any single environmental variable could alone contribute a causal mechanism to the spatial patterns associated with the fire occurrence (Legendre 2000). Partial Mantel's correlations quantify the contributions of each predictor variable for its partial effect on the spatial composition of the dependent variable.

When the fire scar locations were graphically displayed with topography and the clustered groups, it appeared that fire occurrence was structured at finer scales in study areas with complex topography. To determine if the variance was dependent upon the distance between observations, Moran's I (MI) and Semivariance (γ) were used to decompose the spatial variability of the observed variables among distance classes to detect finer scales and gradients of spatial dependence. Empirical variograms were constructed as a function of Euclidean and surface length distances in varying azimuth directions (0, 45, 90, and 135 degrees with a 22.5 degree tolerance) for all variables. By confining the choice of theoretical variogram models to those functions which strictly observe monotonic change the parameters for the models can be predictive and used to make inferences.

3.4 Results and discussion

The cluster analysis showed that fire occurrence was temporally clustered (synchronous fires for groups of recorder trees) for all six study areas using the hierarchical, complete linkage criterion. Under this criterion, the number of groups found within the study areas ranged from 15 to 28: Nile (15), Swauk (28), Entiat (24), Frosty Creek (21), Quartzite (18), and South Deep (17). The identification of groups suggests distinct spatial patterns of non-synchronous fire events occurring within the scale of the study area. Mean fire return intervals and lengths varied within the study areas. Visual evaluation of the hierarchically clustered groups of fire occurrence and the gridded topographic/physiographic data across the six study areas suggested that fire occurrence was spatially structured relative to the amount of aggregate environmental variation at each site. When fire occurrence was spatially clustered, the aggregate variations in elevation, slope, and aspects were necessary to segregate or separate cluster groups. We qualitatively ranked the study areas on a continuum from gentle to complex terrain based on the amount of overlapping, highly variable environment present in the variance maps of the sampled areas. The sites, gentle to complex, are: Frosty Creek, Quartzite, Nile, South Deep, Entiat, and Swauk. The null hypothesis that there was no relationship between temporal patterns of fire occurrence at points and the geographic distances between them was rejected by the Mantel's test. Thus temporal patterns in fire occurrence were clearly more similar between points closer together. we found no significant relationship, however, between fire occurrence and individual environmental variables (elevation, slope and aspect) or physiographic variables (FLUX, winter and summer solar radiation and TRMI, topographic relative moisture index), except at Nile Creek.

Theoretical models of semivariance for MFRI in all six sites exhibited varying ranges of spatial dependence. Empirical variograms fit a spherical model for the Swauk, Entiat and South Deep, suggesting that these sites experienced strong topographic controls on fire (see fig. 6 for topographic barriers between scar locations). Topography is highly complex and dissected in the Swauk and Entiat, but gentle in the South Deep. No significant models were found for Frosty Creek, Quartzite, or Nile Creek, consistent with a lack of strong topographic control. In the case of Nile Creek, topographic barriers existed but all fire-scar samples were within one basin (fig. 5). Semivariance also changed with direction, consistent with direction patterns of topography and topographic variance of combinations of environmental variables (fig. 6).

Results from the Mantel's test, variograms and Moran's I depicted varying scales of spatial structure associated with fire occurrence that could be categorized as having either global (across study area) or local (changing within the study area) spatial dependence, and vary regionally (among study areas). This categorization provides an initial framework from which inferences on the operative controls (top-down or bottom-up) influencing fire regime variability can be made (Lertzman *et al*. 1998).

Strong local spatial dependence with relatively short effective ranges indicates that the variability associated with the fire regime is primarily a function of fine-scale factors (i.e. topography and fuels), collectively imposing constraints on the spatial patterns of fire from the bottom-up (Levin 1992). In contrast, weak, local spatial dependence with relatively long effective ranges indicates that the variability associated with the fire regime is influenced by larger scale constraints (i.e. climate/weather), being imposed from the top-down. When global spatial dependence is strong, the primary control is being exerted from the bottom-up. Conversely, when global spatial dependence is weak but varies regionally, the controls originate from top-down influences.

Spatial controls on low-severity fire regimes within similar dry forest ecosystem types operate at varying spatial scales, reflecting topographic properties of local landscapes. Our results illustrate that the statistical spatial characteristics of fire regimes change with landform characteristics within a forest type, suggesting that a simple relationship between fire frequency and forest type does not exist. Quantifying the spatial structures in fire occurrence associated with topographic variation demonstrated that fire regime variability is scale and location dependent. By identifying the scale dependencies associated with specific fire regimes we can match the regime to the scales of the controlling factors with greater precision, thus increasing our abilities to evaluate their relationship. Understanding these multi-scale dependencies can, in turn, inform the design and application of fire management, including hazardous fuel treatments and the use of fire for ecosystem restoration.

4 Small-scale (Fuel) Constraints on Fire

4.1 Summary

Climate, topography, fuel loadings, and human activities all affect spatial and temporal patterns of fire occurrence, but unlike for climate and topography, we have no record of fuel loadings for our study area during the historical period. Therefore an understanding of how fuels controlled fire occurrence and extent needed to be inferred from other reconstructed relationships. Because fire is a partly stochastic process, for which each fire history is only one realization, a simulation approach is necessary to understand baseline variability, thereby identifying constraints, in our case fuels, that affect fire regimes. We borrowed a modeling approach from the field of landscape ecology. With a suitable neutral model, characteristics of natural fire regimes estimated from fire history data can be compared to a "null hypothesis." In this case, we hypothesized that individual fires were less likely to occur in consecutive years over the same ground because of the time necessary for fuels to build up to be able to carry surface fire. We compared the behavior of randomly generated landscapes (null hypothesis) to our study landscapes with respect to how estimates of both fire frequency and the hazard of burning over time change with spatial scale.

When small areas were examined, the hazard of burning clearly increased over time on some of our study sites (Nile Creek, Swauk Creek, Quartzite), but not on others (Entiat, South Deep), presumably due to the influence of fuel buildup. The scales at which this phenomenon disappeared should roughly correspond to modal fire sizes within each study site. Via modeling, we identified historical fine-scale controls on fire occurrence, completing a picture of how the strength of fire-regime drivers (climate, topography, and fuels) changes across spatial scales in dry forest ecosystems of eastern Washington. Because fuels are the only one of these drivers subject to treatment, information on historical fuel dynamics and the spatial and temporal scales at which they affected fire will be of use in designing spatial and temporal patterns of fuel treatments in the future.

4.2 Introduction

Fire-history reconstructions provide the empirical basis for fine- and coarse-scale modeling of fire regimes and for informed management and restoration of ecosystems (Landres *et al.* 1999, Schmoldt *et al.* 1999, Swetnam *et al.* 1999, McKenzie *et al.* 2004). Reconstructions use different methods, depending on objectives, the nature of the fire regimes being studied, and the spatial and temporal scales of analysis (Clark 1990, Agee 1993, Heyerdahl *et al.* 1995, Lynch *et al.* 2003, Prichard 2003). Estimates of fire frequency from different methods are often combined for modeling and management (Agee 1993, Heyerdahl *et al.* 1995, McKenzie *et al.* 2000). For example, two metrics often associated with high-severity or stand-replacing fire – the "fire cycle" and "natural fire rotation" – explicitly measure area burned over time as a proportion of the total study area, but only record a subset of fire-free intervals experienced on the landscape, because stand-replacing fires destroy evidence of previous events. In contrast, fire-scarred trees contain a record of multiple fire events and the associated fire-free intervals, but estimates of area burned at a point in time must be indirect and estimates of fire interval may be scale dependent (McKenzie *et al.* 2000, Falk and Swetnam 2003). Research is needed to quantify how fire regime statistics change across spatial scales and how these changes may differ in different ecosystems. These statistics, particularly fire return interval, or fire frequency, are widely used in management but estimates of both means and variances are sensitive to the area over which they are sampled (McKenzie *et al.* 2000, Falk and Swetnam 2003).

Understanding the spatial scales over which controls on fire regimes operate is essential both for effective ecosystem management and for anticipating how fire might respond to climatic change or land use. Climatic controls are most evident at regional scales, at which synchronous fire events are associated with drought or quasi-periodic patterns such as ENSO or PDO (Swetnam and Betancourt 1990, Hessl *et al.* 2004). Topography controls fire spread and therefore the synchrony of fire events at watershed scales or smaller, depending on the steepness and complexity of terrain (Taylor and Skinner 2003, Kellogg 2004). Patterns of fuel accumulation associated with time-since-fire, particularly in the era of active fire suppression, are linked with typical fire sizes, i.e., landscape patches of discrete fuel ages should be of the same size as past fires. Given that the scales at which these controls operate are different, and that each one varies with ecosystem type and fire regime, analyses would ideally be conducted at multiple scales to the extent that quality and spatial extent of data permit it. The neutral modeling approach we adopt here is motivated by the need to distinguish a signal (from a such a control) from background variability at multiple scales.

We used a neutral model of low-severity fire regimes to capture the stochastic properties of fire regimes; fire sizes, fire-free intervals, and fire locations are considered to be random variables. We examined two statistical properties of the neutral model: how estimates of fire frequency change with changing sample areas, and how temporal trends in the hazard of burning change with area and number of trees sampled. To estimate the hazard of burning, we borrowed from survival analysis (Hosmer and Lemeshow 1999), wherein the probability distributions in the exponential family are linked to a "hazard function" that quantifies the instantaneous probability of an event – a death, or in our case a fire – given survival to that point. Better understanding of the first property, as a global or local scaling law, could lead to more robust comparisons of fire frequency among ecosystems, and understanding the second will permit more robust identification of key constraints on fire at specific spatial scales. We compared the null properties to the same statistical properties on five of our study sites.

4.3 Methods

The simulated "neutral" landscape consisted of a square grid with unitless X and Y coordinates (range 0-1), in emulation of a watershed. We located 200 points randomly to represent trees that could record fires. A 200-yr fire history was simulated for two watershed-scale mean fire-return intervals (MFRIs), 2 yr and 5 yr. Time steps (years until the next fire) were drawn from an exponential distribution with mean = MFRI, and rounded to the nearest integer, until their sum was >200. The exponential distribution was used because it is "memory-free" (Ross 1988, Johnson and Gutsell 1994), thereby representing a neutral landscape with no time-dependence of fire probabilities. At each time step, a fire was simulated as a circle with its center located randomly in the central 90% of the watershed. Mean fire sizes were defined within a range of proportions of the total area of the watershed, between 0.1 and 0.4, with steps of 0.05. For each round of simulations, the size of each fire was drawn from a gamma distribution, with shape parameter=2 (a right-skewed distribution) and mean equal to the mean fire size.

We then simulated fire-history reconstructions within the watershed. One tree from the interior of the watershed (defined as = 0.1 units from the edge) was randomly selected as a starting location. Using this "tree" as a center, we computed composite fire intervals (CFIs) for circular areas composing proportions of the watershed from 0.15 to 0.45 by identifying all tree locations within the search radius associated with these proportions.

Two features of the Weibull probability distribution make it well suited to modeling both high- and low-severity fire regimes (Clark 1989, Johnson and Gutsell 1994, Grissino-Meyer 1999). The Weibull median probability interval (WMPI) is a robust measure of central tendency, and the shape parameter and its associated hazard function allow changes in the hazard of burning over time to be estimated. For each of the composite fire records, we computed the WMPI and the Weibull shape parameter, the latter as a surrogate for the slope of the hazard function (Clark 1989, Johnson and Gutsell 1994).

We applied the same iterative process to the fire history record for the five watersheds, but restricted sample years to the period 1701-1900. By 1700 most sampled trees had already recorded one fire, and before 1900 fire exclusion had not drastically changed fire frequency (Hessl *et al.* 2004). We created a set of composite fire records (100 replicates x 30 search radii) similar to that for the simulated watershed, wherein any fire-scarred tree defined a fire year, using this 200-year fire record. We then computed means of WMPI and Weibull shape parameters at each search radius in each watershed. We fit simple log-linear regressions to quantify the relationship between search radius and WMPI for the neutral model and for each of the five watersheds. For the five watersheds we used weighted means of WMPI (see above), and examined models for goodness-of-fit and patterns in the residuals. We compared these empirical estimates of WMPI and shape parameters, and how they changed with changing spatial scale, to simulated estimates.

4.4 Results and discussion

Scaling relationships for the estimated fire-free intervals (WMPI) between simulated (neutral) and real watersheds are clearly similar in shape, although the slope terms decrease as mean fire size increases (fig. 8). In other words, fire frequency estimates change in a predictable way as one looks at larger sample areas. The similarities between simulated and real fire regimes suggests that this property can be expected to be true in general for low-severity fire regimes.

Estimates of the Weibull shape parameter, representing the hazard of burning over time, differ substantially between simulated and real watersheds, both in mean value and trends over increasing search radii. For simulated watersheds, mean estimates do not change with spatial scale. In contrast, shape parameter estimates in two of the real watersheds (Nile Creek and Swauk Creek) show a sharp decline over the smaller search radii and little change over larger search radii (fig. 8). Shape parameter estimates for Entiat River increase slightly with search radius, though more than in the other watersheds, except for two outliers at the smallest radii that are in the middle of the small range. Estimates for Quartzite decrease nearly monotonically until ca. 600 m, and are consistently higher than for the other watersheds. Estimates for South Deep cannot be easily compared to those from the other watersheds, because of the lack of parameter estimates for small search radii.

We conclude that there were characteristic (modal) fire sizes associated with each of three sites (Nile Creek, Swauk Creek, and Quartzite) during the historical period – roughly 40 ha, 20 ha, and 130 ha – based on the threshold search radii (fig. 9). The historical fuel constraint operated at approximately these spatial scales to reduce the hazard of burning in years following a fire. Timing, placement, and extent of fuel treatments, to reduce fire hazard or restore fire regimes, need to take account of the variability among sites.

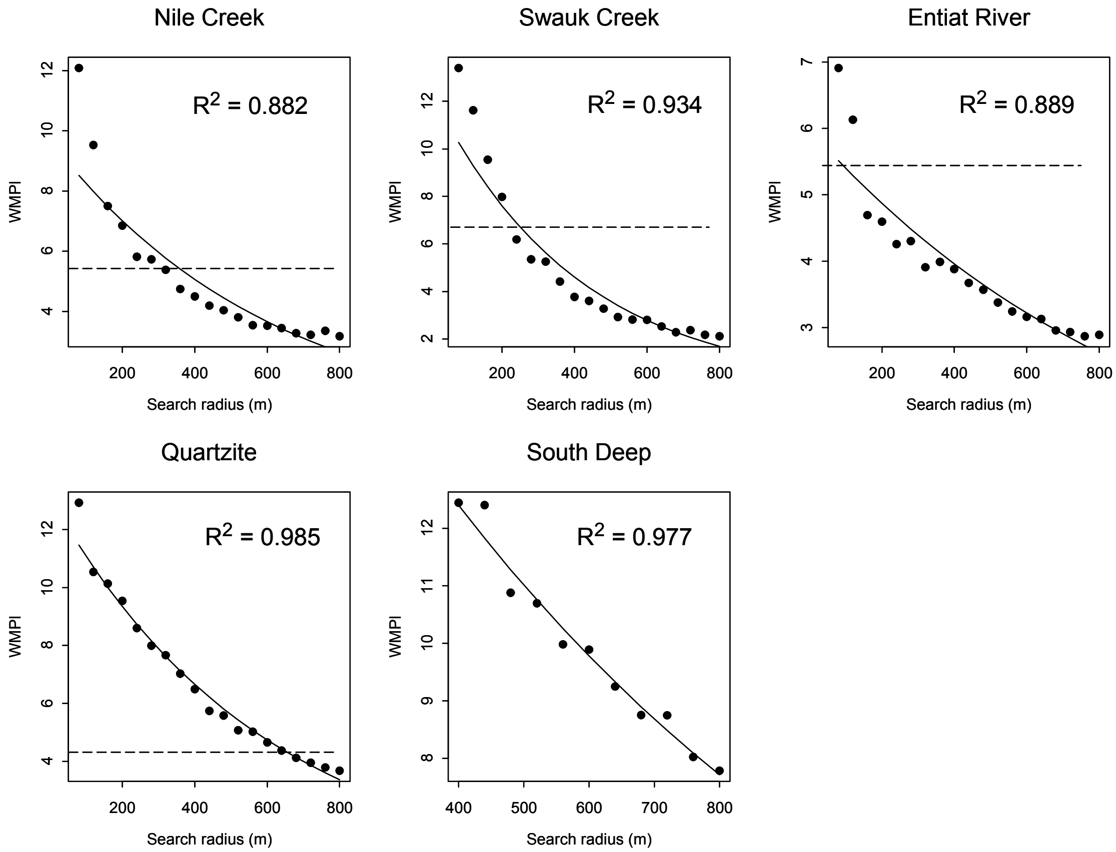

Figure 8—Scaling relationships between sample area and estimated fire frequency (WMPI) for the five study sites. Dotted lines correspond to the frequency of fire within the site of years in which more than 10% of recorder trees were scarred (table 2).

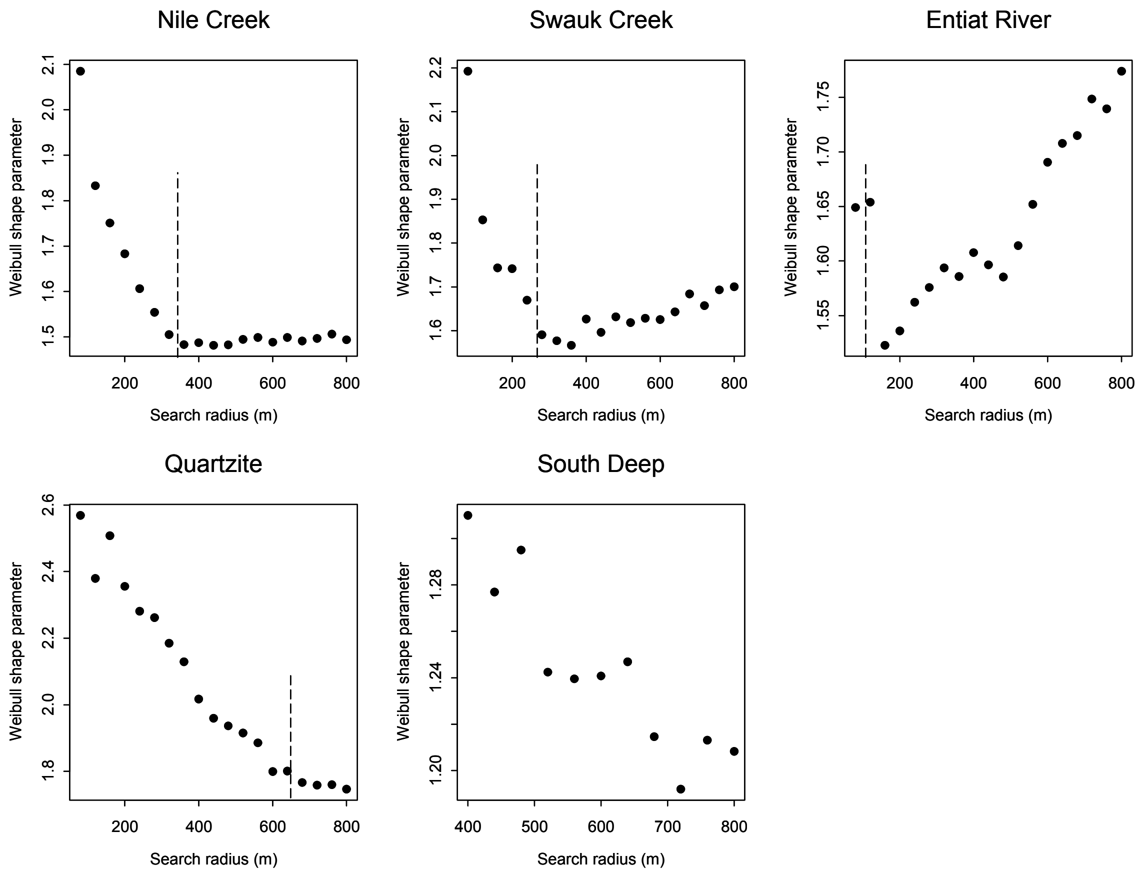

Figure 9—Weibull shape parameters, representing the hazard of burning, as functions of scale on the five watersheds. The vertical dotted lines mark the search radius at which the shape parameter crosses 1.6, the value provisionally associated with a significant increasing trend over time in the hazard function.

5 Human Influences

Human disturbance, especially fire suppression but also fuel discontinuity due to anthropogenic disturbance, has had strong effects on fire frequency in the western United States (Savage and Swetnam 1990, Agee 1993, Swetnam and Baisan 1994, Grissino-Mayer *et al.* 1995, Veblen *et al.* 2000). Fire frequency has been significantly reduced in ponderosa pine forests in the 20th century, likely the result of fire suppression and possibly heavy grazing in some areas. Changes in fire severity from surface fires to less frequent stand-replacing fires are a consequence of this change in fire frequency. Annual area burned in the Western U.S. has steadily increased since the mid-1970s, possibly due to accumulating fuels caused by 20th century fire suppression (Grissino-Mayer and Swetnam 2000). Although similar changes have been documented at individual sites in the Pacific Northwest, human influences, (especially the transition from native to Euro-American management), on fire occurrence are poorly defined. Due to the scarcity of spatially explicit fire-history data, it has been difficult to assess the relative importance of human activities versus climate on fire regimes.

European-American trappers, miners and early settlers were occasionally present in the inland Pacific Northwest early in the 19th century (Hessburg and Agee *in press*), but extensive settlement did not occur until the completion of the Northern Pacific Railroad in 1877 (Ross 1999). Cattle and sheep grazing peaked between 1880 and 1890 (Galbraith and Anderson 1991) but continued to reduce fine fuels into the 1930s. Logging of ponderosa pine forests boomed between 1920 and 1950 when engines used for cutting, transport and milling moved from steam to gasoline power (Robbins and Wolf 1994). Approximately 50% of the fire scar samples in this study were collected from stumps remaining following logging.

Active fire suppression began as early as 1878 when the Northern Pacific Railroad forbade native burning (Ross 1999), and increased after 1908 when the U.S. Forest Service began a program of fire suppression (Pyne 2001) which may not have been effective until the mid-20th century. Logging between 1880 and 1950 also likely reduced the spatial continuity of coarse woody fuels. At the same time, cattle and sheep grazing likely reduced fine fuels. In our study area, within lands currently managed by the Wenatchee and Colville national forests, fire suppression, prescribed burning, and logging are currently practiced.

A century of significant human influence has clearly altered the historical low-severity, high-frequency fire regimes in the region. Fires were frequent between 1700 and 1900 in all study sites, and maximum intervals were also short (range: 16-33 years) with the longest interval occurring in the Swauk watershed. The modern fire regime (1901-1990) was difficult to describe statistically due to the scarcity of fire events. Intervals ranged from 2 to 84 years, including the last incomplete interval (the time since the last fire to the time of sampling). Although all watersheds recorded fires in the 20th century, two of the five watersheds did not have any events that were recorded by ≥10% of the recorder trees, indicating that 20th century fires were probably quite small relative to earlier events.

Major land use changes in the 20th century altered not only the fire regime, but also the relationship between climate and fire on annual time scales. Fire frequency and the number of trees recording fire decreased dramatically in the 20th century in all study sites, reflecting a period of regional land use and land cover change that coincides with reduction of Native American ignition sources, major Euro-American settlement (1890-1910), introduction of domestic livestock, logging, and active fire suppression (>1908). During the 20th century, summer drought was relatively less important in affecting fire extent than it was previously. A wet period occurred between 1900 and 1920 that may have been related to the initial decrease in fire occurrence. However, low annual PDSI values representing severe drought (<-3) did occur seven times during the 20th century. Even so, fires, if they occurred, remained isolated and relatively small and were not detected by this study. Recent large fires in the PNW (not included in this study) associated with drought conditions indicate that although fire extent and climate were weakly associated in the 20th century, current fuel levels may have elevated average fire risk to a point that thresholds will once again be sensitive to the influence of climatic variability in coming decades, regardless of fire suppression activities.

6 Technology Transfer – the GIS Web Server

6.1 Summary

Clear and accurate representation of both spatial and temporal characteristics of fire regimes is a key ingredient of successful communication with fire managers who are responsible for the planning and implementation of effective fuel treatments. We developed a GIS database in an innovative format that allows users to extract or visualize historical spatial patterns and compare them within and among study sites and between fire years. This format takes better advantage of the unique dataset than existing software modules for decision support because of its ability to compare and contrast historical patterns. A relational database (fig. 10) links fire history data and summary fire statistics to spatial coordinates for over 19,000 fire scars on over 2000 trees. GIS software queries the database and creates maps for a given year with symbology that distinguishes individual tree status. A GIS web server enables downloads of fire history information, including maps. The web server will provide data to users worldwide, and ongoing support for users on the Okanogan-Wenatchee and Colville national forests is being provided by PNW Research Station scientists (McKenzie & Kellogg). The GIS web server is located at http://cuatro.cfr.washington.edu/flames/

6.2 Background

Traditional cartographic approaches to geographic data structures, display, and delivery can represent states at a given time, but fail to represent the events that led to the change in state, masking the complexity of causative processes (Langran, 1992, Hornsby and Egenhofer, 2000, Peuquet, 2002). *Identity-based change models*, particularly represented as a visual, iconic symbology, can help mitigate this shortcoming (Hornsby and Egenhofer 2000). These visual systems describe change by identifying the state of an object and defining the transitions between states. In fire research, an identity-based change model can allow the user to visualize trees as they are born, scarred by fires and die. More importantly, such a model can elucidate data uncertainty and facilitate independent interpretations.

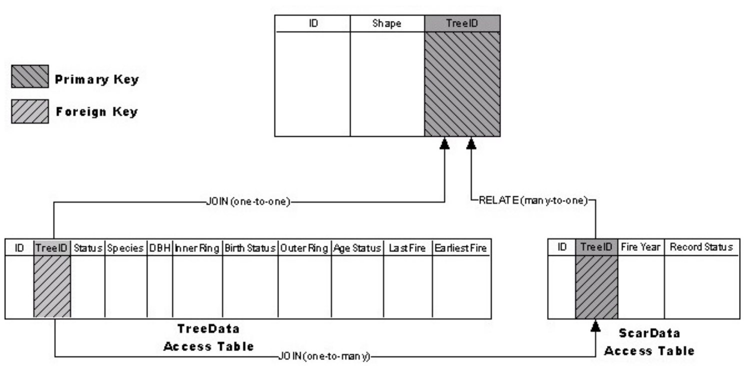

Figure 10—Structure of the relational fire history database.

The shortcomings of existing data structures challenge the creation of intuitive representations that allow users of GIS data to recognize significant spatio-temporal patterns and identify causative processes (Peuquet 2002). Current paradigms in geographic information science incorporate the traditional vector/raster dichotomy with *field and object models* for conceptualizing space (Cova and Goodchild 2002, Peuquet 2002). Representations of the spatial properties of historical fires have used a pure object approach (Baker and Kipfmueller 2001, Wright and Agee 2004), which imposes homogeneous extent and severity within a fire perimeter, rather than continuous varying attributes over space.

Integrated field-object representations may be optimal for illustrating the complex spatio-temporal process of fire in a format that is accessible to scientific analysis and interpretation toward management goals. A spatio-temporal data representation model should facilitate three levels of inquiry: (1) identification of temporal patterns, (2) identification of spatio-temporal trends, and (3) identification of underlying processes (Langran 1992). These correspond with the three levels of progressive information acquisition associated with indirect experience in human cognition: (1) retrieval of specific information, (2) retrieval of groups or subsets of entities, and (3) recognition of patterns and interrelationships (Peuquet 2002). Even the first level of information retrieval in fire research is problematic when spatial and temporal dimensions of data are not integrated.

6.3 Implementation

The integrated field-object paradigm guided the technical implementation of the GIS web server and database. The goals of ease-of-display and interpretability guided the web-user interface. The server combines the Windows 2000 Server operating system, an Apache web server, and ArcIMS software for data representation on the web. The key information and map displays are fire maps by year, by study area, with symbology indicating the status of trees (fig. 11). Key data delivery items include Microsoft Access relational databases for each study site and GIS layers, represented both as tabular information and shapefiles.

We have not exhausted the utility of these fire-history data for scientific research and applications to management. We view the ongoing support we are promising as a collaboration with land managers in eastern Washington, who are faced with complex, often conflicting prescriptions for fuel treatments and other activities. By providing a comprehensive accessible picture of historical fire regimes, which are frequently equated with “reference conditions,” the GIS web server and database facilitate the exploration of alternative scenarios for both fire-regime restoration and extreme fire management and control.

The data delivery format preserves the spatial and temporal complexity of these fire-history records in a way that would be extremely awkward in standard fire-history software (e.g., FHX2). Computations on the database, for example those used in the scientific publications associated with this project, are possible within Access or ArcGIS, or by exporting from these standard file formats to data analysis software.

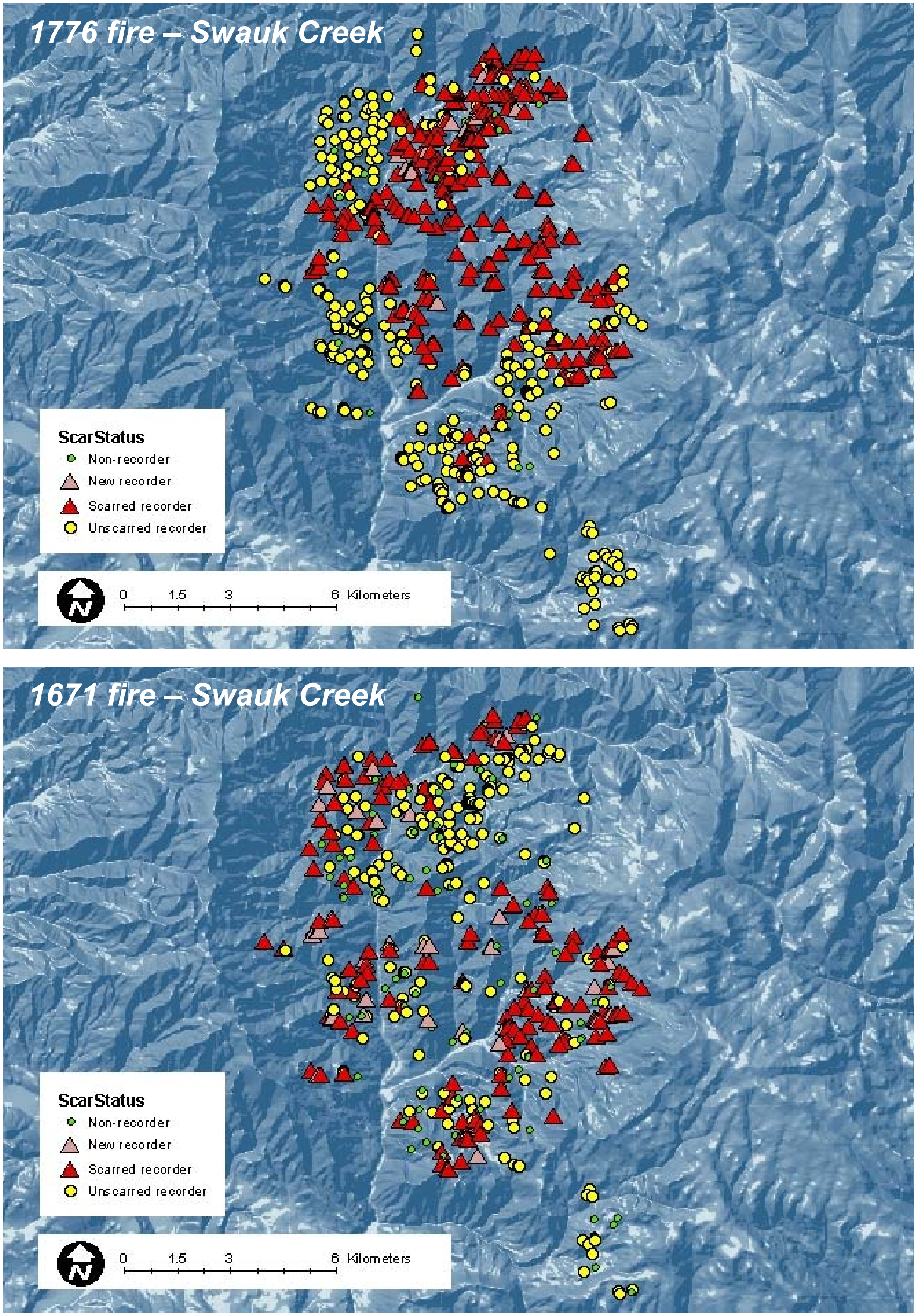

Figure 11—Spatio-temporal representation of fire years in Swauk Creek study area.

7 Publications and Presentations Associated with the Project

7.1 Publications

Hessl, A.E., J. Miller, J. Kernan, and D. Keenum. *In preparation*. Mapping spatial and temporal variability in wildfires from binary point data: comparing approaches. Professional Geographer.

McKenzie, D., A.E. Hessl, L-K.B. Kellogg, and A.M. Morgan-Martinez. *In review*. Using neutral models to identify constraints on low-severity fire regimes. Landscape Ecology.

McKenzie, D., and A.E. Hessl. 2005. A neutral model of low-severity fire regimes. In: Proceedings of the 2002 Fire Conference, USDA Forest Service General Technical Report PSW-GTR-189. *In press*.

McKenzie, D., Z.M. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18:890-902.

Hessl, A.E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14:425-442.

McKenzie, D., S. Prichard, A. E. Hessl, and D.L. Peterson. 2004. Empirical approaches to modeling wildland fire in the Pacific Northwest Region of the United States: methods and applications to landscape simulation. Chapter 7 in A.J. Perera and L. Buse, eds., Emulating Natural Forest Landscape Disturbances. Columbia University Press, New York, NY.

McKenzie, D. 2004. Fire history and its relation to climate. Chapter 1 in L. Villers-Ruiz and J Lopez-Blanco, eds. Forest Fires in Mexico. National Autonomous University of Mexico, Mexico City.

Kellogg, L-K.B. 2004. Quantifying spatial structures associated with low-severity fire regimes in the eastern Cascade Mountains of Washington, USA. Master’s Thesis, University of Washington, Seattle, WA.

7.2 Presentations

McKenzie, D., and C.M. Miller. 2004. Session chairs. Scaling laws in fire regimes: moving landscape fire history into the 21st century. A special session at the annual meeting of the International Association for Landscape Ecology. Las Vegas, NV.

McKenzie, D., A.E. Hessl, and L-K.B. Kellogg. 2004. Neutral landscape models, scaling laws, and constraints on fire regimes. International Association for Landscape Ecology. Las Vegas, NV.

McKenzie, D., and D.A. Falk. 2004. A null model for the temporal distribution of surface fire events. Ecological Society of America, Portland, OR.

Hessl, A.E., and D. McKenzie. 2004. Drought and pacific decadal oscillation linked to fire in the inland Pacific Northwest. Association of American Geographers, Philadelphia, PA.

Kellogg, L-K.B., D. McKenzie, and D.L. Peterson. 2004. Spatial structures associated with fire occurrence in low-severity fire regimes. International Association for Landscape Ecology. Las Vegas, NV.

Kernan, J., and A.E. Hessl. 2004. An evaluation of sampling designs in fire history reconstruction. Association of American Geographers, Philadelphia, PA.

McKenzie, D. 2004. Are there scaling laws in fire regimes? Aldo Leopold Wilderness Institute, Missoula, MT.

McKenzie, D., and A.E. Hessl. 2003. A neutral model of low-severity fire regimes. International meeting of the association for Landscape Ecology. Darwin, NWT. Australia.

McKenzie, D. 2003. Fire history and its relation to climate. International conference on forest fires and their environmental effects. National Autonomous University of Mexico, Mexico City.

Hessl, A.E., and D. McKenzie. 2003. Climatic variability, fire regimes, and carbon dynamics in dry forest ecosystems of the Western US. American Geophysical Union, San Francisco, CA.

Kernan, J., and A.E. Hessl. 2003. Targeting multiple fire-scarred trees during field location and data analysis: introducing bias or improving efficiency in fire reconstructions? Association of American Geographers, New Orleans, LA.

McKenzie, D., and A.E. Hessl. 2002. Climatic, topographic, and human influences on forest fire regimes in eastern Washington, USA. West Virginia University colloquium series, Morgantown, WV.

McKenzie, D. 2002. What is a neutral model of fire regimes. University of Arizona colloquium series.

McKenzie, D., and A.E. Hessl. 2002. A neutral model of low-severity fire regimes. San Diego Fire Conference, San Diego, CA.

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