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Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades

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Abstract

We collected 490 and 233 fire scars on two ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Pseudotsuga menziesii*) dominated landscapes on the east slope of the Washington Cascades that contained a record of 3901 and 2309 cross-dated fire events. During the pre-settlement period (1700/1750–1860), the Weibull median fire-free interval (WMFFI) and the mean fire-free interval (MFFI) were 6.6–7 years at both sites. The MFFI during the settlement period (1860–1910) varied within 3 years of the pre-settlement value, but increased to 38 and 43 years for a truncated fire suppression period between 1910 and 1996. Increased variation in MFFI among aspect polygons suggests fire regimes have become more complex since Euro-settlement. In the pre-settlement period, an area equal to approximately 50–60% of the study areas burned every 6–7 years, an amount of fire disturbance apparently in balance with landscape and stand vegetation structure. Overlapping fires have created a complex mosaic of different fire histories on these forested landscapes. Mapped fire events from the 1700–1910 showed 134 and 157 separate fire history polygons (FHP) at the two sites. Fire disturbance rates and patterns are suggested as ecologically defensible reference points for landscape heterogeneity to reduce the potential for catastrophic fires and to establish vegetation disturbance management guidelines. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ecosystem integrity; Fire-free intervals; Fire history polygons; Fire regimes; Landscape dynamics; Natural fire rotation; Patch mosaic

1. Introduction

Maintaining ecosystem integrity is increasingly being defined as perpetuating natural processes as well as natural conditions (Pickett and White, 1985; Urban et al., 1987; Hansen et al., 1991; Everett and

Lehmkuhl, 1996). Agee and Huff (1985) suggest ‘intelligent wilderness management requires simulation and shepherding of natural disturbance patterns over the landscape.’ Fire was one of many natural disturbance processes that created and maintained ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Pseudotsuga menziesii*) forests of the inland west in different successional stages prior to Euro-settlement. European settlement of the Pacific Northwest occurred in the late 1800s with Washington State’s population

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of approximately 1200 in 1850 increasing to near 1,140,000 by 1910 (Robbins and Wolf, 1994). The continual occurrence of wildfires (both indigenous people and lightning ignitions) reported by the earliest settlers east of the Cascades (Johnson et al., 1994; Robbins and Wolf, 1994) rapidly declined after Euro-settlement. Fire effects were reduced following Euro-settlement because of fewer ignitions set by indigenous people (Barrett and Arno, 1982; Swetnam and Dieterich, 1985; Fisher et al., 1987, reported in Brown and Sieg, 1996), extensive livestock grazing that reduced flash fuels (Zimmerman and Neuenschwander, 1984; Steele et al., 1986; Savage and Swetnam, 1990), roading and farming that broke up continuity of fuels, and active fire suppression (Arno, 1988). Concentrated efforts to suppress fires on the eastern slope of the Washington Cascades occurred after 1910 when new legislation, the Weeks Act of 1911, was enacted to protect forests (Agee, 1994).

Northwest fire regimes have been most altered in ponderosa pine/Douglas-fir forest types that had high fire frequency or short fire-free intervals (Agee, 1993). Although the application of landscape-level fire regime estimates to explain smaller-scale stand structural attributes is to be done with some trepidation (Arthur Zack, personal communication), many authors have felt the alteration of fire regimes and their effects were so pervasive on the landscape that, at the least, some general observations were warranted. Historically, successive fire events within stands continually cropped developing conifer seedlings (Brown and Sieg, 1996) creating open and park-like ponderosa pine conditions (Gruell et al., 1982; White, 1985; USDA, 1993, pp. 20; Covington et al., 1994; Johnson et al., 1994). With the absence of fire for nearly a century in portions of the dry forest types, there are stands and landscapes that are 10–12 fire-free intervals out from historical conditions on the east slope of the Washington Cascades (Everett et al., 1997). In summarizing the literature on historical and current fire regimes in the ponderosa pine/Douglas-fir types, Arno (1988) states that prior to 1900 most stands had recurring surface fires at intervals of 1–30 years and that frequent burning patterns could be traced as far back as 1500 AD from fire scars. Reduced fire occurrence has caused significant increases in tree densities and changes in species composition in the ponderosa pine/Douglas-fir type in eastern Washington (Weaver,

1959; Everett et al., 1996) and elsewhere in the western United States (Arno, 1980; Madany and West, 1983; van Wagendonk, 1985; Steele et al., 1986; Keane et al., 1990; Covington and Moore, 1992; Covington et al., 1994; Fulé et al., 1997). These altered forests have increased hazard for catastrophic stand-replacement fires. The fire regime has shifted from frequent, low-intensity surface fires to low frequency, high-intensity crown fires (Covington and Moore, 1992). The 22,275 ha (55,000 acre) Dinkelman burn in 1988 and the 56,700 ha (140,000 acre) Tye burn in 1994 are case examples of this effect on the east slope of the Cascades (Everett et al., 1996).

Agee (1993) characterized general fire regimes in forest types of the Pacific Northwest, both prior to and after Euro-settlement. However, within the ponderosa pine/Douglas-fir forest series on the east slope of the Washington Cascades, adjacent aspects vary greatly in species composition and forest structure. Site factors such as topography, aspect, and fuel continuity may create different fire regimes between adjacent areas at a scale of tens to hundreds of meters (Lertzman et al., 1997). Under this scenario, the fire regime for a heterogeneous forest landscape becomes more complicated to define. Specifically, fire regimes may vary among areas of homogeneous aspect and slope (aspect polygons) that lie adjacent to each other across a forested landscape. Also, change in fire regimes since Euro-settlement may not have been similar between adjacent aspect polygons.

Landform contributes to development of plant communities with contrasting fire frequencies or intensities (Swanson et al., 1988; Turner and Romme, 1994). Vegetation on broad smooth slopes will burn more completely than broken slopes containing watercourses, ridgelines, or cliffs that interrupt fire spread (Minnich, 1977). Greater tree densities and differences in species composition on north/east versus south/west aspects define potential differences in fire intensity and species mortality. 'Vegetation in the lee of fire breaks may be characterized by older (plant) communities with a higher proportion of fire-sensitive species than in less protected sites' (Wells, 1965, cited in Swanson, 1978). Conversely, once a vegetation type has been created that burns more readily than previous plant assemblages, the probability for reburn is increased. 'A given fire 'sets up' the area for another fire' (Vogel, 1977) with a portion of the type

continually reburning while other portions on the same landform remain unburned.

The physical characteristics of landforms and the vegetation they support greatly affect potential for ignition and fire spread (Swanson, 1978; Swanson et al., 1988; DeLong and Tanner, 1996). Sparsely vegetated areas such as talus slopes, ridge tops, and avalanche tracks are conspicuous firebreaks that control rate and direction of fire spread (Suffling, 1993; Brown and Sieg, 1996). Also, vegetation types and development stages that exhibit low fire-carrying capability can form 'subtle firebreaks' (Swanson, 1978). The effects of landforms and associated vegetation on fire spread are more pronounced for low- and moderate-intensity fires, whereas high-intensity fires may disregard slope effects or natural fire breaks and spread erratically across the landscape (Swanson, 1978). 'Fire storm' events or individual 'runs' often cross many vegetation types regardless of their fuel characteristics (Minnich, 1977). For severe fires, the actual burn mosaic may be more dependent upon fire weather than existing vegetation structure (Countryman, 1964).

Fire regimes are site specific based on forest type, topography, microclimate, ignition sources, and past disturbance history. Land management is also site specific, requiring local information on fire regimes to manage for this important disturbance. The characterization of inherent fire disturbance regimes for an area should serve as an important reference point for potential changes in vegetation patches. Rate of change in vegetation patches over time defines the historical landscape dynamics on which current species and processes have coexisted in the past. There is an urgent need to understand the inherent fire regimes of ponderosa pine/Douglas-fir forests to reduce the potential for catastrophic fire events. Also, this understanding could assist in creating future landscapes with patch mosaic and stand characteristics that are supportable in the long term. As Urban et al. (1987) suggest, 'a knowledge of the characteristic spatial scale and natural frequency of patch dynamics on a landscape lends itself to prescriptive applications in natural resource management.' At the very least, information on disturbance and vegetation patch structure provides 'a benchmark against which to evaluate contemporary conditions and future alternatives' (Fulé et al., 1997).

1.1. Hypotheses

This study investigated the inherent and altered fire regimes of heterogeneous landscapes in ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Our null hypotheses were that: (a) there are no difference in mean fire-free interval (MFFI) or Weibull median fire-free interval (WMFFI) among pre-settlement (1700/1750–1860), settlement (1860–1910), or fire suppression periods (1910–1996) on the two study areas; (b) aspect polygons (defined by slope and aspect) in ponderosa pine/Douglas-fir forests do not vary in MFFI or WMFFI, or natural fire rotation period (NFR); (c) that within an aspect polygon boundary (no change in aspect or slope) the MFFI and NFR remain constant; and (d) fire history is uniform (constant number of fire events) across landscapes with a common historical fire regime (high-frequency/low-severity) at the two study areas. Mean fire-free interval is defined here as the mean period (in years) between consecutive fire events of sufficient magnitude to scar living trees (Kaennel and Schweingruber, 1995). Weibull median fire-free interval gives a probabilistic estimate of fire-return intervals for asymmetrical fire interval distributions (Grissino-Mayer, 1995a). Natural fire rotation period is defined as the years required to burn an area of equal size to the sample area (Heinselman, 1973). Information provided on the spatial heterogeneity of landscape fire regimes should provide insights to those developing coarse-scale fire models (McKenzie, 1998).

2. Methods

2.1. Sample areas

Two subwatersheds, Nile Creek and Mud Creek, in the ponderosa pine/Douglas-fir forest type were selected for fire regime analysis. Both study areas occur on the east slope of the Washington Cascades on the Wenatchee National Forest and are comprised of broken topography with intermixed aspects and slopes (Fig. 1). Historically, these areas were open ponderosa pine stands on south-facing slopes and greater density stands on north-facing slopes from additional Douglas-fir and some grand fir (*Abies grandis*) (Plummer, 1902). The 12,757 ha (31,500 acre) Mud Creek study

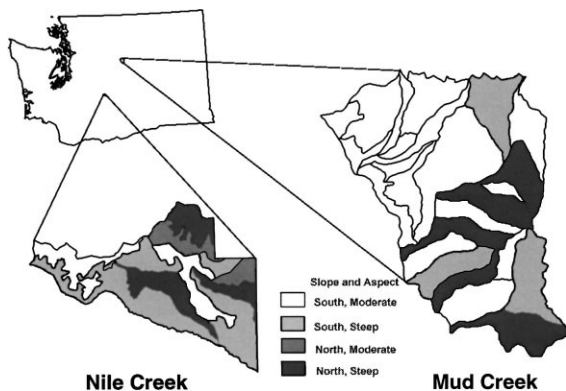


Fig. 1. Aspect (slope) polygons for Mud Creek and Nile Creek study areas. Study sites are located on the east slope of the Washington Cascades.

area on the Entiat Ranger District in the Northern Cascades Province (Franklin and Dyrness, 1973) is at elevations of 366–1220 m (1200–4000 ft). The area has mountain slope landforms with crystalline bedrock parent materials (Davis, 1992). The 3240 ha (8000 acre) Nile Creek study area is on the Naches Ranger District in the Southern Cascades Province at elevations of 735–1280 m (2400–4200 ft) on structurally-controlled mountain slope landforms with volcanic/pyroclastic parent materials (Davis, 1992). For sampling purposes, the land surface within each study area was broken out into aspect polygons based on: (1) aspect, northerly ($291\text{--}110^\circ$) and southerly ($111\text{--}290^\circ$); and (2) percent slope, flat (0–30%), moderate (30–50%), and steep (>50%). All aspect polygons were either moderate or steep on both study sites.

2.2. Sampling design

Aerial photos and topographic maps were used to identify and map aspect polygons that occurred on the two sample areas. Polygons were stratified internally into four or five sections to ensure that fire scars were taken throughout the polygon. Section boundaries were based on small scale topographic features that maximize landscape homogeneity within a section and the probability of a common fire disturbance history across the section. A subjective search of the entire polygon was made to identify and map all candidate fire scar samples. Trees estimated to have the greatest number of fire scars were identified and randomly selected from this ‘high quality’ fire

scar population for sampling within each section of an aspect polygon. A minimum of two fire scar samples were taken within each polygon section (range 2–23, mean = 6.3 scars per section, Mud Creek; range 2–19, mean = 4.9 scars per section, Nile Creek).

Fire scar samples were cut from live trees using the methods described by Arno and Sneek (1977). Cross section samples were collected from stumps, snags, and logs; repeated sections were cut from samples to ensure that the maximum number of fire scar events was captured in the section used for analysis. Sections from live trees were planed and both live and dead sections were sanded (80–600 grit) to discern individual tree rings.

2.3. Analysis

Composite skeleton plots, graphic plots of tree ring patterns (wet-wide ring and dry-narrow ring) associated with specific dates, were developed by examining tree cores from 20 sensitive trees (i.e., sensitive to climatic variables) within each sample area in accordance with the dendrochronology procedures for cross-dating described by Stokes and Smiley (1968). The skeleton plots for the two areas were used to reference fire scar events on collected fire scar sections. Fire-scar chronologies were developed by cross-dating annual rings of the fire scar section with the composite skeleton plot chronology. Date of fire scar occurrence was determined by the position of the fire scar relative to the dated annual rings of the sample cross section (Dieterich and Swetnam, 1984). Tree stump diameter and age at the time of the first fire-scar were recorded for each sampled section.

Fire scar dates at each mapped sample point were identified, and combined within each section of the polygon and for the entire aspect polygon. Fire year dates and locations of individual sample points were used to define occurrence and size of fire events across aspect polygons (polygons) and the entire study area. Sampling of fire scars by individual polygon section gives enhanced distribution of sampled scars across the study areas and should increase the accuracy of derived fire maps and burn area estimates. We established a protocol of requiring at least three ‘fire-susceptible trees’ to be present within the polygon to estimate a fire-free interval as we went back in time. A fire-susceptible tree is a tree that has been scarred at

least once and is considered susceptible from the date of the first scar until it dies (Arno and Sneek, 1977). Having numerous fire-susceptible trees on both sides of an estimated burn boundary increases our confidence in burn area location and extent. Zones of different fire frequency were identified within each polygon and gaps in fire frequency were noted. The NFR period was defined for each aspect polygon. The fire scar record dated back to the 1300s in some polygons. However, fire scar analysis is not exact as every fire may not scar a sampled tree, and a previous fire scar may be lost from subsequent fires or by weathering (Brown and Swetnam, 1994; Brown and Sieg, 1996).

Fire-free interval is area dependent, decreasing with expanding area sampled, but in this case we could not show significant ($P = 0.1$) area effects among the size of aspect polygons sampled even after multiple linear and curvilinear regression analysis attempts. Mean fire-free interval, WMFFI, and NFR data between aspect polygons were analyzed without adjustment for differences in land area in standard analysis of variance tests. For the analysis, data on MFFI, WMFFI, and NFR were divided into pre-settlement (1700–1860), settlement (1860–1910), and suppression (1910–1996) periods. We limited the pre-settlement period from initial Euro-settlement (1860) back in time until there was a minimum of three fire-susceptible trees of adequate age to document a fire within each of the sampled aspect polygons (1700–1860, Nile Creek; 1750–1860, Mud Creek). The settlement period is defined as from the 1860s until 1910 when suppression of fires became more common. We are currently in the fire suppression era and, for purposes of analysis, is defined as the period from 1910–1996. The 86 year time span (1910–1996) was used as the cut-off date for computing the minimum MFFI for aspect polygons that have not had a fire since 1910. If MFFI is found to be greater in the truncated suppression era than the settlement or pre-settlement periods, this difference can only increase as the suppression era increases over time. However, active suppression of fires significantly limits fire extent and nullifies NFR analysis for the suppression period.

The MFFI and WMFFI were computed for each aspect polygon for pre-settlement, settlement, and suppression eras whenever sufficient data were available. The MFFI is the more common statistic in fire regime research and allows comparison with the vast

majority of previous work, whereas WMFFI has been suggested as the more correct statistic for skewed fire frequency distributions (Grissino-Mayer, 1995a). Frequent fires in the pre-settlement and settlement periods and the use of a limited suppression era (lengthy relative to fire cycle) reduced data skewness, a concern of Finney (1995) and Swetnam and Baisan (1996). Our data of aspect polygon means for MFFI and WMFFI were only slightly asymmetric in distribution (skewness < 1) with slightly truncated tails (kurtosis < 2). The WMFFI could not always be determined when too few intervals were present (minimum of four intervals required) for analysis using 'Software for the Analysis of Fire History' (Grissino-Mayer, 1995a, 1995b). The MFFI for polygons were compared among presettlement, settlement, and suppression eras using *t*-test of differences among paired polygons. The WMFFI were similarly compared.

We tested to see if there was commonality in occurrence of fire events between the two study areas. Similarity in fire occurrence (burns occurring in the same year) between the two study sites was estimated using the Jaccard similarity index (Romesburg, 1984).

Each fire creates a new vegetation disturbance patch or patches that overlay previous vegetation patches. The area burned in each fire (minimum size > 40.5 ha (100 acres)) was estimated. The area estimate was based on the presence of fire-scarred trees of sufficient age to record the fire in a polygon section and the topographic boundaries of that section of the aspect polygon. We used topography to estimate fire extent beyond fire-scarred trees (Agee, 1991) because not all trees are scarred in fire events and ground fire boundaries extend beyond fire-scarred trees. The boundary of a polygon section delineates topographic changes and behavior of low severity fires often changes at topographic breaks (Swanson, 1978). A burn mosaic map of fire history polygons (land areas with different fire numbers or times) was created for each study area based on fire occurrence from 1700/1750 to the present after the work of Agee (1991), Johnson and Gutsell (1994), and Brown and Sieg (1996).

Change and rate of change in annual burn area were determined following each major fire (burn $> 50\%$ of study areas). The variance in area burned within sequential time increments was used to define the most consistent burn area per time relationship for the period of 1700/1750–1910. The era was divided in

a reiterative manner into time increments of 1, 2, 3 . . . and >50 year periods. The variance in burn area for each time increment during the era was determined and graphed for each study area. This process is a modification of Kershaw (1968) variance test for random or regular plant distribution patterns. The analysis also provided a first approximation of the hectares expected to burn within set time increments for the dry pine-fir forest type.

Annual tree ring widths provide an indication of the relative favorableness of climate for tree growth with narrow rings denoting adverse conditions such as drought. Using sensitive tree core samples, we measured tree ring widths for 1 year and for a 5 year mean period prior to major burns (>50% of study area burned). These measurements were compared to ring widths for 1 and 5-year periods chosen at random from these same cores. This was replicated for 10 sensitive trees on both study sites and the results analyzed in a paired *t*-test of differences between random and prior burn year widths.

During the preparation and analysis of fire scar sections we noted that the first fire scar frequently occurred at a relatively small tree diameter. Fire scarring, but not mortality of small diameter trees was seen as supporting evidence for low severity fire events. At the suggestion of the journal peer reviewers, we evaluated whether these initial fire scars occurred in conjunction with wide spread (presumably greater intensity) fire events. Our test sample was comprised of 407 fire-scarred tree sections that had fire scars at small diameters (mean diameter of 8.6 cm), had the pith present, and the early fire scar had not been damaged by subsequent reburns.

3. Results and discussion

A total of 490 fire-scarred trees, snags, logs, and stumps were sectioned across cat faces at the Mud Creek site (3901 scars cross-dated) and 233 samples were taken at the Nile Creek site (2309 scars cross-dated). The Mud Creek study site was comprised of 16 aspect polygons: 11 south (mean size of 644 ha (1591 acres)) and five north (mean size of 582 ha (1438 acres)) aspects ranging in size from approximately 199–1697 ha (491–4190 acres). The Nile Creek site was comprised of 11 aspect polygons: six south (mean

size of 363 ha (899 acres)) and five north (mean size 214 ha (529 acres)) aspects ranging in size from approximately 97–709 ha (240–1750 acres).

3.1. Fire-free interval

3.1.1. Pre-settlement period

During the 1700/1750–1860 pre-settlement period, the mean fire-free interval for the Mud Creek and Nile Creek study areas (all aspect polygons combined) was 7 years (Table 1). The Weibull median fire-free interval was 6.8 and 6.6 years at the two sites, respectively. There were no significant differences ($P = 0.05, 0.1$) in MFFI or WMFFI between the populations of north and south aspect polygons at either study site. This can be ascribed to variability in fire-free intervals within individual polygons, differences in fire-free intervals for polygons of the same aspect type (Fig. 2), and to common fires across polygon boundaries. The mean coefficient of variation for MFFI and WMFFI for sections within a polygon was 17 and 16% at Nile Creek and 23 and 24% at Mud Creek. There were significant differences ($P = 0.01$) in MFFI and WMFFI among sections within polygons at the two sites. Sections of some aspect polygons burned twice as often as other sections and MFFI patterns crossed aspect polygon boundaries.

At the Nile Creek site, MFFI for aspect polygons increased in duration with ascending elevation. The MFFI varied from 5.7 to 8.2 years (coefficient of variation (CV) = 13%) among the 16 sampled aspect polygon areas at Mud Creek and from 3.8 to 11.0 years (CV = 32%) among the 11 individual aspect polygons at Nile Creek. The WMFFI varied from 5.3 to 8.0 years (CV = 13%) among aspect polygons at Mud Creek and from 3.6 to 10.4 years (CV = 33%) among aspect polygons at Nile Creek.

Our results most closely approximate the MFFI of 5–8 years reported by Swetnam and Dieterich (1985) for ponderosa pine in New Mexico and the MFFI of 6.5 years for widespread fires in ponderosa pine in Arizona (Fulé et al., 1997). Our coefficient of variation values for MFFI are much less than the 70–100% reported by Brown and Sieg (1996) for ponderosa pine stands of South Dakota. This could be expected as we sampled adjacent aspect polygons rather than widely dispersed stands. Longer fire-free intervals than reported here have been noted for ponderosa pine

Table 1

Mean fire-free interval (MFFI) and Weibull median fire-free interval (WMFFI) for Mud Creek and Nile Creek study areas for pre-settlement, settlement, and suppression periods

	Mud Creek Mean fire-free intervals (years)			Nile Creek Mean fire-free intervals (years)		
	Mean (SD) ^a	North	South	Mean (SD)	North	South
MFFI						
Pre-settlement	7.0 (0.9) a ^b	6.8 (0.8) a	7.1 (1.0) a	7.0 (2.2) a	8.1 (2.3) a	6.1 (1.9) a
Settlement	7.1 (1.8) a	6.5 (0.5) a	7.6 (2.1) a	10.2 (2.2) a	10.6 (1.3) a	9.9 (4.4) a
Suppression ^c	38.3 (24.9) b	51.8 (30.4) b	32.2 (20.1) b	43.0 (22.9) b	60.2 (22.6) b	28.7 (7.9) b
Median fire-free intervals (years)						
WMFFI						
Pre-settlement	6.8 (0.9) a	6.6 (0.8)	6.8 (1.0)	6.6 (2.2) a	7.6 (2.4)	5.7 (1.7)
Settlement	6.6 (0.9) a	5.9 (1.1)	6.9 (2.2)	8.6 (2.3) a	10.5 (2.5)	6.7 (3.1)
Suppression	16.2 (6.1) b	19.9 (5.6)	15.1 (6.2)	24.4 (4.5) b	n.a. ^d	24.4 (4.5)

^a SD: Standard deviation of means.

^b Means with different subscripts within MFFI and WMFFI columns are statistically ($P = 0.05$) different. We were unable to show significant differences for WMFFI by aspect because of the reduced number of polygons with the required number of fire intervals for WMFFI analysis.

^c Suppression fire-free interval is the minimum fire-free interval possible based on 86 year sample period (1910–1996) with no fires having occurred in some sampled aspect polygon areas.

^d n.a.: Not available.

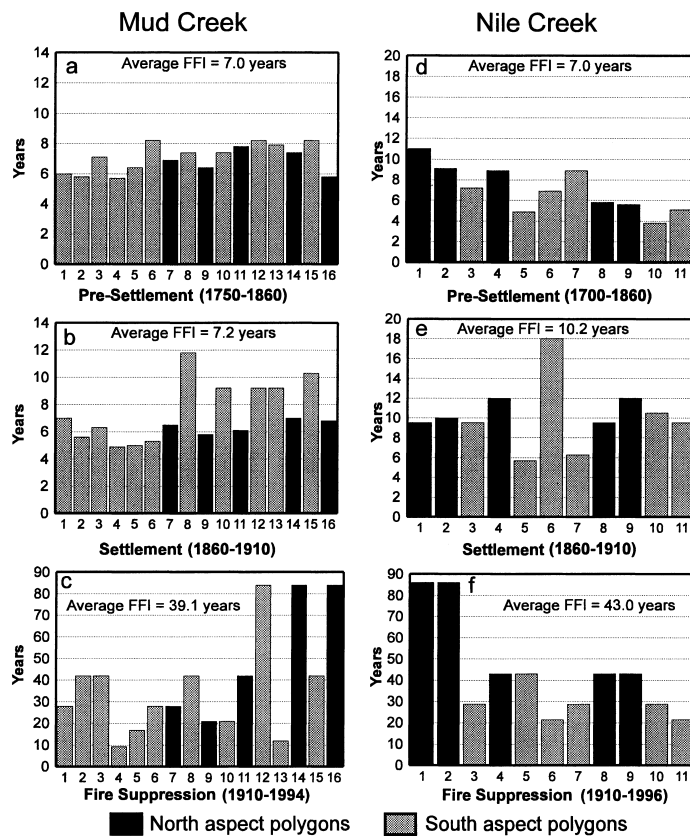


Fig. 2. Fire-free interval (MFFI) for pre-settlement (a, d), settlement (b, e) and suppression (c, f) eras in Mud Creek and Nile Creek study areas.

stands in the Black Hills of South Dakota (16–20 years, Brown and Sieg, 1996) and eastern Wyoming (14–27 years, Fisher et al., 1987; 5–20 years, Arno, 1976; Barrett and Arno, 1982).

We could not show any significant difference ($P > 0.1$) in MFFI or WMFFI between steep or moderate slopes in pre-settlement or settlement periods on either study area. Slope was apparently not a dominant factor in fire occurrence on these study areas although it did affect NFR.

3.1.2. Settlement period

During the settlement period (1860–1910), the mean aspect polygon MFFI increased to 7.1 years at Mud Creek and to 10.2 years at Nile Creek, respectively (Table 1). The modest net change on the Mud Creek site is suggested to be the result of offsetting processes; MFFI on foothill south slopes declined (closer to population centers with increased ignition sources) while MFFI increased on more mountainous south slopes (grazing impacts and associated reduction in fine fuels). Opposing changes resulted in a doubling of the coefficients of variation, 25 and 29.5% in MFFI and WMFFI, among polygons on the Mud Creek site during the settlement era. Differences increased in MFFI and WMFFI between north and south aspects during the settlement period on the Mud Creek site (Fig. 2(d) and (e)). Given the consistency in MFFI prior to settlement between north and south aspects, the varied responses between aspects can be ascribed to differences in human related activities (timber harvest, livestock grazing) or random fire events within the short settlement period.

At Mud Creek, WMFFI decreased on north aspects and increased on south aspects as occurred for MFFI. The overall trend for the site was an increase in MFFI and a decline in WMFFI. The WMFFI median emphasized the increase in number of short FFI on the north aspect, but with the MFFI mean statistic weighting, longer FFIs were present on south slopes. The trend was similar between MFFI and WMFFI values at Nile Creek.

3.1.3. Suppression period

In the suppression era, MFFI increased significantly ($P = 0.05$) for both north and south aspects, but more so for north aspects (Table 1). Using the truncated fire suppression period (1910–1996), the minimum MFFI

possible was 39 and 43 years, respectively, for Mud Creek and Nile Creek sites (Fig. 2(c) and (f)). These values are conservative as some aspect polygons had not had a fire occurrence since 1910 and values reflect the artificially applied 86 year cut-off date. The estimated length of the MFFI in the suppression period is confounded to some degree by rapid fire suppression that limits the number of fire scars created and our ability to detect fire occurrence.

The WMFFI for the suppression era was estimated at 42–56% of the estimated MFFI at Mud and Nile Creek sites respectively, (Table 1). The reader is provided the WMFFI values with several caveats. Although, the d statistic (<0.35) for goodness of fit suggests the Weibull distribution fits the data (Grisino-Mayer, 1995b, FHX2 model), the WMFFI values are based on a limited number of fire-return intervals during the suppression era. The absence of the minimum of four fire-return intervals required to estimate WMFFI for a polygon reduced the number of polygons that could be analyzed from 11 to 6 for the Nile site. For the Mud Creek site, the number of polygons analyzed dropped from 16 to 9. We suggest the difference between MFFI and WMFFI values are an artifact of restricting WMFFI analysis to only those polygons that burn most frequently. Also, with an abrupt decrease in fire frequency during a specified time period (suppression era) the longer fire-free interval could not be completed. The WMFFI reflects only the shorter fire-free intervals at the start of the era and not the entire era.

The CV for MFFI among aspect polygons increased to 53 and 65% on the Nile and Mud Creek study areas, respectively, during this period. On the Nile Creek study area, aspect polygon areas with a north aspect had significantly ($P = 0.05$) longer MFFI (60.2 years) than south-facing aspect polygon areas (28.7 years). The CV for WMFFI increased to 37.5% on the Mud Creek site during the suppression era. Apparently the MFFI among aspect polygons and across larger landscapes have become more dissimilar since Euro-settlement. Contrary CV results (decline to 18%) on the Nile site can be ascribed to the reduced number of polygons that met the minimum interval requirement, hence creating a more homogeneous sample in the analysis.

The data suggest an increase in MFFI and WMFFI between pre-settlement and suppression, and settlement and suppression eras as previously reported for

the dry pine forest type. Swetnam and Dieterich (1985) report MFFI increased from 5 to 8 years before 1900 and from 47 to 82 years after 1900 on ponderosa pine sites in the Gila Wilderness of New Mexico. Similarly, the MFFI was 16 years in ponderosa pine sites in South Dakota prior to 1890, but no fires had occurred since (Brown and Sieg, 1996). The specific cause for the shift in fire cycle is not readily defined (Finney, 1995), but has been attributed to road building, livestock grazing, reduced ignitions by indigenous people, and fire suppression as previously described.

Our results report the mean fire-return interval for an aspect polygon on the two study areas. If we consider the study areas in their entirety, the MFFI in pre-settlement, settlement, and suppression eras was 2.7, 2.6, and 3.1 years for Mud Creek, and 2.6,

4.6, and 7.2 years for Nile Creek, respectively. Both MFFI and NFR are area dependent metrics. The decline in fire-return interval from an aspect polygon to an entire site basis could be anticipated to continue if the study area was increased and additional fire events recorded. With a sufficiently large study area, a fire could be anticipated every year and there would be no difference in MFFI among pre-settlement, settlement, and suppression eras.

3.2. Natural fire rotation

The mean NFR (all aspect polygons) for the pre-settlement period in the Mud Creek study area was 11.0 years, only 4 years greater than the MFFI for this time period (Fig. 3(a)). The closeness in the two values results because approximately 61% of an individual

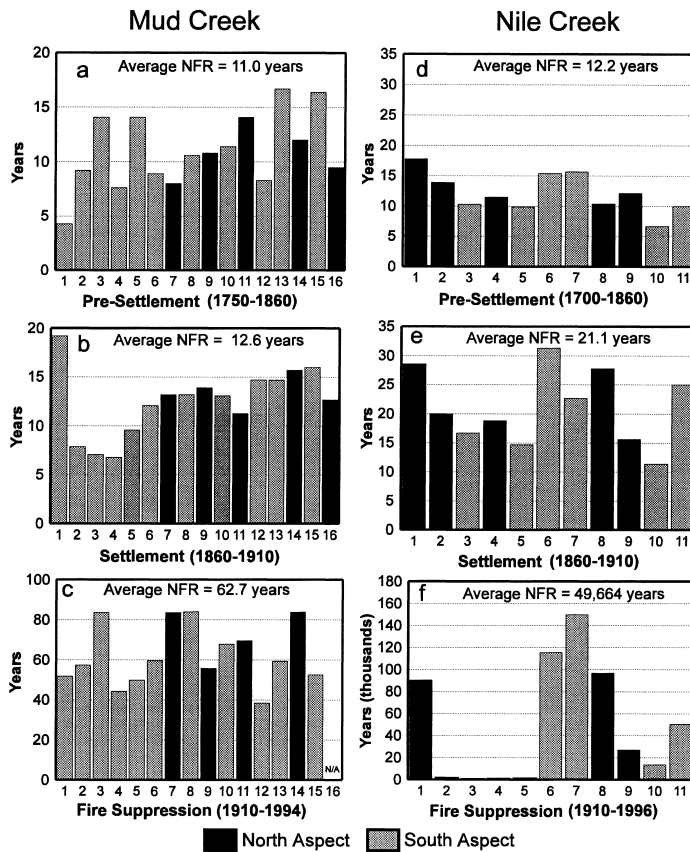


Fig. 3. Natural fire rotation period (NFR) for pre-settlement (a, d), settlement (b, e) and suppression (c, f) eras in Mud Creek and Nile Creek study areas.

aspect polygon area burned when a fire occurred within its boundary. The NFR on the Nile Creek study area was 12.2 years, 5.4 years greater than the MFFI for that site (Fig. 3(d)). The somewhat larger difference results because only 53% of an individual aspect polygon burned when a fire occurred. Greater topographic heterogeneity within the Nile Creek study area or larger individual aspect polygons may explain this phenomenon.

There was a significant ($P = 0.05$) increase (42%) in NFR from pre-settlement to settlement eras at Nile Creek (Fig. 3(d) and (e)) as a result of an increased fire-free interval (Fig. 2(d) and (e)). NFR increased by 13% at Mud Creek from the settlement to the suppression era. NFR did not significantly ($P = 0.1$) differ between north and south aspect polygons in pre-settlement and settlement periods in either Mud Creek or Nile Creek study areas. The increase in NFR between pre-settlement and settlement eras was apparently a general landscape level phenomenon across heterogeneous topography.

Rapid fire suppression in the suppression period precluded a meaningful analysis of NFR among aspect polygons. Through fire suppression activities, the amount of burn area is no longer cyclic, but limited to episodic events when fuels and weather combine to exceed fire suppression capabilities.

Slope steepness appeared to play only a minor role in NFR on these study areas. During the pre-settlement era, steep slopes on the Mud Creek study area had lower NFRs (9.6 years) than moderate (13.6) slopes, but there were no differences on the Nile Creek site. There were no differences in NFR based on slope in the settlement era at either site.

The NFR values decline if we analyze the study areas in their entirety rather than by separate aspect polygons. The NFR was 8.4–9.9 and 10–21.1 years for pre-settlement and settlement eras for Mud and Nile Creek, respectively. We found that specific aspect polygons that rarely burn increase the mean aspect polygon NFR, while other polygons or sections of polygons that burn repeatedly lower the NFR for the entire area.

3.3. Fire history on the landscape

Large fire events, those that covered at least 1/4 of the sample areas, occurred 23 times in the Mud Creek

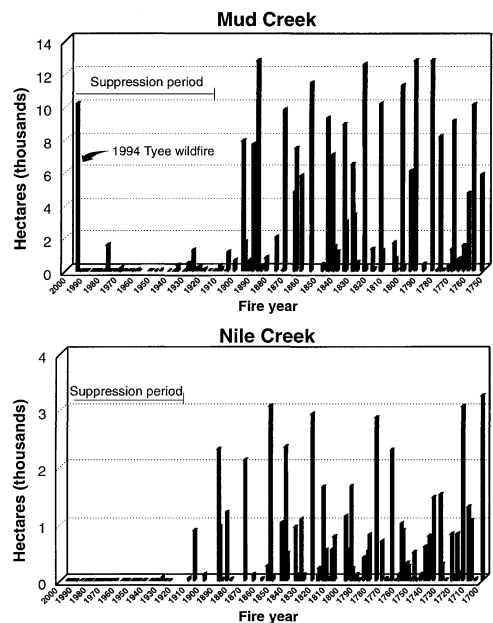


Fig. 4. Fire events and hectares burned during pre-settlement (<1860), settlement (1860–1910) and suppression (>1910) eras at Mud Creek and Nile Creek study areas. The 1994 Tye fire was a stand-replacement event that burned an additional 46,575 ha (115,000 acres) adjacent to the study area.

drainage from 1750 to 1910 and 32 times in Nile Creek from 1700 to 1910 (Fig. 4). In the 160 year pre-fire-suppression sample period (1750–1910) common to both sites, there were only nine major fire events that occurred simultaneously (a 25% similarity-Jaccard Index). Our results differ from those of Swetnam and Dieterich (1985) that indicate large fire occurrence on three widely separated study areas was highly correlated as a result of climatic driven (regional) events common to all areas. On our sites, a major proportion of the large fire events appear the result of storm cells or human ignitions that occurred independently on each site.

There were six fires that burned >50% of the two sample areas that occurred in the same years and these were on 20–30 year cycles between 1776 and 1889. This large fire cycle supports Swetnam (1990) suggestion of 3–4 regional fire year opportunities per century. He speculates this is a result of a regional climatic phenomenon that enhances opportunities for ignition and fire occurrence. Our analysis of tree ring widths at both Mud Creek and Nile Creek study areas

Table 2
Percent reduction in tree ring widths for a 5 year mean and a 1 year period prior to large burns compared to ring widths for randomly selected years on Mud Creek and Nile Creek study areas

Study area	Mean reduction in ring width ^a (%)
Mud Creek	
1 year	27
5 years	17
Nile Creek	
1 year	19.8
5 years	16

^a All comparisons between random and pre-fire periods were significantly different ($P = 0.05$) in paired *t*-test of differences.

supports this hypothesis. Mean tree ring widths (a bioassay for drought years — Fritts, 1976) were significantly ($P = 0.05$) less for 5 years and 1 year immediately prior to the major fire events (1776, 1794, 1822, 1841, 1870, 1889) than for random ring widths at both study areas during this time period (Table 2).

3.4. Landscape fire regimes

Fire extent often exceeded the boundaries of individual aspect polygons (Fig. 5) and created larger scale fire patterns on the landscape (Fig. 6). The sequence of fires that burned and reburned different

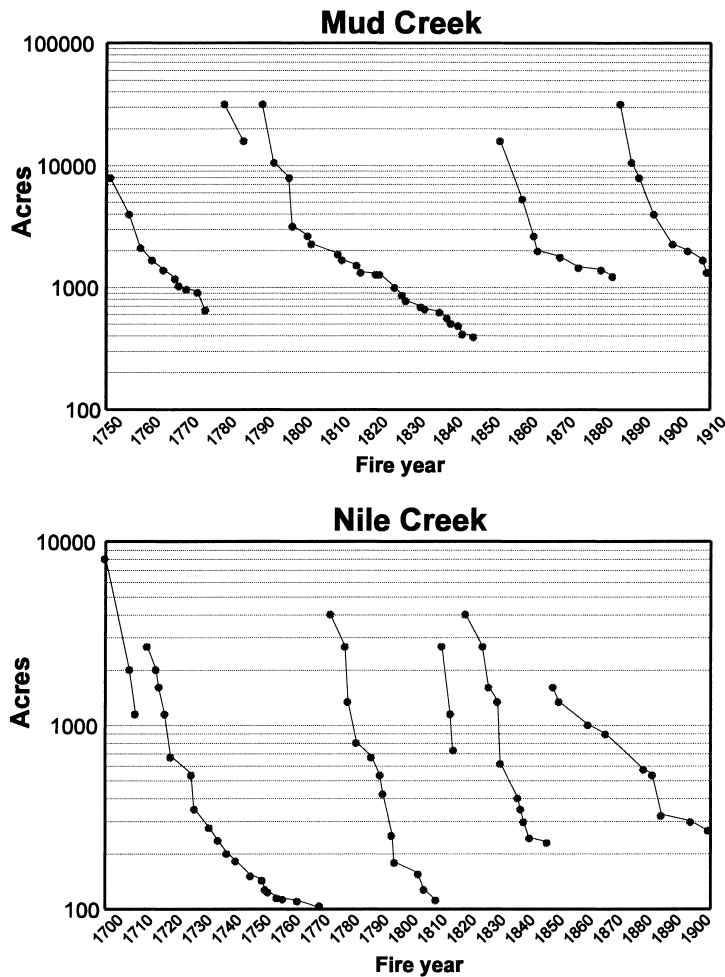


Fig. 5. Bimodal pattern comprised of large episodic and small regular fires events at the Mud Creek and Nile Creek study areas.

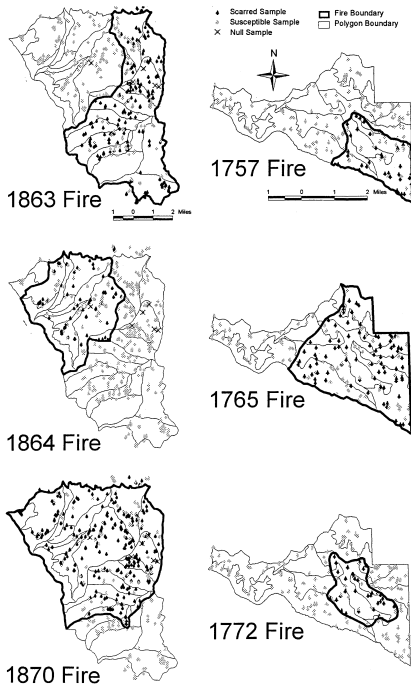


Fig. 6. Overlapping fire events in Mud Creek and Nile Creek study areas.

portions of the Mud and Nile Creek is a typical example (Fig. 6). These sequential fire events create a heterogeneous patchwork of different fire histories (fire history polygons, FHPs) on the landscape as previously reported by Swetnam and Dieterich (1985) and Johnson and Gutsell (1994). The FHPs in Fig. 7 show the fire history mosaic created between 1750 and 1910 and between 1700 and 1910 on the Mud and Nile Creek study areas. In these time periods, we estimate 157 and 134 separate fire history polygons were created at Mud and Nile Creek study areas, respectively. Each FHP differs from adjacent FHPs in numbers of fires or fire dates. The average size of the FHP was 81 and 24 ha (200 and 60 acres) in Mud Creek and Nile sites, respectively. However, the reader is cautioned that fire boundaries are ‘best estimates’ and resulting area computations must be viewed similarly.

The mean size of the FHP is still much greater than the individual cohorts (stand replacement/development patches) that characterize ponderosa pine forests. Cooper (1960) reports the southwestern ponderosa pine type to be an all age forest comprised of even age groups or cohorts with average patch sizes

Fire history polygons

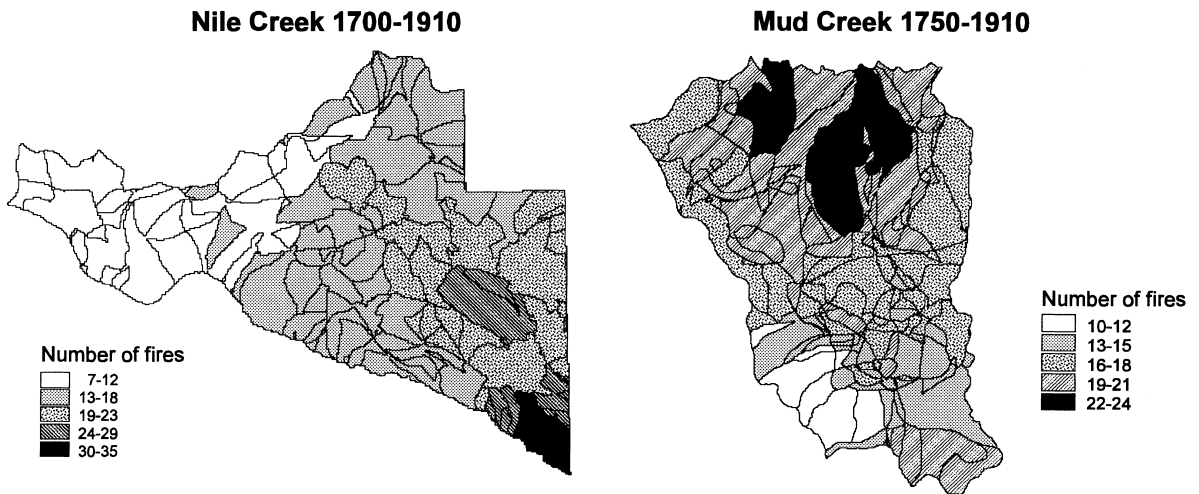


Fig. 7. Fire history polygons for Mud Creek and Nile Creek study areas. Each polygon has a different fire history (numbers or dates) with increased shading corresponding to increased numbers of fires within a polygon.

of 0.06–0.13 ha (0.16–0.32 acre). White (1985) reports ages within groups range from 33 to 268 years and patches are 0.02–0.28 ha (0.05–0.70 acre) in size. We found small (2.4–40 ha (6–100 acres)) single-layered stands, indicating stand-replacement events occurred on north slopes at these study sites.

Overlaying FHPs over aspect polygons demonstrates the heterogeneity in fire history and the potential for vegetation diversity in aspect polygons. There was an average of 6–10 FHPs within each of the homogeneous aspect polygons present on the study areas. The FHP patch size defines a level of landscape heterogeneity created by fire for the pre-settlement/settlement eras (1700/1750–1910). The FHP mosaic may be useful in defining appropriate landscape patchiness in forest management with several caveats. The FHP mosaic and size of polygons is only a transient condition that changes with reoccurring fires. And, although we can describe the fragmentation of previous burns by new fires to establish new FHPs, we do not know when FHPs become insignificant because of severe fire event effects or successional and developmental convergence of FHPs over time.

A large-scale bimodal pattern in area burned occurred on the two study areas (Fig. 5). Large episodic fire events occurred at both sites, followed by a series of progressively smaller fire events. The amount of area burned annually declined rapidly (exponentially) following a major fire event, but rate of decline slowed at 300–1000 ha (740–2740 acres) per year. We suggest that this annual amount of ground fire disturbance created patch heterogeneity in fuels and stand structure that impeded the propagation of fires across the landscape and further reduced the annual amount of area burned. The phenomenon is short lived because as the amount of annual area burned declines the amount of ground fuels and fuel continuity increases. The increased amount of disturbance-prone habitat on the landscape increases the potential spread of fire disturbance (Turner et al., 1989) and sets the stage for the next large-scale fire event.

The variance in numbers of hectares burned during the pre-settlement era (1700/1750–1860) rapidly declined when 6 year sequential increments were used to divide the sampled time period (Fig. 8) and the CV leveled off at 25% for 15–25 year sequential increments for both study areas. Number of hectares burned

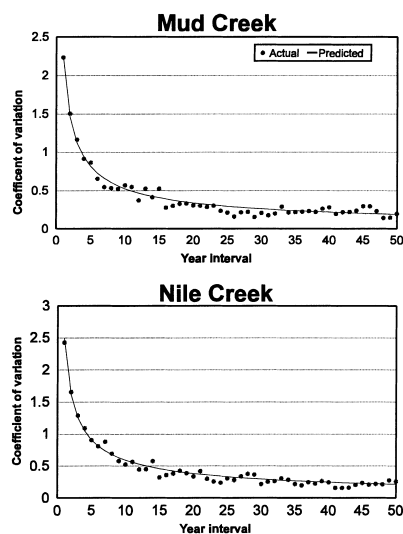


Fig. 8. Coefficient of variation curves for burned hectares based on 1–50 year intervals.

in the 6–7 year period was equal to approximately 50% of the area (1652 ha (4080 acres)) in the Nile and 60% (9312 ha (23,000 acres)) of the area at the Mud Creek sites. These results provided a first approximation to the ‘expected’ or ‘regular’ burn extent for years between major fire events on these sites. The absence of a second sharp decline in variance along the curve indicates the larger fires are episodic and not regular in occurrence.

Examination of tree age at date of pith for the fire scars indicated that minimum tree ages present in aspect polygons ranged from 138 years (1859) to 637 years (1360) in Nile Creek and 82 years (1915) to 491 years (1506) at Mud Creek. There were no major gaps in ages back to the earliest dates. Stand-replacement fire events were absent for several centuries prior to fire suppression on our study sites, but a large stand-replacement fire event occurred within a century of Euro-settlement at Mud Creek. Large stand-replacement fire events may be more regular in the future (Fig. 4) because ground fires no longer maintain fuels at lower levels and fuel ladders to tree crowns are ubiquitously present.

3.5. Estimated fire severity in pre-settlement era

The historical open stand structure in this forest type (Plummer, 1902; Arno, 1988; Fulé et al., 1997)

and a MFFI of 7 years (this study) suggests that fuel loadings were light and regularly consumed by ground fires (Steele et al., 1986) of low severity from 1700/1750 to 1910. We suggest that the small tree diameter at which we found fire scars also supports this view of low fire severity. Pine mortality from fire is mainly the result of crown scorch (Saveland and Neuenschwander, 1991). Flame length and associated fire severity must not have scorched the crowns of these small trees enough to kill the following year's foliage buds. Fires were not severe as the thin bark of small diameter trees was adequate to insulate cambial tissues and prevent mortality (Bevins, 1980). Arno (1988) states that when a Douglas-fir reaches about 15 cm in diameter, it develops the capability to resist surface fires. Fire scars on smaller diameter Douglas-fir trees on our sites indicate low fire severity. In the 407 sampled tree sections (over half of all sections collected) the mean diameter of the tree base at the first fire scar was 8.6 cm (3.4 inch) at Mud Creek and 8.1 cm (3.2 inch) at Nile Creek with a standard deviation of 7.1 cm (2.8 inch) for Mud and 6.4 cm (2.5 inch) for Nile. The mean tree age at the first fire scar was 32–34 years. Average diameter for first fire scars on ponderosa pine (8.6 cm (3.4 inch)) was 3/4 that of the less fire tolerant Douglas-fir (11.2 cm (4.4 inch)). Greater than 80% of these small diameter fire scars occurred in years other than those with widespread (regional) fire events. If widespread fire events can be associated with more severe fire conditions, then small diameter fire scarring is associated with reduced fire severity.

Some trees did escape several fire events and had reached 34 cm (13.4 inch) and 48.3 cm (19 inch) diameter at Nile Creek and Mud Creek sites, respectively, before a fire scar was present. The presence of these larger tree diameters before fire scarring occurred supports evidence of gaps in fire-return intervals and that in at least some cases the subsequent fires were not stand-replacement events.

There were no significant differences ($P = 0.1$) in mean diameter at first fire scar between north and south aspects. This result supports our previous findings of no significant differences in MFFI between aspect polygons; pre-settlement fire events readily crossed aspect polygon boundaries. The extent of the burns and the survival of small diameter trees indicate continuous and fairly light ground fuels. Gaps between fire events sufficient to allow the

development of fuel ladders may predispose certain portions of the landscape to crown fires and maintain a vegetation patch mosaic of different successional stages.

3.6. Gaps in pre-settlement fire frequency

Mean fire-free interval is an average over time that masks periods of reduced fire frequency (gaps). Fire history polygons with reduced numbers of fire events denote gaps in MFFI for that area. Brown and Sieg (1996) suggest variations in MFFI are a determinate in spatial heterogeneity of the landscape, a factor in both stand and landscape diversity. Gaps in large-scale MFFI values can not be directly applied to individual stands, but gaps would denote that a portion of the stands within the area should differ from others as a result of reduced fire effects. Gaps in fire occurrence eliminate the constant cropping of tree seedlings (ladder fuels) and provide opportunities for establishment and growth of Douglas-fir (Arno et al., 1995). We found fire scars on Douglas-fir as young as 12 years of age with 66% of first fire scars occurring between 17 and 49 years of age. On these sites, Douglas-fir can reach sufficient height (4.5 m (15 ft)) and densities within 17–19 years to act as fuel ladders to overstory trees.

On the Nile Creek study area, FHPs with fire histories of more than 24 fires had zero to one fire gaps more than 17 years. Fire history polygons with 13–23 fires had one–two gaps and those areas with 12 fires or less had four–six fire gaps. The areas with fewer fires and the greatest potential for fire gaps and fuel ladders were 245 m (800 ft) higher in elevation than the areas with the highest fire frequency. Since the initiation of effective fire suppression, the potential for MFFI gap areas has expanded across the landscape reducing elevational differences in fire regimes and increasing potential for crown fires across large landscapes. There has been an extended fire-free interval (MFFI gap) on these study sites and elsewhere in the inland West since the late 1800s.

Swetnam and Dieterich (1985) analyzed 800 fire scars on 44 ponderosa pine cross sections that spanned a period of 345 years (1633–1978). Fire-free intervals of 4–8 years were common, but a maximum MFFI of 26 years occurred. Their fire scars indicate that extensive surface fires were a common occurrence in the

ponderosa pine forests in the Gila Wilderness of New Mexico before 1900. However, there were periods of no fire scars on their three study sites (12 years (1825–1837), 18 years (1819–1837), 22 years (1815–1837)), and fire scars ceased to occur after about 1900 (Swetnam and Dieterich, 1985). Arno (1988) reports the last extensive fire in the Bitterroot National Forest, Montana, was in 1895; the last fire in ponderosa pine forests in the Black Hills, South Dakota, was 104 years ago (Brown and Sieg, 1996). Barrett (1988) reports fuel accumulation in southwestern mixed conifer forests over an 81 year period since the last fire occurred in 1893.

3.7. Subsequent severe fire events

Fire size by year was highly variable in pre-settlement and settlement periods, but was uniform and much reduced in the following suppression era at both sites (Fig. 4). From the 1700s to the 1900s there were only three decades where fires greater than 810 ha (2000 acres) in size did not occur on the Nile Creek site, but no fires of that size have occurred since. The Mud Creek site had a severe stand-replacement fire in 1994 that burned much of the area (10,165 ha (25,100 acres)), a similar event can be anticipated for the Nile Creek site in the future given current tree densities and fuel loadings.

The size of the 1994 Tye burn was similar to many of those that occurred in the pre-settlement era, but in that era fires can consistently be characterized as ground fires. Surface fuels provided fire continuity in the pre-settlement era, while tree crowns provide fuel continuity now. Swetnam (1990) reports increased numbers of large and more severe fires from 1950 to present in the southwest region, and a similar increase in fire size and severity was reported for the inland northwest (Steele et al., 1986; Covington et al., 1994). Covington and Moore (1992) describe the phase preceding these catastrophic fire events as the 'coalescing of patches into larger and larger areas capable of supporting crown fire.' Agee (1998) suggests the loss of sharp boundaries among adjacent vegetation patches (patch coalescence) is contributing to the potential for severe fire events. Large-scale stand-replacement fires are now probable over much of this forest type after 80 years of fire suppression effects.

4. Summary

Contrary to our stated null hypothesis, the results show a significant ($P = 0.05$) increase in MFFI and WMFFI between pre-settlement and suppression, and for MFFI between settlement and suppression era values. The lack of a significant difference ($P = 0.1$) between pre-settlement and settlement eras is speculated to result from opposing processes. We suggest Euro-settlement activities reduced fuels and fuel continuity that limited fire spread (Arno, 1988), but this effect may have been offset by increased numbers of human-caused ignitions.

Our spatially heterogeneous landscapes had a mix of fire regimes as previously hypothesized by Johnson and Gutsell (1994). We rejected our null hypothesis that fire history was uniform across the landscape by demonstrating differences in fire history among aspect polygons. We also found and mapped a complex landscape mosaic of fire history polygons that varied in numbers and dates of fire events. The coefficient of variation in MFFI among aspect polygons at the two sites increased from 17 to 23% in the pre-settlement era to 53 and 65% in the suppression era. These results suggest fire regimes have become more complex since Euro-settlement.

We were unable to reject the null hypothesis that MFFI and WMFFI values are constant between north and south aspect polygons. We ascribe this to variability in MFFI and WMFFI values for the same type of aspect polygon because of stochastic processes (Lertzman et al., 1998). Also, fires (1700–1910) readily crossed aspect polygon boundaries and contributed to similar MFFI and WMFFI values for the different polygon types present. Fire history polygons overlap aspect polygons and previous burns may predispose an area to burn again. We found MFFI values varied as much within as among aspect polygons. Fire history polygons may be the appropriate mapping unit for defining local differences in high-frequency/low-severity fire regimes in heterogeneous landscapes.

There is a clear shift to a less frequent, but greater severity fire regime at our study sites as reported elsewhere in the western United States (Barrett, 1988; Covington and Moore, 1994; Mutch, 1994). Excluding the 1994 fire event, there is little evidence for landscape level stand-replacement fires at our sites over the time period covered by the fire scars. Stand

replacement appeared to be limited to individual stands or portions of stands where fire gaps were of sufficient duration for fuels to accumulate and fuel ladders were present to carry the fire to the tree crowns. Now stands with MFFI gaps and greater fuel loads have coalesced across the landscape. The increase in disturbance interval and subsequent fire severity causes longer recovery intervals and jeopardizes ecosystem integrity in this forest type (Turner et al., 1993).

We propose that the fire regime information developed here can be used as a tentative estimate of required fire disturbance for maintaining landscape heterogeneity to reduce catastrophic fire hazard. We suggest a rate of annual burn of 300–1000 ha (740–2470 acres) fragmented disturbance prone vegetation (Turner et al., 1989) on these sites and reduced the hazard for larger-scale fire events.

Our results showed that there was a repeatable burn cycle (CV 60%) during the pre-settlement/settlement eras where an area approximately equal to 50–60% of the Nile and Mud Creek sites burned every 6–7 years. This level of fire disturbance and resultant changes in vegetation patch dynamics provides a biologically defensible reference for vegetation management on these landscapes. This amount of disturbance would appear to support more open forests with reduced hazard to ‘non-historical’ stand replacement events (Everett et al., 1996, 1997). The reduction of current fuels and potential for crown fire appears a prerequisite to reintroduction of inherent fire effects. The dilemma we face is reintroducing fire onto landscapes with continuous disturbance prone vegetation. This suggests the need for large-scale, light treatments to reduce hazard across the landscape (large-scale thinning), with more intense small patch treatments (fuel breaks). In the long term, these treatments should improve ecosystem integrity in the form of a landscape structure supportable under the fire regimes of the area.

The current size of the fire history polygons (24–81 ha (60–200 acres)) created since the 1700s is a transient value and will decline over time as more fire events occur. However, this area may serve as a tentative reference point for the size of vegetation management projects. Management projects of this extent would re-establish the pre-settlement disturbance history patch size, a desired element of the

landscape ‘coarse filter’ approach to conserving biodiversity (Hunter, 1991). Within these disturbance patches, more intense vegetation manipulation (stand replacement) could be practiced on small (e.g., 0.4–1.2 ha (1–3 acres)) sites that mimic even-aged cohort patches characteristic of historical ponderosa pine forests (Cooper, 1960; White, 1985; Arno et al., 1995). Upon verification of the occurrence and size of even-aged cohorts on site, small group selection cuts can be made. The conservation of snags and logs for future forest legacies would need to be considered within these small cut areas since timber harvest does not mimic fire effects.

Using natural fire regimes as spatial and temporal models for managing forests has been previously suggested (Urban et al., 1987; Hunter, 1993; Fulé et al., 1997; Agee, 1998; DeLong, 1998; Lertzman et al., 1998) and linked to viable land-use policy (Everett and Lehmkuhl, 1996; Bovio and Camia, 1997). The restoration of inherent fire disturbance effects is an integral part to restoring and maintaining ecosystem integrity (Agee and Johnson, 1988). A valid land management goal is the creation of an ecologically defensible patch mosaic upon the landscape (DeLong and Tanner, 1996). However, the reader is cautioned that the estimates of annual burn area, size of fire polygons, and cohort patch size given here are only tentative and numerous areas in the northwest need to be examined to verify these initial findings. The use of the stated fire regime parameters as reference points in forest management remains unproven and should only be tested in small areas with adequate monitoring. Also, there is no historical precedent for mechanical soil compaction or roading that may be associated with vegetation treatments and these factors would require other considerations beyond the scope of this paper. Such difficulties should not deter our investigations as ‘there is a need to integrate various aspects of disturbance regimes with (other) human activities’ (Peterson, 1998).

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