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PRACTICES AND APPLICATIONS IN FIRE ECOLOGY

SPATIALLY HETEROGENEOUS ESTIMATES OF FIRE FREQUENCY IN PONDEROSA PINE FORESTS OF WASHINGTON, USA

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ABSTRACT

Many fire history studies have evaluated the temporal nature of fire regimes using fire interval statistics calculated from fire scars. More recently, researchers have begun to evaluate the spatial properties of past fires as well. In this paper, we describe a technique for investigating spatio-temporal variability using a geographic information system (GIS). We used a dataset of fire-scarred trees collected from four sites in eastern Washington, USA, ponderosa pine (*Pinus ponderosa* C. Lawson) forests. The patterns of past fires recorded by individual trees (points) were converted to two-dimensional representations of fire with inverse distance weighting (IDW) in a GIS. A map overlay approach was then used to extract a fine-grained, spatially explicit reconstruction of fire frequency at the four sites. The resulting classified maps can supplement traditional fire interval statistics and fire atlas data to provide detailed, spatially heterogeneous estimates of fire frequency. Such information can reveal ecological relationships between fire and the landscape, and provide managers with an improved spatial perspective on fire frequency that can inform risk evaluations, fuels reduction efforts, and the allocation of fire-fighting resources.

Keywords: fire frequency, GIS, inverse distance weighting, *Pinus ponderosa*, ponderosa pine, spatial, Washington state

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INTRODUCTION

Fire is a key ecological process as it interacts with other processes (Agee 1993, Dale *et al*. 2001); controls landscape patterns and species diversity (Swetnam and Betancourt 1997, Norman and Taylor 2003, Haire and McGarigal 2009); influences resource availability, nutrient cycling, water yield, mass wasting, and erosion (Agee 1993); affects air quality (Sampson *et al*. 2000); and may exert climate feedbacks (Houghton and Hackler 2000, Westerling *et al*. 2006). Given the significant role of fire in natural systems, there is continued discussion among managers, scientists, and the public regarding fuel management, prescribed fire, and the suppression of wildfires (Hunter 1993, Agee 1997, Allen *et al*. 2002, Nash 2003). Reconstructing fire regimes can guide fuel reduction and controlled burns to reduce fire risk, inform decisions for controlling wildfires, and provide targets for ecological restoration (Allen *et al.* 1995, Fulé *et al.* 1997, Swetnam and Betancourt 1997, Morgan *et al*. 2001, Parsons *et al.* 2007, Brown *et al.* 2008). Furthermore, reconstructions can characterize the range of natural variability in fire frequency and extent to help scientists distinguish between climatic and anthropogenic influences on fire (Swetnam and Westerling 2003), define the factors that control fire (Heyerdahl *et al.* 2001, Hessl *et al.* 2004), evaluate the relationship between forest structure and fire (Beatty and Taylor 2001), and predict process-driven vegetation responses to a changing climate (Brown 2006). Natural variability has been discussed in the context of its applications and limitations in management, most notably in a series of papers in *Ecological Applications* in 1999 (volume 9 number 4). Many authors concluded that, at a minimum, an understanding of natural variability can guide broad management objectives in many dry forests in the western United States (Cissel *et al.* 1999, Landres *et al.* 1999, Moore *et al.* 1999, Swetnam *et al.* 1999). More recent literature has continued to discuss the importance of reconstructing patterns of natural variability to inform management decisions (Baker and Kipfmueller 2001, Morgan *et al*. 2001, Allen *et al.* 2002, Hessl *et al*. 2007, Lombardo *et al.* 2009).

Many fire history investigations have emphasized the temporal aspects of historical fire regimes (Allen *et al.* 1995, Baker and Kipfmueller 2001, Parsons *et al.* 2007). This may be due in part to the inherent spatial uncertainty of available data sources, such as fire-scarred trees and charcoal sediment, which may challenge spatial reconstructions. Not all fires are recorded by fire scars; the area represented by sediment deposits may be spatially ambiguous, and scars and sediments may be lost through natural processes (Kilgore and Taylor 1979, Fall 1998, Baker and Ehle 2001, Van Horne and Fulé 2006, Parsons *et al.* 2007). As a result, data can be incomplete and may incorporate false negatives (unrecorded fires or destroyed scars) in both spatial and temporal inquiries, potentially underestimating fire size and frequency (Baker and Ehle 2001, Collins and Stephens 2007). Regardless of these uncertainties, investigations of historical fire regimes that use fire scar data often discuss fire occurrence (Swetnam and Betancourt 1997, Hessl *et al.* 2004) or fire frequency (McBride 1983, Grissino-Mayer 1999, Everett *et al.* 2000, Heyerdahl *et al.* 2001) as summary measures of fire regimes. Fire frequency, often expressed as a fire interval, provides a site-scale estimate of the prevalence of fire, and allows generalized comparisons between sites. However, such measures do not provide the spatially explicit data needed for comprehensive ecological analyses and informed management (Heyerdahl and Card 2000, Baker and Kipfmueller 2001).

Fire Interval Statistics

Fire interval statistics have been used for decades to describe surface fire regimes recorded by fire scarred trees (Agee 1993, Baker and Ehle 2001). Mean fire interval (MFI) is commonly used to estimate fire frequency (Agee 1993, Heyerdahl 1997, Baker and Ehle 2001). A mean point fire interval (MPFI) is calculated from a single tree, indicating fire frequency at that point (Agee 1993). The MPFI is susceptible to false negatives (Kilgore and Taylor 1979, Fall 1999, Baker and Ehle 2001), as fires may not be recorded or scars may be lost by subsequent fires, so this measurement may overestimate fire interval. Sampling several trees in close proximity, averaging the MPFIs, and treating them as a point (Agee 1993) may help address such false negatives. However, a tree or a cluster of trees only records fire at a single location on the landscape, and may not represent broader areas. MPFI has been described as a minimum measure of fire interval (estimates longer fire intervals), and may provide a conservative measure of fire frequency (Baker and Ehle 2001).

Composite mean fire intervals (CMFI) are calculated by incorporating fire scars from multiple trees in a master list (Agee 1993). The CMFI can offset the occurrence of some false negatives in that most events in a low-severity surface fire regime should be recorded by at least one tree, potentially identifying new intervals that cannot be accounted for using MPFI. The CMFI can also represent broader areas, but is scale sensitive (McKenzie 2000, McKenzie *et al.* 2006). The larger the study area, the more fire events are incorporated and the lower the CMFI; thus, CMFI may represent a maximum estimation (estimates shorter fire intervals) of fire frequency (Baker and Ehle 2001). However, CMFI homogenizes the fire interval within the study area and does not allow finer grain analyses. Compositing is also performed by analyzing subsets of data based on how many trees recorded a given fire event. Researchers have analyzed widespread fires that scarred ≥25 % of trees (Grissino-Mayer *et al.* 2004, Gonzalez *et al.* 2005), and fires that scarred ≥50 % of trees to isolate large fire events (Barton *et al.* 2001). Hessl *et al.* (2004) composited fire years that scarred ≥10 % of trees to eliminate small spot fires, and fire years that scarred ≥25 % of trees to identify regional fires. This method can prevent estimates of extremely short fire intervals and, assuming spatially uniform sampling, provides information about the relative extent of given fire events.

Spatial Reconstruction of Wildfire Boundaries

Over the past few decades, there has been an increasing trend in using spatial representations of fire in conjunction with traditional statistical approaches (Everett *et al.* 2000, Kellogg *et al.* 2008, Haire and McGarigal 2009 among others) to provide a spatially explicit context that can inform management decisions (Heyerdahl and Card 2000, Morgan *et al*. 2001, Baker and Kipfmueller, 2001). Morgan *et al*. (2001) reviewed wildland fire mapping and discussed four methods: rule-based maps derived from fire history data, modeled maps, atlases (for contemporary fire regimes), and the interpretation of fire scar data to infer relative fire extents. The authors presented a broad overview of the role of mapping in management and science and affirmed the usefulness of mapping fire regime parameters.

In this paper, we review a very specific aspect of wildland fire mapping, the reconstruction or estimation of fire perimeters in the context of fire history research. The review was not intended to be exhaustive, but to sample a range of approaches and identify representative studies. Our discussion then focuses on the methods of mapping perimeters in order to demonstrate the usefulness of a geographic information system (GIS) approach that integrates spatial and temporal data. We identified four methods for mapping fire perimeters that were frequently described (Table 1). First, there have been numerous studies in regions with high-severity fire regimes in which the authors reconstructed fire boundaries using stand age mapping, often in conjunction with fire scar data (Heinselman 1973, Hemstrom and Franklin 1982, Romme 1982, Agee *et al*. 1989, Duncan and Stewart 1991, Agee and Krusemark 2001, Baker and Kipfmueller 2001, Hessburg *et al*. 2005) (Table 1). The frequent application and longevity of this approach speaks to its strength; the use of stand boundaries (particularly in conjunction with fire scar data) likely produces fairly accurate perimeters. However, this method is not transferable to low-severity fire regimes that lack stand replacing fires and may have homogeneous stand ages over broad areas. Furthermore, the tendency for large stand replacing fires to elimi-

Table 1. Summary of four methods for mapping fire perimeters that appear frequently in fire history literature.

Method	Strengths	Weaknesses	Representative Studies
Stand age	Accurate reconstruction of recent fires with stand boundaries.	Limited to stand replacing or mixed fire regimes. Older fires may not be captured.	Heinselman 1973 Hemstrom and Franklin 1982 Romme 1982 Agee *et al*. 1989 Duncan and Stewart 1991 Agee and Krusemark 2001 Baker and Kipfmueller 2001 Hessburg *et al*. 2005
Fire scar and topography (expert)	Based on expert knowledge.	May be very subjective. May not be reproducible in other ecosystems.	Cissell *et al*. 1999 Everett *et al.* 2000 Niklasson and Granstrom 2000 Beatty and Taylor 2001 Heyerdahl *et al*. 2001
Fire atlas remote sensing	Accurate reconstruction of recent fires.	Limited to recent fire history. Records may be inconsistent.	Turner *et al*. 1994 Rollins *et al.* 2001 Moritz 2003 Collins and Stephens 2007 Miller *et al.* 2007 Farris *et al*. 2008 Morgan *et al*. 2008 Wittkuhn and Hamilton 2010
GIS mapping	Objective and reproducible.	Requires large georeferenced datasets.	Heyerdahl *et al.* 2006 Hessl *et al*. 2007 Shapiro-Miller *et al*. 2007 Farris *et al.* 2010

nate earlier stands may result in shorter reconstructions. Second, fire perimeters have been reconstructed from fire scars using an expert approach (Cissel *et al*. 1999, Everett *et al*. 2000, Niklasson and Granstrom 2000, Beatty and Taylor, 2001, Heyerdahl *et al*. 2001) (Table 1) as described by Hessl *et al.* (2007). In these cases, the authors delineate fire perimeters based on the scarring characteristics of trees and expert knowledge on the fire regime, ecology, and topography. While this approach provides expert-based reconstructions, the decision-making process may not be transparent and may not be readily reproducible. Third, many reconstructions have used fire atlas or remotely sensed data to analyze the spatial nature of fire regimes (Rollins *et al.* 2001, Moritz 2003, Collins *et al.* 2008, Farris *et al*. 2008, Morgan *et al.* 2008) (Table 1). Lastly, recent studies have used GIS to reconstruct fire perimeters from fire scar data (Heyerdahl *et al*. 2006, Hessl *et al*. 2007, Shapiro-Miller *et al*. 2007, Farris *et al.* 2010) (Table 1). Heyerdahl *et al.* (2006) and Shapiro-Miller *et al*. (2007) constructed convex hulls around fire scarred trees to reconstruct fire perimeters. Farris *et al.* (2010) generated Thiessen polygons, constructing area features around scarred trees (similar to convex hulls) to represent perimeters. Hessl *et al*. (2007) evaluated several mapping approaches, including the expert approach; kriging, which models a geostatistical representation of fire boundaries; Thiessen polygons, which construct area features around scarred trees (similar to convex hulls); and inverse distance weighting (IDW), which spatially interpolates fire boundaries. The authors recommend IDW as it was accurate, produced perimeters that represented the ecological patterns produced by wildfire, and emphasized local similarities in scarring characteristics. The GIS approach presented in our work uses the IDW method for reconstructing fire perimeters.

Although there is a long history of reconstructing fire perimeters, less has been done to integrate the spatial representations with temporal measures of fire frequency. This can be addressed with a spatially explicit method for calculating and representing MFI, or a spatial mean fire interval (SMFI), to improve the assessment of spatio-temporal heterogeneity of fire regimes by enabling finer grain analyses of the causes and effects of fire within study areas. An SMFI could also be visually represented in the form of a map, improving the accessibility to users with different levels of expertise (Tang and Bishop 2002). Furthermore, while an SMFI cannot address false negatives associated with fires that left no scar evidence, it may compensate for low-severity fires that may have burned over broad areas and scarred few trees, as the method estimates fire perimeters over an area based on a set of scarred trees.

Objective

In this paper, we describe a method for generating an SMFI using a GIS and fire scar data collected in ponderosa pine (*Pinus ponderosa* C. Lawson) forests in Washington state, USA, on eastern slopes of the Cascades and in the Selkirk Range. These sites have been previously investigated in the context of fire history, climate-fire relationships, and topography-fire relationships (Everett *et al*. 2000, Hessl *et al.* 2004, McKenzie *et al.* 2006, Kellog *et al.* 2008), and Hessl *et al.* (2007) discussed a GIS approach for estimating fire perimeters using these data. This paper extends the application of GIS to fire scar data using a spatial approach similar to methods described by Baker and Kipfmueller (2001), Moritz (2003), and Wittkuhn and Hamilton (2010). However, Baker and Kipfmueller (2001) used stand-age data and orthophotos to define fire perimeters, and defined fire boundaries based on image properties. Wittkuhn and Hamilton (2010) also describe "digitizing fires" and using existing GIS datasets of fire perimeters. This method is best suited to areas with high-severity, stand-replacing fire regimes. Moritz (2003) used mapped perimeters of modern fires and focused his inquiry on the recent fire regime in a chaparral ecosystem. The method presented in this paper is based on spatially interpolated fire scar point data, and is novel in that it reconstructs spatially continuous two-dimensional estimates of fire frequency. This extends Baker and Kipfmueller's (2001) and Moritz's (2003) approaches to regions with frequent low-severity fires. This is significant in that estimating fire extent in low-severity fire regimes has been problematic (Morgan *et al*. 2001, Rollins *et al.* 2001, Jordan *et al.* 2005, Shapiro-Miller *et al.* 2007). Furthermore, the GIS approach provides data that can supplement statistical methods (MPFI, CMFI) that represent discrete point locations, may be influenced by false negatives, or are scale sensitive, and fire atlas data that may be temporally limited. Collins and Stephens (2007) compared fire scar reconstructions with fire atlas data in the Sierra Nevada, California, USA, and described a tendency for fire scar data to produce longer fire rotations than fire atlas data. However, Fulé *et al.* (2003) found a strong correspondence between fire scar records and fire atlases, and Shapiro-Miller *et al.* (2007) found that fire perimeters generated from fire scars were statistically similar to fire atlas records, and that reconstructed perimeters compensated for lapses in fire atlas record-keeping. Farris *et al.* (2010) suggested that spatial reconstructions based on fire scars may be more useful than previously discussed. After describing the GIS approach, the remainder of this paper focuses on discussing how SMFI differs from statistical methods in the context of sampling design, data characteristics, and the landscape. We conclude by discussing how the SMFI may provide a tool to support management decision-making, much as fire atlases are used to provide spatial data about the more recent past.

METHODS

Study Sites and Data

Ponderosa pine forests in Washington are distributed in a 15 km to 30 km wide band on the east slope of the Cascade Range, extending into a broader range in the northeastern part of the state in the Selkirk Range. Ponderosa pines grow between 600 m to 1200 m in elevation, and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.) dominate higher elevations (Franklin and Dyrness 1988). We investigated four study sites in this ponderosa pine region, spanning a latitudinal gradient from 48º 45' N in the northeast to 46º 52' N in the southwest, a distance of 275 km (Figure 1). Mean annual temperatures range from 8.3 ºC (Colville, Washington station 48º 33' N, 117º 54' W) to 8.7 ºC (Ellensburg, Washington station 47º 02' N, 120º 31' W) from the northeastern to southwestern portions of the gradient (WRCC 2008). Average total annual precipitation ranges from 43.5 cm yr^{-1} in the northeast to 22.5 cm yr^{-1} in the southwest. Thus climate is warmer and drier in the southwest, and cooler and wetter in the northeast. Precipitation is concentrated in the winter months and peaks in December (WRCC 2008), typical of the eastern Cascades region that is heavily influenced by a rain-shadow effect.

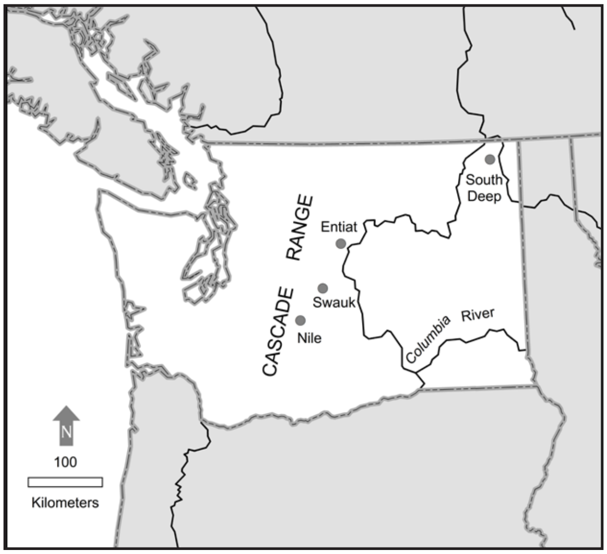

Figure 1. Approximate location of study sites in eastern Washington state, USA.

Staff at the Forest Service's Forestry Sciences Laboratory in Wenatchee, Washington, collected the fire scar data using a stratified sampling method designed to obtain the greatest number of fire-scarred trees from the broadest range of topographic settings (Everett *et al.* 2000). Study sites were divided into topographic facets with homogeneous slope and aspect using aerial photographs and topographic maps. These facets were further subdivided based on fine scale topographic features (i.e., stream divides, draws) to ensure the distributed sampling of trees. Subdivisions were field searched for fire-scarred trees, and quarter cross-sections were removed with a chainsaw. Samples were collected from 1559 trees, incorporating more than 11 000 fire scars (Figure 2). Tree locations were recorded in the field using topographic maps, pocket transits, and altimeters. Although this method of georeferencing allows for variation in accuracy and precision, the potential error for individual tree locations is small given the size of fire events and density of fire-scarred trees. Samples were processed in the laboratory and fire scars were dated using standard dendrochronological methods (Stokes and Smiley 1968, Everett *et al.* 2000). Finally, the tree locations were entered into a GIS shapefile as point features, and attributes describing species, inner- and outermost dated rings, and earliest and last fires were assigned to each point.

GIS Data Processing and Analysis

We selected a subset of these raw fire scar data to develop a supplemental approach for interpreting spatio-temporal variability of pa-

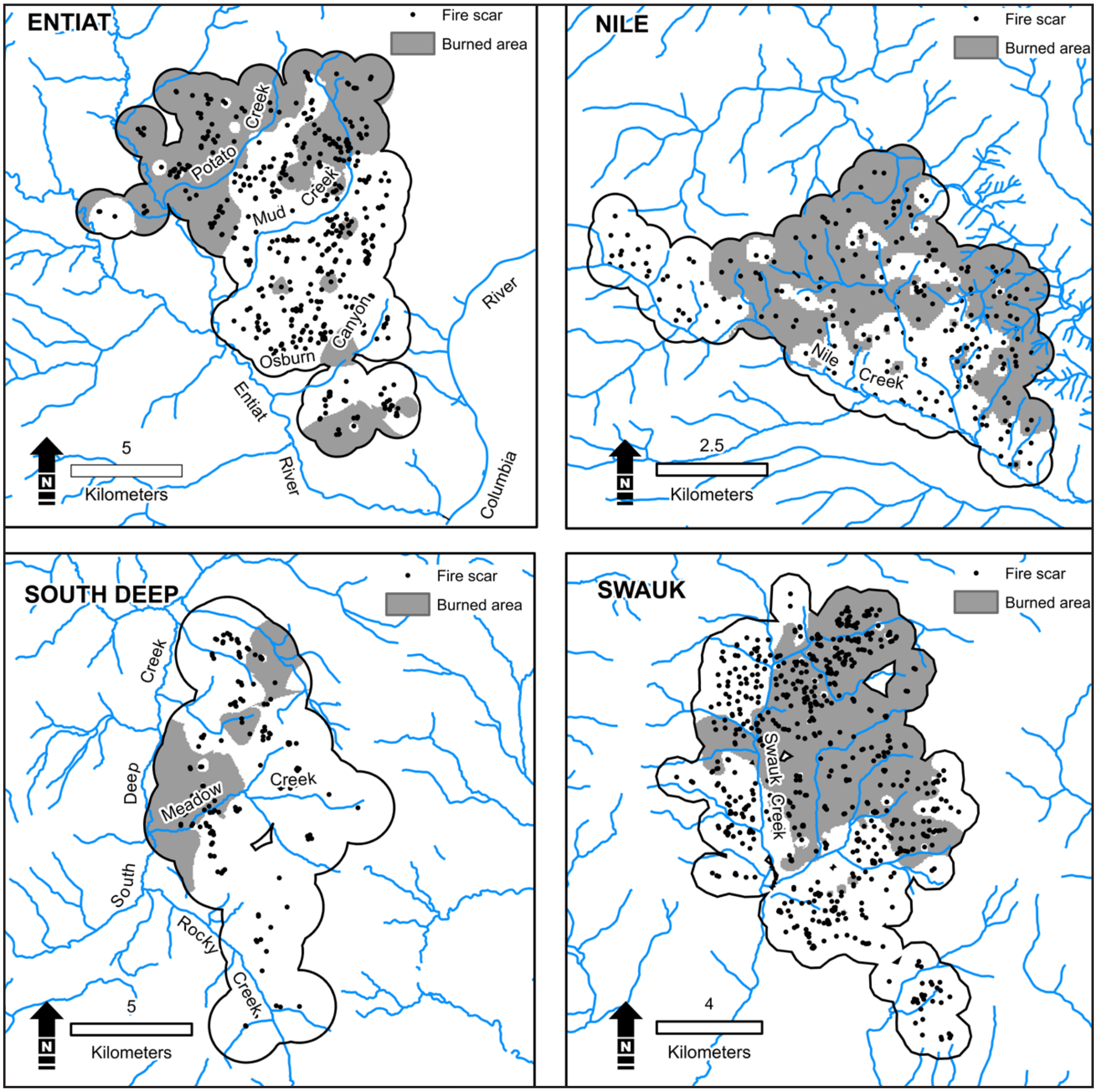

Figure 2. Study sites illustrating sampled fire-scars (black dots). In each map, the gray area represents an estimated fire perimeter for the year 1776. The perimeters were produced using inverse distance weighting to produce interpolated surfaces from the fire-scar point data. The resulting surfaces were used to generate the spatial mean fire interval (SMFI) for the four sites.

leo-fires. The period between 1700 and 1850 was analyzed, as the number of live trees able to record fires (recorders) declines prior to 1700, and the mean time between fire events is known to have increased in the region following Euro-American settlement in the mid 1800s (Everett *et al.* 2000). Therefore, the selected time frame maximizes sample depth and minimizes the impacts of logging, land use change, and twentieth century fire suppression, facilitating the analysis of the pre-European fire regime. Although it is well-documented that Native Americans modified the landscape through the use of fire and horse grazing in the region (Robbins and Wolf 1994), their influence on fire regimes was not addressed in our work. Furthermore, the effect of native peoples on fire regimes is complicated by changes in population during epidemics and recovery periods. Denevan (1992) argues that the landscape in much of the Americas was humanized prior to the arrival of European explorers in the late fifteenth century. Early epidemics decimated native populations, and succession resulted in more natural landscapes during the seventeenth century settlement period. Historical records for the Pacific Northwest compiled by Robbins and Wolf (1994) appear contrary to this concept. Early settlers reported an open, managed landscape and directly observed Native Americans using fire. Although anecdotal reports of smallpox were documented, to our knowledge there does not appear to have been a significant population decline. Source data for this period of analysis included 1517 trees recording 7858 scars (Table 2), resulting in an average sampling density of 0.035 trees ha^{-1}. Fire events that scarred less than four trees were excluded from the analysis to eliminate small spot fires or non-fire injuries.

Next, we added a new field to each study site attribute file for each fire event that occurred during the period of analysis. Every fire-scarred tree was coded to indicate if it scarred or not (0 = unscarred, 1 = scarred) during each event. The MPFI was then calculated and entered for each tree (point) to serve as a reference for comparing the SMFI. Finally, we generated study area boundaries for each site by buffering the set of points by the minimum distance necessary to create a single polygon. We evaluated the potential bias of edge effects using methods similar to McKenzie *et al.* (2006). Convex hulls were constructed around the sampled trees for each study site. Euclidean nearest-neighbor distances were calculated and were used to create interior buffers on the convex hulls, eliminating the unsampled edge and isolating the site interior. Analyses were performed on each site for the entire area and for the interior to determine the degree of edge effects. Average SMFI was compared for the entire area and the buffered interior for each study site to determine the degree of edge effect.

We then converted the point data to two-dimensional representations by performing inverse distance weighting (IDW) on the binary codes assigned to each point for each fire year, *sensu* Hessl *et al.* (2007). Only fire events that scarred four or more trees at each site during the period of analysis were processed (n = 187) as events recorded by fewer trees could represent small spot fires or non-fire injuries. The resulting continuous surfaces, with a 50 m cell resolution, represented the likelihood that each cell had burned during each fire event.

Estimated fire perimeters were then extracted from the burn likelihood surfaces (n = 187). First, the continuous surfaces representing the likelihood that each cell burned were converted to binary surfaces (0 = unburned or 1 = burned) representing estimated fire perimeters (Hessl *et al.* 2007). Perimeters were estimated by selecting cells that exceeded a threshold proportional to the percent of live, fire-scarred trees that recorded a scar during each event relative to the total number of living fire-

Table 2. Location, area, sample size, and fire events for the four Washington study sites. Fire events were included if they scarred four or more trees during the period of analysis, 1700-1850.

Site	Latitude (N)	Longitude (W)	Area (ha)	Trees	Scars	Fire events
Entiat	47° 48’	120° 20’	15 708	469	1 988	45
Nile	46° 52’	121° 05’	4 033	232	1 446	44
South Deep	48° 45’	117° 40’	10 809	151	296	16
Swauk	47° 15’	120° 38’	12 644	665	4 128	82
Total			**43 194**	**1 517**	**7 858**	**187**

scarred trees, or potential recorders. This method has been used in predictive ecological studies addressing fire (Hessl *et al*. 2007), vegetation mapping (Franklin 1998), and land cover studies (Pontius and Batchu 2003). We used map overlay operations to produce the SMFI. First, the estimated fire perimeter surfaces were combined into a single surface indicating the total number of fires for each cell (numfire). An arithmetic operation (numfire – 1) reassigned cell values to indicate the total number of fire intervals (numfireinterval). Next, the time between the first and last fires was calculated for each cell. A final surface was constructed by dividing this time by the number of fire intervals (time/numfireinterval), representing the SMFI for each cell.

Next, area burned was also calculated for every reconstructed fire perimeter for each site. We also calculated descriptive statistics (mean and standard deviation) for the SMFI maps to compare with the results generated from the point data for MPFI, CMFI (all trees for each site composited), and for a composited dataset of fire events that scarred ≥20 % of all recorder trees for each site. Because the GIS approach estimates fire frequency from perimeters generated from clusters of trees rather than an average of all intervals within the site, we expected that the SMFI would be less sensitive to scale dependency at the site level and would produce a longer average fire interval than a CMFI estimated from points.

We reclassified the SMFI surfaces in the GIS to produce generalized fire frequency maps. Initially, a natural breaks classification was used to objectively classify clusters of cells that had statistically similar SMFI values. As the distribution of fire intervals differed among study sites, the reclassification resulted in different class breaks for each site. However, with the exception of the South Deep site, classes were very similar. As such, maps were reclassified using manual breaks based on the average natural class breaks, so that the four sites could be compared. These reclassified maps were visually interpreted in the context of the landscape, using hillshade models derived from digital elevation models (DEMs).

RESULTS

Fire interval results indicate different patterns of variability among the four sites (Table 3). Most significantly, South Deep burned least frequently. Average SMFI, MPFI, and CMFI were the highest among sites, indicating fire intervals of 45 yr, 58 yr, and 9 yr, respectively. Furthermore, only five large fires (>20 % scarred) occurred at South Deep, and these larger fires also occurred less frequently (Table 3.). This may be due partly to the fact that South Deep did not have as many samples as the other sites (Figure 2). Only 151 trees (density = 0.014 ha^{-1}) were sampled. However, the high MPFI (58 yr) indicates that fewer

Table 3. Fire interval statistics for the four study sites. Results are for all fires occurring between 1700 and 1850 that scarred four or more trees. Statistics include spatial mean fire interval (SMFI) and standard deviation (SD) derived from the GIS, mean point fire interval (MPFI) and standard deviation (SD), and mean fire interval (CMFI) and standard deviation (SD) derived from the original point data. Minimum and maximum values are shown in parentheses for SMFI, MPFI, and CMFI. The number and average return interval for large fires (>20 % scarred) are also shown.

		Point data				>20 % Scarred		
Site	**SMFI**	**SD**	**MPFI**	**SD**	**CMFI**	**SD**	**Fires**	**Interval**
Entiat	13.1 (6, 20)	8.35	57.3 (10, 144)	44.1	3.3 (1, 9)	2.0	20	7
Nile	17.0 (6, 150)	10.2	46.2 (8, 150)	39.9	3.3 (1, 8)	2.1	13	10
South Deep	45.3 (14, 131)	33.4	58.1 (14, 145)	38.6	9.3 (1, 28)	7.5	5	26
Swauk	15.8 (3, 148)	9.4	39.3 (8, 144)	32.1	1.8 (1, 6)	1.0	9	14

fires were recorded on individual trees, suggesting that the area did in fact burn less frequently. Fire sizes ranged from 300 ha to 9000 ha, with a mean of 2460 ha. The Entiat site had more large fires and the largest mean fire size. Swauk and South Deep fires were smaller than at Entiat, and the Nile site had the smallest fires. Although this gives some indication of fire sizes in the region, many of the fires extended beyond site boundaries, thus the values are sensitive to the extent of the study sites.

The distribution of SMFI values for individual cells illustrates the range of variability relative to statistical measures of central tendency (mean CMFI, SMFI and MPFI) (Figure 3). Swauk had the broadest distribution and was bimodal with peaks at ~11 yr and ~15 yr.

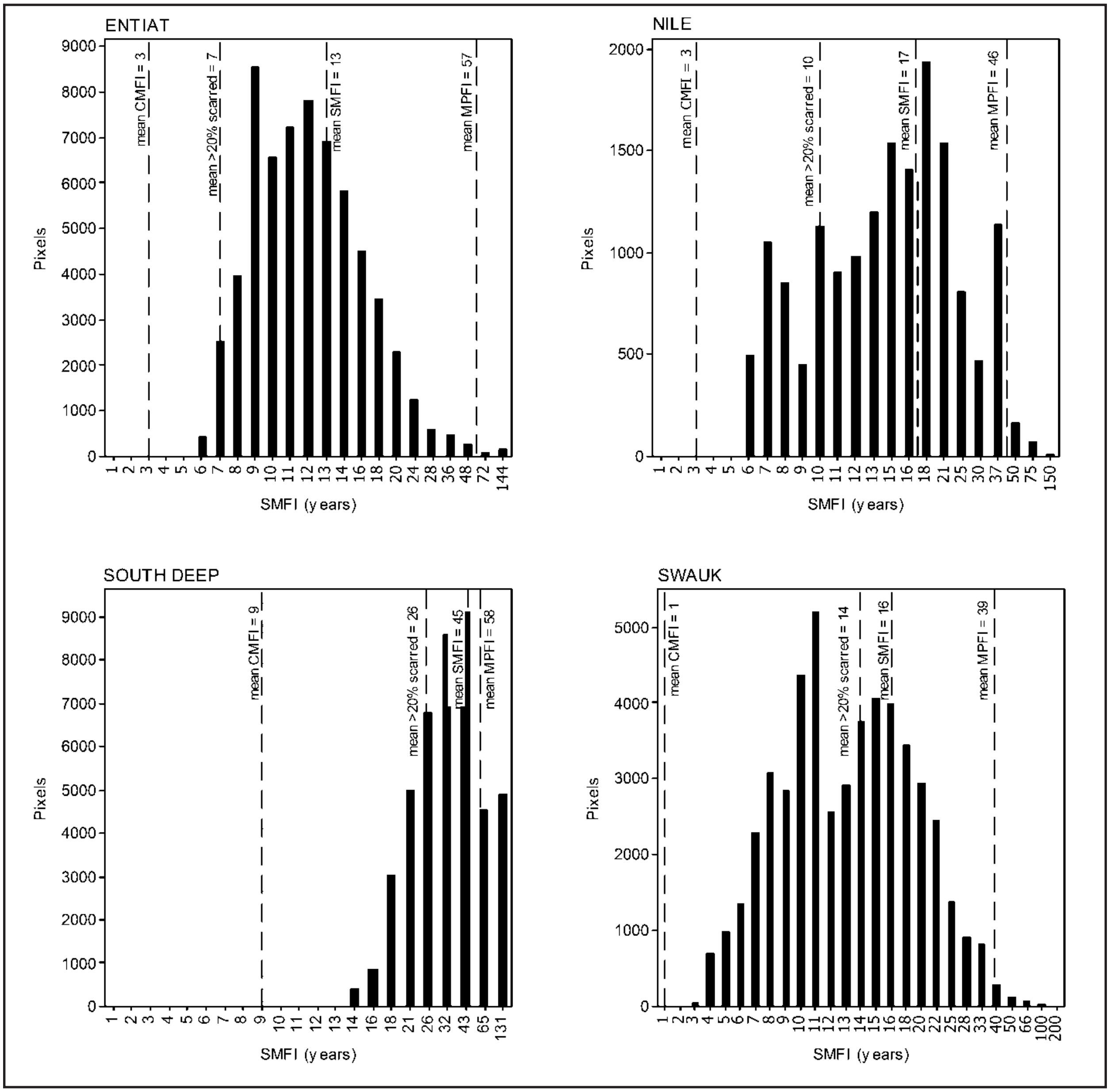

Figure 3. Distribution of spatial mean fire interval (SMFI) values for raster layers for the four study sites. Dashed lines represent mean values for traditional statistical measures of fire frequency (CMFI and MPFI), mean interval at which larger fires (>20 % scarred) burned, and the mean SMFI for each site. Mean SMFI consistently represents a fire interval between CMFI and MPFI.

The Nile site had a multimodal distribution with peaks at ~7 yr, ~17 yr, and ~37 yr. Entiat had a slightly right-skewed distribution, while South Deep had the narrowest distribution and a slight left skew. In all sites, CMFI was low and outside of the distribution of SMFI values, confirming the tendency of CMFI to estimate low fire intervals. The MPFI was at the upper end of the distribution for all sites, confirming the tendency for this statistic to estimate higher fire intervals (Baker and Ehle 2001).

SMFI values were also calculated for the site interiors. The interior buffers of the convex hulls were used to perform a zonal average on the total site SMFI. Although the total number of grid cells was reduced by 10% to 25% for the interiors, there was no difference between interior and entire site SMFI values for Entiat, Nile, or Swauk, suggesting minimal edge effects. The average SMFI for the South Deep interior did increase from 45 yr to 49 yr. South Deep had the largest study site buffer and lowest sampling density, explaining this slight edge effect.

Although no statistical tests of topographic relationships were performed, a visual inspection of the SMFI maps suggested that topographic factors may influence fire variability on the east slope of the Cascade Range in Washington, particularly in Swauk and Nile (Figure 4). The SMFI maps indicate that areas that burned more frequently appear to be located along main stream valleys, while areas that burned least frequently were in higher elevations separated from stream valleys by ridges, or located near the headwaters of tributary streams.

DISCUSSION

Entiat had the second highest MPFI, but an intermediate CMFI (3 yr) and the lowest SMFI (13 yr). This can be explained in part by the occurrence of larger fires at Entiat, and to the scarring characteristics of the recorder trees. First, the highest number of large fires (scarring ≥20% of trees, *n* = 20 fires) occurred at this site. In the interpolation process, larger fires predict burning over a broad portion of the study area, compensating for false negatives that may affect statistical estimates. During the overlay process, many instances of these large fires (numerous cells indicating the presence of fire) were incorporated into the average SMFI, estimating more frequent burning for the entire site. Therefore, the spatial interpolation method represents the influence of larger fires on site-level fire frequency differently than statistical measures. Furthermore, the Entiat site had a large cohort of trees (*n* = 60) that established after 1700 and recorded only one or two fires during the period of analysis. It is expected that the high number of trees with few scars strongly influenced the MPFI at Entiat. More importantly, the maps reveal that many of these infrequent recorders were in high elevation areas removed from stream corridors, indicating that there may be areas of refuge where trees are isolated from exposure to fire for long periods of time. These results suggest that the statistical measures (MPFI and CMFI) may be more sensitive to data trends such as high numbers of trees that record few scars than is the SMFI.

The SMFI indicates that fire burned most frequently at the Entiat site (13 yr). Hessl *et al.* (2004) arrived at the same conclusion, although they used different selection criteria for fire events (≥10% of all trees scarred) and different periods of analysis (1700 to 1900 and 1901 to 1990). The southernmost sites, Swauk and Nile, also tend to burn frequently. Their SMFI values of 16 yr and 17 yr, respectively, are similar to the fire regime at Entiat. However, MPFI and CMFI tend to be lower, suggesting more frequent fires. Again, it is expected that this was partially due to the cohort of younger trees at the Entiat site. Swauk and Nile also have a wide range of values and approximate a normal distribution (Figure 3). This suggests that these sites do burn at an average of 16 yr to 17 yr. However, portions of

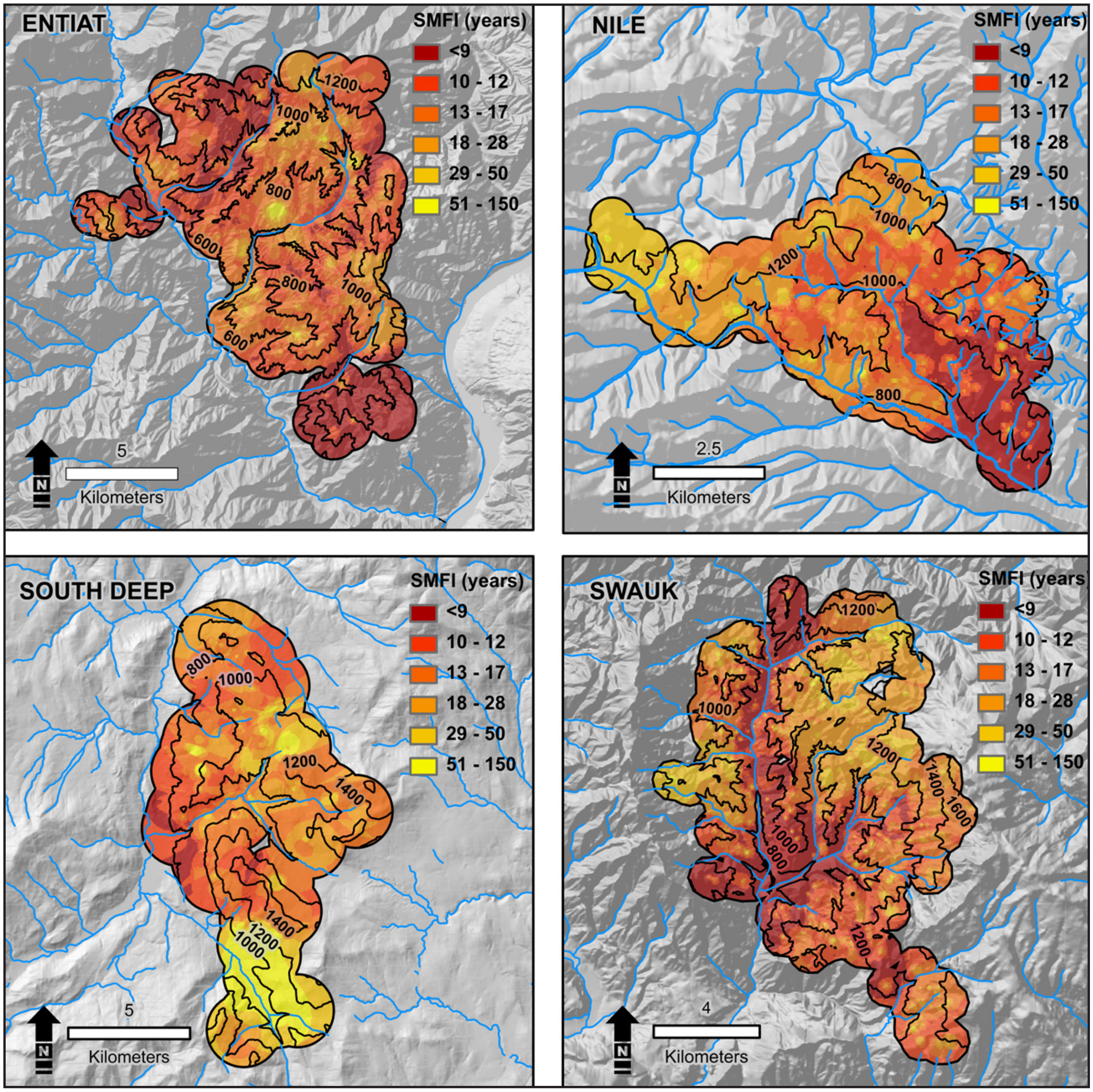

Figure 4. Spatial mean fire interval (SMFI) maps for Washington state study sites illustrating areas that burn most frequently in red shades and areas that burn least frequently with yellow shades. Reference contour lines are shown in black and labeled in meters.

each site did burn much more frequently (every 3 yr to 6 yr) and much less frequently (>50 yr). Areas that burn more frequently may either have different fuel characteristics related to microclimate (i.e., proximity to a stream accelerating fuel accumulation), or a greater likelihood of ignition, either natural or anthropogenic. The slight right skew in the Entiat data reflects the tendency of this site to burn frequently (Figure 3). Over 35% of Entiat burns at an interval ≤10 yr, while only 31% of Swauk, 25% of Nile and 0% of South Deep burn this frequently. Finally, the left skew in South Deep supports the conclusion that this site tends to burn less frequently (Figure 3).

The SMFI maps suggest that topography may influence both the variation in fire frequency between sites and the spatio-temporal variability within individual sites. The portions of the landscape that burned most frequently were adjacent to main stream channels, and areas that burned less frequently were separated from streams by ridges, or located in high elevation sites with complex topography. These patterns were most evident in the Swauk and Nile sites, and to a lesser degree in Entiat (Figure 4). This interpretation is supported by a study of topographic controls conducted on seven sites in eastern Washington, including the four sites investigated in this paper (Kellogg *et al.* 2008). The authors statistically analyzed the spatial structure of fire in relation to topography, and concluded that more complex topographic settings exerted a stronger control on the fire regime. Although we present broad interpretations of the SMFI maps to demonstrate the potential use in defining fire regimes, further analysis may extend the work done by Kellogg *et al*. (2008) by quantifying the relationships between fire and specific topographic features such as streams and ridges.

While interval statistics such as MPFI and CMFI generalize the temporal variability to a single number and do not represent site variability, the SMFI maps illustrate spatial heterogeneity, enabling finer-grained interpretations of fire patterns. The Swauk site, which encompasses the headwaters of Swauk Creek, is almost entirely encircled by a high ridge. The area that burned most frequently follows the Swauk Creek corridor from south to north through the western side of the site. Swauk Creek cuts through this encircling ridge in the southwestern portion of the site, and may be the point of entry for fire to burn into the enclosed area. It is possible that ignitions occur further downstream and burn upslope, following the stream valley into the headwaters region. The Nile demonstrated a similar relationship between variability in the fire regime and the landscape (Figure 4). The area that burned most frequently was located at the southeastern portion of the site along a primary stream valley. It appears that fires burned most frequently along Nile Creek, spreading through the eastern portion of the site along the north fork of Nile Creek and through several valleys that are perpendicular to the main branch of Nile Creek. Fire frequency patterns at the Entiat site were similar to that of the Swauk and Nile sites (Figure 4). The areas that burned most frequently were at the northern and southeastern portions of the site, again near primary stream corridors. However, fire appears to have burned fairly frequently throughout the Entiat site, and the frequent occurrence of larger fires discussed previously suggests that the landscape at Entiat has fewer topographic barriers than Swauk or Nile, and that the stream corridors facilitate site-wide spread of fires. Heyerdahl *et al.* (2001) described a similar relationship between fire and topography in the Blue Mountains in Oregon. Sites with less complex topography tended to burn more frequently and fire spread over larger areas.

The SMFI for South Deep is more problematic to interpret, primarily because fewer samples were collected, and the samples were not as spatially distributed as they were at Swauk, Nile, and Entiat. Periodic surface fire appears to have burned throughout much of the site, although less frequently than at the other sites (Figure 4). This may be due in part to the many streams, which may act as corridors for fire spread as observed in the other sites. Furthermore, the topography at South Deep is gentler than at the southern sites, producing fewer barriers to fire spread as observed in the Blue Mountains (Heyerdahl *et al*. 2001). The large area that burned infrequently in the southerly portion of the site may indicate a different fire regime than the northern portion, although no clear topographic barrier is evident. This pattern may also be due to the fact that only a dozen samples were collected in the area, which may not be adequate to capture all of the fire events.

Management Implications

The SMFI maps can provide managers with additional spatial information to help characterize fire regimes and to visualize fire variability in the context of the physical landscape. This visualization can provide insights on the relationship between fire and topography, provide direction for further investigation, guide additional sampling efforts, and ultimately inform management. Traditionally, managers have had access to statistical results such as fire intervals, statistical topographic indexes that evaluate fire relative to terrain (Kellogg *et al.* 2008), or, in the case of historical fires, spatial tools such as fire atlases and remotely sensed imagery. Although these resources are critical to support decision-making on issues such as allocating and dispatching suppression resources, planning thinning and burning operations, and public safety and awareness, spatially explicit data for pre-Euro-American fire regimes has been less accessible in dry ponderosa pine forests characterized by low-severity fire regimes. In this paper, we have demonstrated how GIS-based estimates of fire perimeters and the SMFI approach can supplement existing data sources and have practical management implications in supporting spatial decision-making.

Conclusions

The purpose of this paper was to demonstrate how standard GIS approaches can be used to facilitate spatial reconstructions of pre-European fire regimes. The SMFI provides a more detailed, finer-grained estimate of spatio-temporal variability in paleo-fire regimes than do statistical measures of fire frequency. The average SMFI for all sites lies in between MPFI, a minimum measure, and CMFI, a maximum measure, and maintains spatial heterogeneity within sites. The SMFI maps also suggest topographic controls on the spatio-temporal variability of fire, although further research is required to quantify such relationships. Finally, it must be considered that this study benefited from a very large, georeferenced fire-scar database, and the generation of such primary data is not practical in many cases. However, the GIS approach may still be effective at similar or even lower sampling densities. Hessl *et al.* (2007) worked with a dataset with an average density of 0.05 trees ha^{-1}. The authors randomly removed 30 % of the trees, reducing the density to 0.03 trees ha^{-1}, and found no significant difference in fire extents calculated from the high and low density datasets. Furthermore, the GIS approach may be practical for individual sites that require intensive management that would benefit from reconstructed fire perimeters and a spatially explicit SMFI. Finally, with online data sharing resources such as the International Tree-Ring Data Bank, secondary data collected across similar landscapes could be used to implement the methods presented.

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LITERATURE CITED

Agee, J.K., M.A. Finney, and R. de Gouvenain. 1990. Forest fire history of Desolation Peak, Washington. Canadian Journal of Forest Research. 20:350-356. doi: 10.1139/x90-051

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Agee, J.K. 1997. The severe weather wildfire—too hot to handle? Northwest Science 71: 153-156.

Agee, J.K., and F. Krusemark. 2001. Forest fire regime of the Bull Run Watershed, Oregon. Northwest Science 75:293-305.

Allen, C.D., R. Touchan, and T.W. Swetnam. 1995. Landscape-scale fire history studies support fire management action at Bandelier. Park Science 15(3): 18-19.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12: 1418-1433. doi: 10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2

Baker, W.L. 1989. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 70: 23-35. doi: 10.2307/1938409

Baker, W.L., and D. Ehle. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 1205-1226. doi: 10.1139/cjfr-31-7-1205

Baker, W.L., and K.F. Kipfmueller. 2001. Spatial ecology of pre-Euro-American fires in a southern Rocky Mountain subalpine forest landscape. Professional Geographer 53: 248-262.

Barton, A.M., T.W. Swetnam, and C.H. Baisan. 2001. Arizona pine (*Pinus arizonica*) stand dynamics: local and regional factors in a fire-prone madrean gallery forest of southeast Arizona, USA. Landscape Ecology 16: 351-369. doi: 10.1023/A:1011189408651

Beatty, R.M., and A.H. Taylor. 2001. Spatial and temporal variations of fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography 28: 955-966. doi: 10.1046/j.1365-2699.2001.00591.x

Brown, P.M. 2006. Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. Ecology 87: 2500-2510. doi: 10.1890/0012-9658(2006)87[2500:CEOFRA]2.0.CO;2

Brown, P.M., C.L. Wienk, and A.J. Symstad. 2008. Fire and forest history at Mount Rushmore. Ecological Applications 18: 1984-1999. doi: 10.1890/07-1337.1

Cissel, J.H., F.J. Swanson, and P.J. Weisburg. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecological Applications 9: 1217-1231. doi: 10.1890/1051-0761(1999)009[1217:LMUHFR]2.0.CO;2

Collins, B.M., and S.L. Stephens. 2007. Fire scarring patterns in Sierra Nevada wilderness areas burned by multiple wildland fire use fires. Fire Ecology 3(2): 53-67. doi: 10.4996/fireecology.0302053

Collins, B.M., J.D. Miller, A.E. Thode, M. Kelly, J.W. van Wagtendonk, and S.L. Stephens. 2008. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems: 12: 114-128. doi: 10.1007/s10021-008-9211-7

Dale, V., L. Joyce, S. McNulty, R. Neilson, M. Ayres, M. Flannigan, P. Hanson, L. Irland, A. Lugo, C. Peterson, D. Simberloff, F. Swanson, B. Stocks, and B. Wotton. 2001. Climate change and forest disturbance. BioScience 51: 723-734. doi: 10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2

Denevan, W.M. 1992. The pristine myth: the landscape of the Americas in 1492. Annals of the Association of American Geographers 82: 369-385. doi: 10.1111/j.1467-8306.1992.tb01965.x

Duncan, R.P., and G.H. Stewart. 1991. The temporal and spatial analysis of tree age distributions. Canadian Journal of Forest Research 21:1703-1710. doi: 10.1139/x91-236

Everett, R.L., R. Schellhaas, D. Keenum, D. Spurbeck, and P. Ohlson. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129: 207-225. doi: 10.1016/S0378-1127(99)00168-1

Fall, J.G. 1998. Reconstructing the historical frequency of fire: a modeling approach to developing and testing methods. Thesis, Simon Fraser University, Burnaby, British Columbia, Canada.

Farris, C.A., E.Q. Margolis, and John A. Kupfer. 2008. Spatial characteristics of fire severity in relation to fire growth in a Rocky Mountain subalpine forest. USDA Forest Service General Technical Report PSW-GTR-189. Pacific Southwest Research Station Albany, California, USA.

Farris, C.A., C.H. Baisan, D.A. Falk, S.R. Yool, and T.W. Swetnam. 2010. Spatial and temporal corroboration of a fire-scar-based fire history in a frequently burned ponderosa pine forest. Ecological Applications 20: 1598-1614.

Franklin, J.F., and C.T. Dyrness. 1988. Natural vegetation of Oregon and Washington. Oregon State University Press, Corvallis, USA.

Franklin, J. 1998. Predicting the distribution of shrub species in southern California from climate and terrain-derived variables. Journal of Vegetation Science 9: 733-748. doi: 10.2307/3237291

Fulé, P.Z., W.W. Covington, and M.M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications 7: 895-908. doi: 10.1890/1051-0761(1997)007[0895:DRCFEM]2.0.CO;2

Fulé, P.Z., T.A. Heinlen, W.W. Covington, and M.M. Moore. 2003. Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. International Journal of Wildland Fire 12: 129-145. doi: 10.1071/WF02060

Gonzalez, M.E., T.T. Veblen, and J.S. Sibold. 2005. Fire history of Araucaria-Nothofagus in Villarrica National Park, Chile. Journal of Biogeography 32: 1187-1202. doi: 10.1111/j.1365-2699.2005.01262.x

Grissino-Mayer, H.D. 1999. Modeling fire interval data from the American Southwest with the Weibull Distribution. International Journal of Wildland Fire 9: 37-50. doi: 10.1071/WF99004

Grissino-Mayer, H., W. Romme, M. Floyd, and D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 85: 1708-1724. doi: 10.1890/02-0425

Haire, S.L., and K. McGarigal. 2009. Changes in fire severity across gradients of climate, fire size, and topography: a landscape ecological perspective. Fire Ecology 5(2): 86-108. doi: 10.4996/fireecology.0502086

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3: 329-382. doi: 10.1016/0033-5894(73)90003-3

Hemstrom, M.A., and J.F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quaternary Research 18: 32-51. doi: 10.1016/0033-5894(82)90020-5

Hessburg, P.F., J.K. Agee, and J.F. Franklin. 2005. Dry mixed conifer forests of the inland Northwest, USA: contrasting the landscape ecology of the presettlement and modern eras. Forest Ecology and Management 211: 117-139. doi: 10.1016/j.foreco.2005.02.016

Hessl, A., 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. doi: 10.1890/03-5019

Hessl, A., J. Miller, J. Kernan, D. Keenum, and D. McKenzie. 2007. Mapping paleo-fire boundaries from binary point data: comparing interpolation methods. Professional Geographer 59: 87-104. doi: 10.1111/j.1467-9272.2007.00593.x

Heyerdahl, E.K. 1997. Spatial and temporal variation in historical fire regimes of the Blue Mountains, Oregon and Washington: the influence of climate. Thesis, University of Washington, Seattle, USA.

Heyerdahl, E.K., and V. Card. 2000. Implications of paleorecords for ecosystem management. Trends in Ecology and Evolution 15: 49-50. doi: 10.1016/S0169-5347(99)01779-6

Heyerdahl, E.K., L.B. Brubaker, and J.K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82: 660-678. doi: 10.1890/0012-9658(2001)082[0660:SCOHFR]2.0.CO;2

Heyerdahl, E.K., R.F. Miller, and R.A. Parsons. 2006. History of fire and Douglas-fir establishment in a savanna and sagebrush–grassland mosaic, southwestern Montana, USA. Forest Ecology and Management 230: 107-118. doi: 10.1016/j.foreco.2006.04.024

Houghton, R.A., and J.L. Hackler. 2000. Changes in terrestrial carbon storage in the United States. I: The roles of agriculture and forestry. Global Ecology and Biogeography 9: 125-144. doi: 10.1046/j.1365-2699.2000.00166.x

Hunter, M.L. 1993. Natural fire regimes as spatial models for managing boreal forests. Biological Conservation 65: 115-120. doi: 10.1016/0006-3207(93)90440-C

Jordan, G.J., M. Fortin, and K.P. Lertzman. 2005. Assessing spatial uncertainty associated with forest fire boundary delineation. Landscape Ecology 20: 719-731. doi: 10.1007/s10980-005-0071-7

Kellogg, L.B., D. McKenzie, D.L. Peterson, and A.E. Hessl. 2008. Spatial models for inferring topographic controls on historical low-severity fire in the eastern Cascade Range of Washington, USA. Landscape Ecology 23: 227-240. doi: 10.1007/s10980-007-9188-1

Kilgore, B., and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. Ecology 60: 129-142. doi: 10.2307/1936475

Landres, P.B., P. Morgan, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9: 1179-1188.

Lombardo, K.J., T.W. Swetnam, C.H. Baisan, and M.I. Borchert. 1999. Using bigcone Douglas-fir fire scars and tree rings to reconstruct interior chaparral fire history. Fire Ecology 5(3): 35-56. doi: 10.4996/fireecology.0503035

McBride, J.R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bulletin 43: 51-67.

McKenzie, D., D.L. Peterson, and J.K. Agee. 2000. Fire frequency in the interior Columbia River Basin: building regional models from fire history data. Ecological Applications 10: 1497-1516. doi: 10.1890/1051-0761(2000)010[1497:FFITIC]2.0.CO;2

McKenzie, D., A.E. Hessl, and L.B. Kellogg. 2006. Using neutral models to identify constraints on low-severity fire regimes. Landscape Ecology 21: 139-152. doi: 10.1007/s10980-005-0147-4

Morgan, P., C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: understanding coarse and fine-scale patterns. International Journal of Wildfire 10: 329-342. doi: 10.1071/WF01032

Morgan, P., E.K. Heyerdahl, and C.E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89: 717-728. doi: 10.1890/06-2049.1

Moore, M.M., W.W. Covington, and P.Z. Fulé. 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecological Applications 9: 1266-1277. doi: 10.1890/1051-0761(1999)009[1266:RCAERA]2.0.CO;2

Moritz, M. 2003. Spatiotemporal analysis of controls on shrubland fire regimes: age dependency and fire hazard. Ecology 84: 351-361. doi: 10.1890/0012-9658(2003)084[0351:SAOCOS]2.0.CO;2

Nash, J.M. 2003. Fireproofing the forests. Time 163(7): 18 August 2003. <http://www.time.com/time/magazine/article/0,9171,1005437,00.html>.

Niklasson, M., and A. Granstrom. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81: 1484-1499. doi: 10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2

Norman, S.P., and A.H. Taylor. 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA. Journal of Biogeography 30: 1081-1092. doi: 10.1046/j.1365-2699.2003.00889.x

Parsons, R.A., E.K. Heyerdahl, R.E. Keane, B. Dorner, and J. Fall. 2007. Assessing accuracy of point fire intervals across landscapes with simulation modelling. Canadian Journal of Forest Research 37: 1605-1614. doi: 10.1139/X07-013

Pontius, R.G., Jr., and K. Batchu. 2003. Using the relative operating characteristic to quantify certainty in prediction of location of land cover change in India. Transactions in GIS 7: 467-484. doi: 10.1111/1467-9671.00159

Robbin, W.G., and D.W. Wolf. 1994. Landscape and the intermontane Northwest: an environmental history. USDA Forest Service General Technical Report PNW-GTR-319. Pacific Northwest Research Station, Portland, Oregon, USA.

Rollins, M.G., T.W. Swetnam, and P. Morgan. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31: 2107-2123. doi: 10.1139/cjfr-31-12-2107

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecological Monographs 52: 199-221. doi: 10.2307/1942611

Sampson, N.R., R.D. Atkinson, and J.W. Lewis, editors. 2000. Mapping wildfire hazards and risks. The Hawthorn Press, Binghamton, New York, USA.

Shapiro-Miller, L.B., E.K. Heyerdahl, and P. Morgan. 2007. Comparison of fire scars, fire atlases, and satellite data in the northwestern United States. Canadian Journal of Forest Research 37: 1933-1943. doi: 10.1139/X07-054

Stokes, M., and T. Smiley. 1968. An introduction to tree-ring dating. The University of Arizona Press, Tucson, USA.

Swetnam, T., and A. Westerling. 2003. Interannual to decadal drought and wildfire in the western United States. EOS 84.

Swetnam, T.W., and J.L. Betancourt. 1997. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11: 3128-3147. doi: 10.1175/1520-0442(1998)011<3128:MDAERT>2.0.CO;2

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1998. Applied historical ecology: using the past to manage for the future. Ecological Applications 9: 1189-1206. doi: 10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2

Tang, H., and I.D. Bishop. 2002. Integration methodologies for interactive forest modelling and visualization systems. The Cartographic Journal 39: 27-35.

Turner, M.G., W.H. Hargrove, R.H. Gardner, and W.H. Romme. 1994. Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. Journal of Vegetation Science 5: 731-742. doi: 10.2307/3235886

Van Horne, M.L., and P.Z. Fulé. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forests. Canadian Journal of Forest Research 36: 855-867. doi: 10.1139/X05-289

Westerling, A.L., H.G. Hidalgo, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313: 940-943. doi: 10.1126/science.1128834

Western Regional Climate Center. 2008. <http://www.wrcc.dri.edu/>. Accessed 27 December 2008.

Wittkuhn, R.S., and T. Hamilton. 2010. Using fire history data to map temporal sequences of fire intervals and seasons. Fire Ecology 6(2): 97-114. doi: 10.4996/fireecology.0602097