Comparison of fire scars, fire atlases, and satellite data in the northwestern United States

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Abstract: We evaluated agreement in the location and occurrence of 20th century fires recorded in digital fire atlases with those inferred from fire scars that we collected systematically at one site in Idaho and from existing fire-scar reconstructions at four sites in Washington. Fire perimeters were similar for two of three 20th century fires in Idaho (1924 and 1986). Overall spatial agreement was best in 1924 (producer's accuracy = 94% and 68% and user's accuracy = 90% and 70% for the 1924 and 1986 fires, respectively). In 1924, fire extent from the atlas was greater than for fire scars, but the reverse was true for 1986. In 1986, fire extent interpreted from the delta normalized burn ratio derived from pre- and post-fire satellite imagery was similar to that inferred from the fire-scar record (producer's accuracy = 92%, user's accuracy = 88%). In contrast, agreement between fire-scar and fire-atlas records was poor at the Washington sites. Fire atlases are the most readily available source of information on the extent of late 20th century fires and the only source for the early 20th century. While fire atlases capture broad patterns useful at the regional scale, they should be field validated and used with caution at the local scale.

Résumé : Nous avons évalué la concordance entre la localisation et l'occurrence des feux survenus au 20e siècle et consignés dans les atlas électroniques des incendies forestiers et les résultats obtenus à partir des cicatrices de feu que nous avons systématiquement relevées à un endroit en Idaho et à partir de reconstructions existantes basées sur les cicatrices de feu à quatre endroits dans l'État de Washington. Le périmètre du feu était semblable dans le cas de deux des trois feux survenus au 20e siècle en Idaho (1924 et 1986). La concordance spatiale globale était meilleure en 1924 (justesse des producteurs = 94 % et 68 % et justesse des utilisateurs = 90 % et 70 % respectivement pour les feux de 1924 et 1986). En 1924, l'étendue du feu était plus grande selon l'atlas que selon les cicatrices de feu mais l'inverse était vrai pour le feu de 1986. En 1986, l'étendue du feu interprétée à partir du ratio delta normalisé de brûlis dérivé de l'imagerie satellitaire antérieure et postérieure au feu était semblable à celle qui a été déduite à partir des données de cicatrices de feu (justesse des producteurs = 92 %, justesse des utilisateurs = 88 %). Par contre, la concordance entre le relevé des cicatrices de feu et les données de l'atlas des incendies forestiers était faible dans le cas des sites de l'État de Washington. Les atlas des incendies forestiers sont la source d'information la plus facilement disponible concernant l'étendue des feux survenus à la fin du 20e siècle et la seule source dans le cas des feux survenus au début du 20e siècle. Tandis que les atlas des incendies forestiers produisent des patrons grossiers utiles à l'échelle régionale, ils devraient être validés sur le terrain et utilisés avec prudence à l'échelle locale.

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Introduction

Modern fire regimes have economic, ecological, and social implications, creating a need to understand how and why they differ from past regimes and how they have responded to changes in land use and climate variation. The types of data available for reconstructing fire frequency, size, and location differ but are seldom compared on the same sites. Without a sense of the relative accuracy of the data sets used to reconstruct them, it is difficult to assess changes in fire regimes over time and space.

While 20th century fire regimes can be characterized from a variety of fire records such as fire-scarred trees, aerial photographs, fire atlases, fire-occurrence records, and satellite data, these records vary in spatial and temporal resolution and the period of time they cover. As a consequence, they vary in their ability to accurately record fire regime descriptors such as fire size, frequency, location, and severity (Morgan et al. 2001; Rollins et al. 2001). Fire scars are often used to characterize past fire regimes because they are a physical proxy for fire (Arno and Sneck 1977; Dieterich and Swetnam 1984), and when crossdated, they yield annually accurate fire dates (Stokes and Smiley 1968; Dieterich and Swetnam 1984). However, the utility of fire scars for characterizing 20th century fire regimes can be limited. Fire scars are not reliably formed in all vegetation types and are often limited to low- to mixed-severity fire regimes. In many areas of the northwestern United States, logging and prescribed and wildland fires have consumed fire scars and (or) killed live trees, thus reducing the number of trees that could record 20th century fires. After many decades of fire

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exclusion, fire-scar wounds may close, concealing existing fire scars (Dieterich and Swetnam 1984; Agee 1993; Morgan et al. 1994; Smith and Sutherland 2001). Finally, it is challenging to estimate area burned from fire scars because they are point records (Hessl et al. 2007).

Where fire atlases are available, they are a digitized record of fire perimeters (Minnich 1983; Barrett et al. 1991; McKelvey and Busse 1996; Keeley et al. 1999; Morgan et al. 2001; Rollins et al. 2001, 2002; Teske 2002). They can be used to infer fire extent by vegetation type (Morgan et al. 2001; Rollins et al. 2001; Gibson 2006). However, fire-atlas records are also limited in several ways. Small fires (e.g., those <40 ha) are often not mapped and the accuracy of the location and date is often unknown and likely has varied through time (McKelvey and Busse 1996; Rollins et al. 2001; Gibson 2006). Fire perimeters have been mapped using a variety of methods, are often approximate, and usually do not indicate within-perimeter heterogeneity in fire such as unburned islands. For example, early 20th century perimeters were digitized from hand-drawn perimeters on topographic maps, personal journals, archived fire reports, and word of mouth (Minnich 1983; Teske 2002; Gibson 2006). Finally, there are gaps in fire atlases in time and space due to staff and resource limitations.

Late 20th century fires may also be mapped from satellite data using indices derived from the spectral and thermal properties of pre- and post-fire landscapes. These maps include within-perimeter heterogeneity in burning but can only be generated for late 20th century fires (Lentile et al. 2006) and the accuracy of these maps has not been fully assessed at fine scales or for low- to mixed-severity fires (but see Fraser et al. 2004; Cocke et al. 2005; Holden et al. 2005; Roy et al. 2006).

There are few studies quantifying agreement among these record types despite their importance in evaluating changing fire regimes across landscapes, managing areas influenced by 20th century human practices, and guiding ecological research. Fire-atlas records have been compared with fire perimeters derived from satellite data (Holden et al. 2005), aerial photographs (Teske 2002), and fire scars (Fulé et al. 2003). However, all of these studies were conducted in designated wilderness areas or national parks, where record keeping is often more consistent than in areas with more intensive land use.

Our objective was to evaluate the agreement in fires reconstructed from fire scars with those recorded in fire atlases at five sites. We reconstructed fires from fire scars that we collected systematically at one site in Idaho and from existing fire-scar reconstructions at four sites in Washington. We used digital fire-atlas records maintained by the USDA Forest Service for all five sites. In addition, we compared fire scars from a recent fire at the Idaho site with a fire reconstructed from a delta normalized burn ratio (dNBR) classification that we derived from satellite data for the same area. Because fire scars are undisputable evidence of fire at points (Fulé et al. 2003), we used them as the reference with which we compared the fire atlases and dNBR classification.

Methods

Study areas

We reconstructed 20th century fire regimes from fire scars collected near Powderhouse Gulch on the west side of the Middle Fork of the Payette River, Boise National Forest, Idaho (Fig. 1). We selected this 611 ha site because it included three 20th century fires in the fire-atlas record, appeared to have recent fire scars on ponderosa pine and Douglas-fir trees, and had not been harvested or otherwise disturbed (e.g., terraced). Surrounding this site (i.e., in the Boise, Nez Perce, and Payette National Forests), 20th century fire extent ranged from 0.3 to 70 054 ha with a median of 138 ha (computed from 300 fire polygons, 1900–2003; Gibson 2006). It is typical of dry ponderosa pine (*Pinus ponderosa* P. & C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) forests that occur between 900 and 1900 m in central Idaho (Rehfeldt 1986). The topography is heavily dissected with slopes at plots ranging from 15% to 75% and overall aspect west to southwest. Summers are dry (average annual precipitation 62 cm, 1948–2005; Western Regional Climate Center 2006) and most annual precipitation falls as snow (79%).

Fig. 1. Sites in Idaho and Washington, USA, showing the location of new (P = Powderhouse) and existing (F = Frosty, Q = Quartzite, S = South Deep, and T = Twenty Mile; Everett et al. 2000) tree-ring reconstructions of fire history for which we assessed agreement with fire-atlas and satellite (dNBR) records. Shaded regions are managed by the USDA Forest Service (from west to east: Okanogan-Wenatchee, Colville, and Boise National Forests).

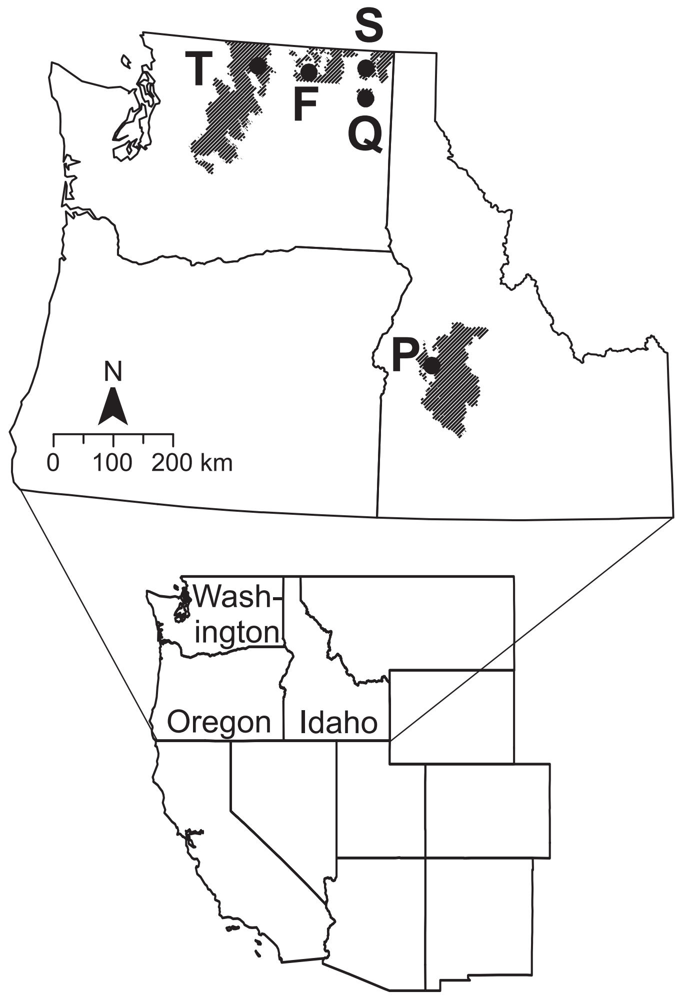
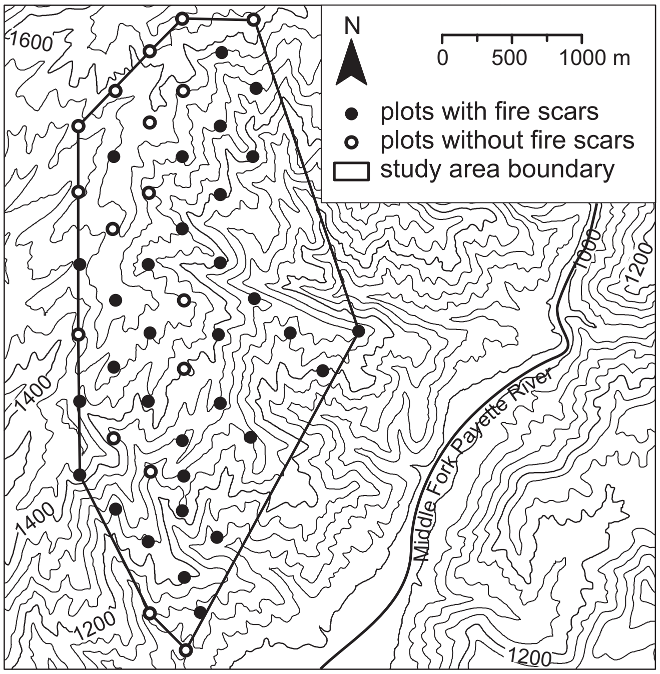


Fig. 2. Powderhouse site showing location of the 49 plots sampled for fire scars for this study. The symbols refer to 20th century fire scars only. Some of the plots that lacked 20th century fire scars did have fire scars from prior centuries.



We obtained existing fire-scar reconstructions from four sites in Washington, all of which are also dominated by ponderosa pine and Douglas-fir (Everett et al. 2000; Hessl et al. 2004) (Fig. 1). Climate at these sites is similar to that at Powderhouse, with dry summers (average annual precipitation 29–49 cm, 1948–2005; Western Regional Climate Center 2006), much of which falls as snow in winter (46%–68%).

Fire-scar records

In 2004 and 2005, we systematically collected 79 fire-scarred samples over 611 ha at Powderhouse Gulch on a staggered grid of 49 plots in which the plots are 338 m apart on average (range 224–441 m) (Fig. 2). Within 50 m of each plot center (corresponding to a plot size of 0.8 ha), we used a chain saw to remove a partial cross section from up to five trees with the best-preserved recent fire scars (average three trees; Arno and Sneck 1977). Most sampled trees were live (76%) with the rest stumps, snags, and logs. From the majority of the live trees with only a single visible fire scar (44% of sampled trees), we removed an increment core that intersected that scar (Barrett and Arno 1988). Nearly all sampled trees were ponderosa pine (96%) with the rest Douglas-fir. We recorded the location of each sampled tree with a global positioning system.

We hand-planed and then sanded all samples until we could discern cell structure under a binocular microscope. To assign the exact calendar year to each tree ring, we visually crossdated tree rings using a master ring-width chronology generated from our samples and checked against regional chronologies (Stokes and Smiley 1968). We verified the quality of our crossdating using cross-correlation of measured ring-width series (Holmes 1983; Grissino-Mayer 2001*a*) and by having two dendrochronologists review the dating of each sample. We excluded samples from five trees that were not recording during the 20th century, leaving samples from 74 trees for analysis. We determined the exact calendar year of each fire scar by noting the date of the annual ring in which it occurred (Dieterich and Swetnam 1984). We assigned ring-boundary scars to the preceding calendar year because modern fires near the study area generally burn in mid- to late summer (Schmidt et al. 2002).

Some plots had no 20th century fire scars (17 plots or 35%) (Fig. 2). We determined if the existing live trees at 13 of these plots established before or after our 20th century fires by estimating the establishment dates of up to 31 trees (≥5 cm in diameter at 20 cm above ground on the downhill side) that were closest to but within 30 m of plot center (Lynch and Wittwer 2003). We estimated the establishment date of most of these trees by removing an increment core near the ground (average 22 cm above ground level, range 20–80 cm). Increment cores were prepared and crossdated as described above. Most increment cores (75%) did not intersect the pith. To estimate the pith date of these trees, we estimated the number of years to pith from the curvature of the innermost rings sampled (average 6 years, range 1–22 years) and subtracted this estimate from the innermost ring date. To estimate establishment dates from pith dates, we subtracted 1 year for every 5 cm of core height based on the height growth of five saplings planted in 1990 in the study area. For trees <5 cm in diameter (11%) within 10 m of plot center, we sampled destructively or counted branch whorls, assuming that one branch whorl was added each year after the tree established.

The four existing fire histories were sampled systematically by Everett et al. (2000) over areas ranging from 4330 to 7537 ha in size, but not on a grid of plots. Rather, each study area was divided into topographic facets (contiguous areas of relatively homogeneous aspect) that were searched for fire-scarred trees. The number of trees sampled at each site ranged from 141 to 420 and within each facet from 3 to 87. The fire-scarred partial cross sections were processed and crossdated using techniques similar to those that we used for Powderhouse (Everett et al. 2000). We filtered the data set to include only trees with a record of 20th century fires (range 110–243 trees per site).

At each of the five fire history sites, we excluded fire dates recorded on fewer than three trees so that we could compute fire extent for each fire date. We defined the recording period for an individual tree as the period after the first scar on that tree (Grissino-Mayer 2001*b*) and defined the recording period for each site as the composite of the recording periods for all trees at that site. We evaluated the probability that additional sampling would detect additional fire dates by computing the cumulative percentage of fire dates detected by an increasing number of randomly selected trees, analogous to a species–area curve (Falk and Swetnam 2003; Fulé et al. 2003; Stephens et al. 2003; Hessl et al. 2004). If this percentage reaches 100% (i.e., all fire dates are included) before most of the sampled trees have been included, we assumed that sampling additional trees would likely not yield new fire dates.

Fire-atlas records

We used a digital fire atlas compiled from records kept at the Boise (Gibson 2006), Okanogan-Wenatchee, and Colville National Forests. We obtained the year of each fire from the attribute fields associated with the fire perimeters and determined fire extent by clipping perimeters to and calculating the area that lay within study area boundaries (defined by a convex hull around fire-scar plots or locations) using a geographic information system. The fire atlases include both individual years without fires and multiyear periods without fires. Such periods could merely lack fires large enough to map (i.e., >40 ha), but they could also be periods when no records were kept. Therefore, for each national forest, we defined recording years as those when any fires were recorded and assessed agreement in fire occurrence only during those years when both fire scars and fire atlases were recording.

dNBR classification

To identify burned areas from satellite data for the most recent fire at Powderhouse, we used terrain-corrected scenes (Landsat 5 thematic mapper + path 41 row 29) for a fire that burned from 10 August to 30 September 1986. We obtained cloud-free pre- and post-fire images as close to the date of the fire as possible (20 August 1985 and 10 October 1986, respectively) and calculated dNBR from an initial assessment of burning (López Garcia and Caselles 1991; Chander and Markham 2003; Key and Benson 2006). We compared pre- and post-fire images in false color for indications of seasonal differences and determined that annual phenological changes in vegetation between the end of August and the beginning of October were minimal across the images. We also deemed that atmospheric normalization was unnecessary (black body spectral reflectance <2.5% in band 4 and zero in band 7) and verified that the images were coregistered (Key and Benson 2006). We classified each pixel as unburned (dNBR ≤ 100) or burned (dNBR >100) using suggested default values (Key and Benson 2006). Approximately nine 30 m × 30 m pixels from the images fall within each of the 49 plots that we sampled for fire scars.

Agreement among record types

At Powderhouse, we identified 20th century fires from our three types of fire records by assuming that a fire occurred at a plot during a given year (*i*) in the fire-scar record if a fire scar was present on at least one tree in that plot and three or more trees across the site, (*ii*) in the fire-atlas record if it lay on or within a fire perimeter, and (*iii*) in the dNBR classification if any of the nine pixels at that plot were classified as burned. We tallied agreement and disagreement in fire occurrence between record types (fire scar and fire atlas or dNBR) in 2 × 2 error matrices for each fire year (Congalton 1991). Fire-atlas perimeters do not include information on intraperimeter variation in burning, so we used only plots on or adjacent to fire perimeters in error matrices including fire-atlas records. In contrast, dNBR does record intraperimeter variation in burning, so we used all plots in error matrices including this record type. Because the fire records in adjacent plots burning during the same year were autocorrelated (Moran's I = 0.13–0.46), we assessed agreement among record types by applying McNemar's test with an autocorrelation penalty to each of the error matrices under the null hypothesis of marginal homogeneity (Daniel 1978; Upton and Fingleton 1985; PROC FREQ, SAS Institute Inc. 2003). For this test, we identified significant differences among record types when the significance level (α) was <0.05 for years with only fire-scar and fire-atlas records or <0.025 for years with all three record types (Bonferroni adjustment, Ott and Longnecker 2001). In addition to assessing agreement among record types using McNemar's test, we computed two descriptive statistics. The producer's accuracy quantifies errors of omission (1 minus the number of plots with fire in both records divided by the total number of plots with fire in the fire-scar record) whereas the user's accuracy quantifies errors of commission (1 minus the number of plots without fire scars outside the fire-atlas perimeter (or unburned in dNBR) divided by the total number of plots outside the fire-atlas perimeter (or unburned in dNBR) (Jenson 1996). Perfect agreement between two records would yield accuracies of 100%.

We compared fire extent between records types (fire scars compared with fire atlas or dNBR) for years common to both. For the fire-scar record, we computed fire extent as the area of a convex hull around fire-scar plots with evidence of fire because we assumed that such a fire boundary would be most similar to those in the fire atlas. For the fire-atlas record, some fires extended beyond the boundary of our study area, so we computed fire extent as the area that was within a fire perimeter but confined to the study area boundary. For the dNBR classification, we computed fire extent as the summed area of all pixels classified as burned within a subjectively digitized perimeter, excluding unburned pixels or islands, confined to the study area boundary.

At the four existing fire history sites in Washington, we identified 20th century fires as described above and tallied agreement between record types (fire atlas and fire scar only) in error matrices for years with fires common to both types. However, we did not statistically test these matrices because the sampling design was not ideal for this analysis (largely disproportionate number of samples outside the fire-atlas boundary will inflate agreement: Congalton 1991; Congalton 2001). We also excluded fire-scarred trees that were not recording during the recording periods of the fire atlas (37 trees from South Deep, 146 trees from Frosty).

Results

Fire-scar records

At Powderhouse, we reconstructed two 20th century fires from 88 fire scars on 74 trees (1924 and 1986) (Table 1). These data are available from the International Multiproxy Paleofire Database (Shapiro 2006). Fire extents derived from convex hulls were ≥40 ha for both. We excluded one year (1938) from further analyses because it was recorded by a fire scar on only one tree. At the existing fire history sites in Washington, the fire-scar record included 5–24 years with fires of any size and 0–10 years with fires >40 ha per site (Table 1). At the existing sites, we excluded 28 years from further analyses (2 from Frosty, 8 from Quartzite, 13 from South Deep, and 5 from Twenty Mile) because they were recorded by a fire scar on only one or two trees. At all sites, the fire scar records that we used in this analysis were recording throughout the 20th century (Fig. 3).

Table 1. Twentieth century fires recorded in the fire-scar (only years recorded on three or more trees per site are included) and fire-atlas records.

		Fire extent (ha)	
Site	Fire date	Fire-scar record	Fire-atlas record
Powderhouse	1924	291	529
	1926	No fire-scarred trees	40
	1986	337	297
Frosty	1909	25	No record
	1910	5 760	84
	1917	2 490	No record
Quartzite	1910	3 320	No record
	1914	101	No record
	1917	1 240	No record
	1918	205	No record
	1920	20	No record
	1922	56	No record
	1931	Fire scars on 2 trees	236
	1934	Fire scars on 2 trees	1757
	1949	4	No record
	1973	5	No record
South Deep	1909	227	No record
	1914	910	No record
	1916	10	No record
	1917	9 990	No record
	1919	10 900	No record
	1921	7 730	No record
	1922	4 360	No record
	1924	41	No record
	1926	No fire-scarred trees	2510
	1929	1 630	350
	1938	247	Atlas not recording
	1973	820	Atlas not recording
Twenty Mile	1914	No fire-scarred trees	15
	1916	No fire-scarred trees	24
	1973	No fire-scarred trees	3

Note: At South Deep, there was a long midcentury gap in the fire atlas record (1941–1970 and 1972–1984). Fire years recorded by fire scars on fewer than three trees that do not correspond to fire atlas dates are not shown (1 year at Powderhouse, 2 at Frosty, 6 at Quartzite, 13 at South Deep, and 5 at Twenty Mile).

Before each of the three 20th century fires in the fire atlas, trees that could be scarred had established in most of our plots. We estimated the establishment dates of 319 trees at 13 of the 17 plots that lacked fire scars. From these establishment dates and tree rings from fire-scarred trees, we determined that of the plots within the 1986 fire perimeter all contained trees that established before 1986. Within the 1924 and 1926 perimeters, five plots lacked trees that established before each of these fire years.

Fire-scar sampling was adequate to detect fires of any size at Powderhouse and at all of the existing fire history sites except Twenty Mile. The cumulative percentage of fire dates sampled reached 100% when <50% of sampled trees per site were randomly included. We could not assess sampling adequacy at Twenty Mile because no fires were recorded on three or more trees during any year at this site (Table 1).

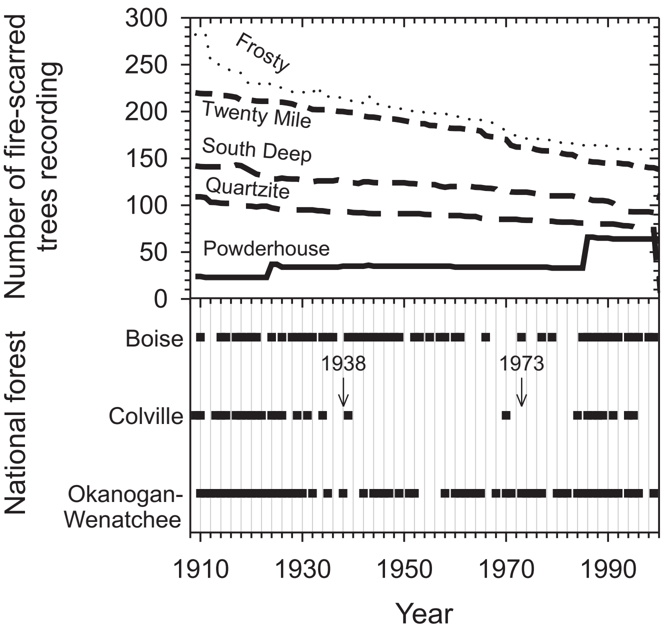
Fire-atlas records

At Powderhouse, the fire-atlas record included three fires, all ≥40 ha (Table 1). The atlas record at the existing fire history sites included one to three years with fires of any size per site and zero to two years with fires ≥40 ha. The fire-atlas record was not continuous during the 20th century but was generally sufficient for our analysis. The Boise (Powderhouse) and Okanogan-Wenatchee (Frosty and Twenty Mile) National Forest fire atlases included no gaps longer than 6 years, and none of the fires ≥40 ha in the fire-scar record occurred during these gaps (Fig. 3). In contrast, the Colville National Forest (Quartzite and South Deep) fire atlas included a long gap in recording from 1935 to 1982 during which the 1938 and 1973 fires at South Deep occurred (Fig. 3).

Agreement among record types

At Powderhouse, all of the fires >40 ha were recorded by both the fire-scar and the fire-atlas records (1924 and 1986) (Fig. 4). The atlas record also included a 40 ha fire that was not recorded by fire scars (1926). In 1924, the fire perimeters derived from the fire-scar and fire-atlas records were

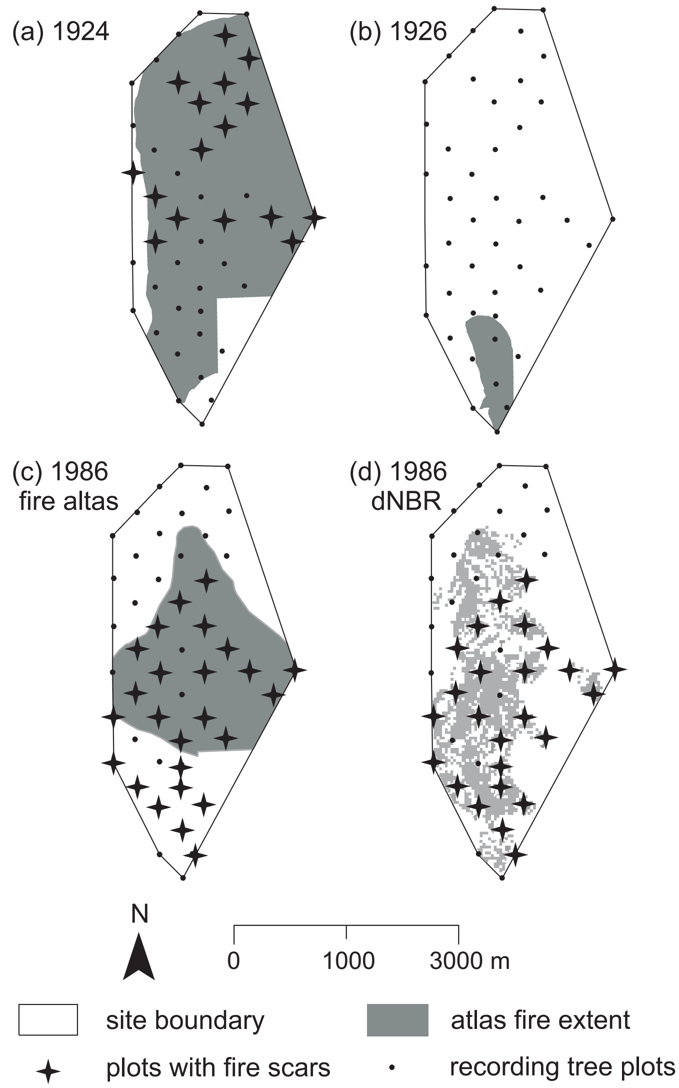
Fig. 3. The 20th-century period of documentation for fire-scar (top) and fire-atlas records (bottom). Powderhouse is within the Boise National Forest, South Deep and Quartzite within the Colville, and Twenty Mile and Frosty within the Okanogan-Wenatchee. All fires with extents ≥40 ha in the fire-scar record burned during years when the fire atlas was recording, except 1938 and 1973 at South Deep (shown by arrows).



similar (McNemar's $p = 0.197$) (Table 2). For this year, fire extent in the fire-atlas record was greater than that in the fire-scar record (87% versus 48% of the study area, respectively) (Fig. 5). However, most of the recording plots with fire scars (15 of 16) were within the fire-atlas perimeter, yielding a 94% producer's accuracy, and very few of the plots outside this perimeter (1 of 10) had fire scars from this year, yielding a 90% user's accuracy (Tables 2 and 3). In 1986, the fire perimeters derived from the fire-scar and fire-atlas records were also similar (McNemar's $p = 0.796$) (Table 2). Most of the plots with fire scars in this year (17 of 25) were within the fire-atlas perimeter, yielding a 68% producer's accuracy, but some of plots outside this perimeter (8 of 27) had fire scars from this year, yielding a 70% user's accuracy (Tables 2 and 3). For this same year, fire-scar and dNBR records were also similar (McNemar's $p = 0.302$). Additionally, most of the plots with fire scars from this year (23 of 25) were also interpreted as burned based on dNBR, yielding a 92% producer's accuracy, and few of the plots interpreted as unburned (2 of 16) had a fire scar in this year, yielding an 88% user's accuracy (Tables 2 and 3). Fire extent computed from the fire-scar record was nearly identical to that from the dNBR (55% versus 53% of the study area, respectively) and the two extents overlap but were not coincident (Fig. 5).

At all of the existing fire history sites except Twenty Mile, more 20th century fires were reconstructed from fire scars than were recorded in the fire atlases (Table 1). For fires ≥40 ha, neither record contained fires at Twenty Mile, but at the other sites the fire-scar record included 2–10 fire years per site whereas the fire-atlas record included only one

Fig. 4. Fire-scar and fire-atlas records and dNBR classification (1986 only) at Powderhouse. Of the 49 sampled plots, 5 did not have trees that established before (*a*) 1924 or (*b*) 1926 and so are not shown. (*c* and *d*) All 49 plots had trees in 1986. The fire-atlas and dNBR boundaries both extend beyond the sampling area.



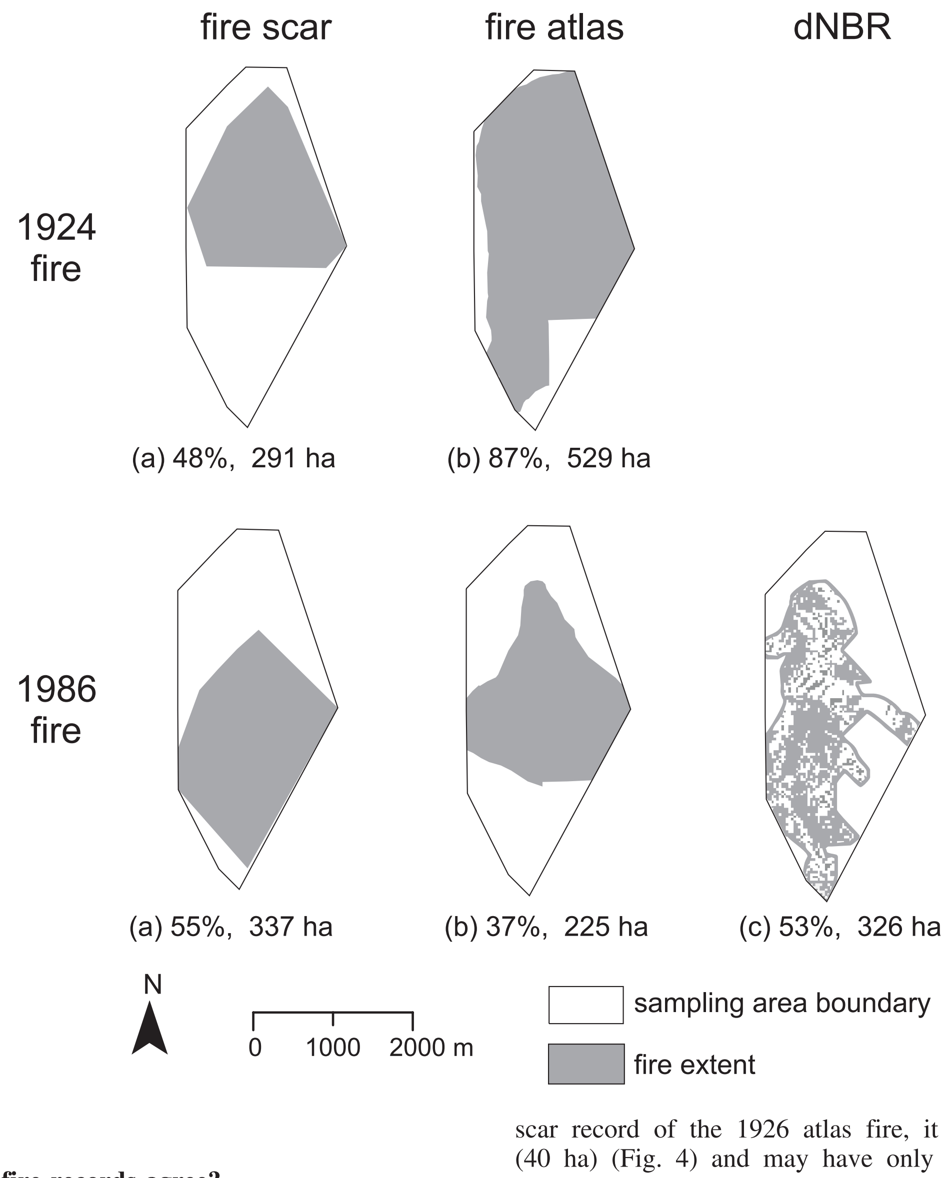
or two such years. For fires of any size, the fire-scar record included 0–11 fire years per site whereas the fire-atlas record included only one to three such years (three or more trees scarred). Only two years were common to both record types (1910 at Frosty and 1929 at South Deep) (Fig. 6), both of which had fire extents ≥40 ha in both record types. However, spatial agreement was poor. At South Deep, no trees within the 1929 fire-atlas perimeter had fire scars for that year (0% of 16 recording trees), while three trees sampled outside the fire-atlas perimeter had fire scars for that year (3% of 115 recording trees outside the perimeter) (Table 2; Fig. 6). At Frosty, two of the trees sampled within the 1910 fire-atlas perimeter had fire scars for that year (two of three recording trees within the atlas perimeter), while 115 trees sampled outside the fire-atlas perimeter had fire scars for that year (42% of 271 recording trees outside the perimeter) (Table 3; Fig. 6).

Table 2. Agreement between the fire-scar and fire-atlas records or dNBR classification at Powderhouse using descriptive statistics (producer's and user's accuracies) and McNemar's test of agreement with a penalty for autocorrelated sampling locations (Daniel 1978; Upton and Fingleton 1985).

				McNemar's test		
Fire record	Fire year	Producer's accuracy (burned)	User's accuracy (unburned)	Plots included	Test statistic	*p*
Fire atlas	1924	94	90	Perimeter	1.667	0.197
Fire atlas	1986	68	70	Perimeter	0.667	0.796
dNBR	1986	92	88	All	1.067	0.302

Note: For the 1924 fire, McNemar p values <0.05 indicate that the fire-atlas record differs significantly from the fire-scar record. For the 1986 fire, this p value is 0.025 due to a Bonferroni adjustment (Ott and Longnecker 2001).

Fig. 5. Fire extent at Powderhouse calculated from the three different fire history records: (*a*) fire scar (convex hull around plots with fire scars), (*b*) fire atlas, and (*c*) dNBR (subjectively drawn perimeter). Note that fire-atlas boundaries extend beyond the sampling area.



Discussion

How well do the fire records agree?

Agreement among records of 20th century fire was good at the Powderhouse site that we sampled to specifically assess this agreement. The fire-scar and fire-atlas records both included large fires (>40 ha), with statistically similar perimeters, during the same years. While there was no fire-scar record of the 1926 atlas fire, it was small in extent (40 ha) (Fig. 4) and may have only scarred trees outside plots in our sampling grid or there may not have been sufficient fuel to scar trees if this area burned 2 years prior during the 1924 fire recorded in the fire atlas. We expected fire-atlas records to be more consistently accurate in the late than in the early 20th century because later perimeters could be mapped using helicopters, global positioning sys-

Table 3. Error matrices tallying agreement in fire occurrence between fire-scar and fire-atlas records or dNBR classification.

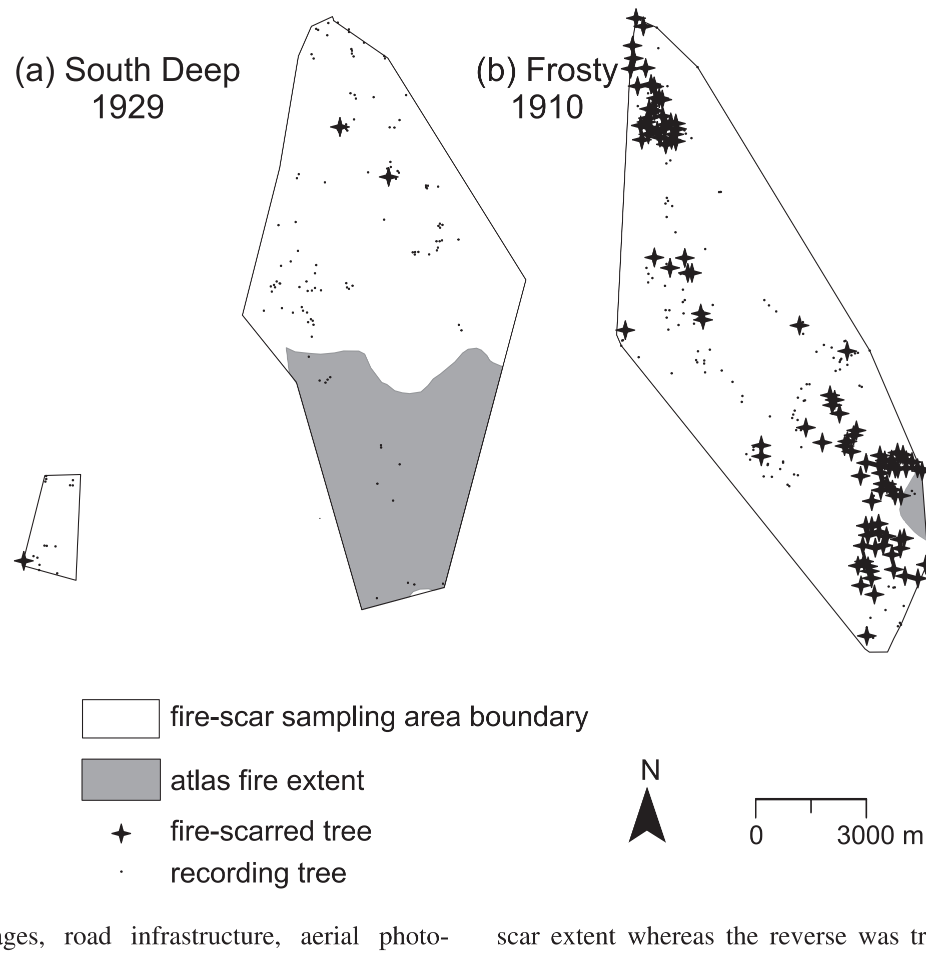
Site	Record type	Recorded?	Fire year	Fire-scar record, all plots/samples*		Fire-scar record, perimeter plots (number of plots)	
				Recorded	Not recorded	Recorded	Not recorded
Powderhouse†	Atlas	Recorded	1924	15	19	3	11
		Not recorded		1	9	1	8
	Atlas	Recorded	1926	0	4		
		Not recorded		0	40		
	Atlas	Recorded	1986	17	5	9	2
		Not recorded		8	19	1	9
	dNBR	Recorded	1986	23	10		
		Not recorded		2	14		
Frosty	Atlas	Recorded	1910	2	1		
		Not recorded		115	156		
South Deep	Atlas	Recorded	1929	0	16		
		Not recorded		3	112		

Note: Fire atlas boundaries that extended beyond our Powderhouse sampling area are not shown. Therefore, numbers shown for perimeter plots cannot be derived from figures.

*For Powderhouse, this is the number of plots. For the existing fire history sites in Washington, it is the number of trees.

†By 1924 or 1926, 44 of 49 sampled plots had trees. All 49 plots had trees in 1986.

Fig. 6. Fire-scar (Everett et al. 2000; Hessl et al. 2004) and fire-atlas records for the only two years common to both records at the existing fire history sites. Fire scars were collected in two separate areas at South Deep.



tems, satellite images, road infrastructure, aerial photographs, and large crews. However, the difference between fire extent shown by fire-scar and fire-atlas records was similar, but of opposite sign, early and late in the 20th century. For one year (1924), the atlas extent was greater than the scar extent whereas the reverse was true for the other year (1986). If, as we have assumed, the fire-scar record is correct, then the 1924 atlas perimeter was mismapped. Alternatively, the fire-scar record may be incomplete. However, while the presence of a fire scar is incontrovertible evidence of fire, the absence of fire scars is not necessarily evidence of a lack of fire for a variety of reasons (Fulé et al. 2003). For example, the fire in 1924 may not have been severe enough to scar trees in the southern end of the study area (i.e., the fire left large unburned or lightly burned islands) or scars created in 1924 or 1926 may have been consumed by the 1986 fire. In contrast, the atlas perimeter for the 1986 fire appears to have been mismapped based on the presence of fire scars outside the atlas perimeter. The dNBR classification yields a perimeter similar to that from fire scars and so supports this. However, it is not likely that the fire-scar sampling area included the full extent of most fires at any site.

While the agreement was good among fire record types at Powderhouse, we had only a small number of 20th century fires with which to test this agreement. Although we searched extensively, we found few accessible sites in Idaho or western Montana that had 20th century fires recorded in a fire atlas in forests with ponderosa pine trees, stumps, or logs. Few sites in this region are well suited to this sort of comparison between fire history records, in part because there are relatively few locations where 20th century fires burned with sufficiently low severity to leave many fire-scarred trees. This suggests broad agreement between the data sources in that there were many locations with no fires recorded in fire scars or fire atlases, but we did not assess that quantitatively. We may have found greater agreement if we had included fires recorded on one or two trees (e.g., 1931 or 1934 at Quartzite) or if all small fires (<40 ha) had been recorded in the fire atlas. The agreement between fire-atlas and fire-scar records is likely to be good for fires severe enough to leave a structural legacy that can be seen in the field or on aerial photographs many years after the fire, but our study included only tree-ring evidence of low-severity fires. We suggest that if we had tested the agreement among tree-ring records, fire-atlas records, and a dNBR classification for a stand-replacing fire, overall spatial and perimeter agreement in fire occurrence would be better than we found in this study, as others have suggested (Holden et al. 2005).

Agreement was poor between the fire-scar and fire-atlas records at the existing fire history sites in Washington. None of these sites were sampled to assess agreement among fire record types. Although some 20th century fire scars may have formed but been destroyed by subsequent fires or not sampled because they had too few scars, the fact that many more fires were identified in the fire-scar than in the fire-atlas record implies that record keeping for the fire atlases may have been poor in the early 20th century at these sites. The 1938 and 1973 fires at South Deep occurred during a likely gap in record keeping, and the other fires that were recorded by fire scars but not in the atlas may have occurred in temporal gaps that we failed to identify or in areas that were not regularly patrolled.

Estimating historical fire extent and area burned in stands that most likely experienced low- to mixed-severity fire is one of the major challenges associated with mapping fire over landscapes (Morgan et al. 2001; Rollins et al. 2001; Jordan et al. 2005). Fire extent provides information about the total area potentially affected by fire whereas area burned provides information about within-perimeter heterogeneity in fire severity and (or) the size of burned patches and unburned islands. While fire extent in 1986 at Powderhouse was nearly identical when computed from the fire-scar and dNBR records (55% versus 53% of the study area), the dNBR area burned was only 29% of the study area. This is due to heterogeneity of burning within the fire perimeter. However, our analysis was a difficult test of dNBR classification because the ability of the satellite images to differentiate burned from unburned pixels was limited by low tree density, hence high soil exposure, low postfire tree mortality, senesced vegetation in both pre- and post-fire images, low, late-season sun angles, and minimal scorching of the top of the canopy (the vantage point of the satellite: Rollins et al. 2001; Cocke et al. 2005; Key and Benson 2006; Lentile et al. 2006). As a consequence, area burned may be underestimated. While some information on within-perimeter heterogeneity can be derived at some spatial scales from fire scars, no such information is provided by the fire-atlas record.

Using fire atlases to describe fire regimes

Despite their limitations, fire atlases will continue to be the most readily available source of information on the extent of late 20th century fires and they remain a primary source of such information for the early 20th century. Fire atlases are likely to be inaccurate at the local scale for several reasons (Gibson 2006). Our data suggest that temporal agreement is better than spatial agreement, and agreement is better for larger fires than for smaller ones. Unfortunately, we have too few fires to draw general conclusions. Although fire atlases contain some inaccuracies in fire locations and some gaps in recording, they are the only spatially explicit record of fire for the entire 20th century (Morgan et al. 2001). They are consistent with shorter records of fire such as those stored in the National Interagency Fire Management Integrated Database (USDA Forest Service 1993; Gibson 2006) and satellite imagery as well as with longer tree-ring records of fire. The records they contain are sufficiently accurate to reveal climate drivers of fire that are consistent with those reconstructed from fire scars for several prior centuries (e.g., Westerling et al. 2006). While new sensors, indices, and techniques to discern burned from unburned areas using satellite data continue to evolve, the cost associated with these images, along with the availability of smoke- and cloud-free images, currently limits their widespread use (Holden et al. 2005; Lentile et al. 2006).

Can fire atlases be used in ways that take advantage of their strengths while minimizing the effect of their limitations? We suggest that they are useful at coarse scales, for example to identify regional fire years, those years with widespread synchronous fires. For example, a fire atlas for the Northern Rocky Mountains correctly identified regional fire years in 1889, 1910, 1919, 1994, 2000, and 2003 (Gibson 2006). Large fires are socially, economically, and ecologically more significant than small, local fires and are therefore more likely to be accurately documented in fire-atlas records (McKelvey and Busse 1996; Gibson 2006). The role of climate in driving fire is most evident in the occurrence of widespread regionally synchronized fires (Swetnam and Betancourt 1990, 1998; Westerling et al. 2006).

It is challenging to assess agreement among historical records of fire but essential to understand the relative accuracy of these records before they are used to inform policy, make land-management decisions, or guide ecological research. Given that mapping standards are not consistent across land-management units or through time (Gibson 2006) and that the differences between record types varied among land-management units in our study, fire-atlas records should be verified locally if they are to be used at that scale, for example by identifying gaps in recording and the minimum mapping unit. In addition to verifying atlases using fire scars or remotely sensed data as we have done here, some atlas records can be compared with aerial photographs, newspaper accounts, journals, or other digital fire records such as those stored in the National Interagency Fire Management Integrated Database.

Fire-atlas records are a bridge between historical fire occurrence interpreted from tree-rings, 20th century fire patterns, and future predictions of the location, size, and pattern of fires. Understanding the complex interrelationships between fire, vegetation, topography, and climate hinges on synthesizing findings across multiple data sets (Morgan et al. 2001). More studies like this one are needed to help us interpret fire occurrence, location, and frequency information from different sources of information, each of which has different values for inferring fire regimes across time and space (Morgan et al. 2001).

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References

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

Arno, S.F., and Sneck, K.M. 1977. A method for determining fire history in coniferous forests of the mountain west. U.S. For. Serv. Gen. Tech. Rep. INT- 42.

Barrett, S.W., and Arno, S.F. 1988. Increment-borer methods for determining fire history in coniferous forests. U.S. For. Serv. Gen. Tech. Rep. INT-244.

Barrett, S.W., Arno, S.F., and Key, C.H. 1991. Fire regimes of western larch – lodgepole pine forests in Glacier National Park, Montana. Can. J. For. Res. **21**: 1711–1720.

Chander, G., and Markham, B. 2003. Revised Landsat-5 radiometric calibration procedures and postcalibration dynamic ranges. IEEE Trans. Geosci. Remote Sens. **41**: 2674–2677. doi:10.1109/TGRS.2003.818464.

Cocke, A.E., Fulé, P.Z., and Crouse, J.E. 2005. Comparison of burn severity assessments using differenced normalized burn ratio and ground data. Int. J. Wildland Fire, **14**: 189–198. doi:10.1071/WF04010.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens. Environ. **37**: 35–46. doi:10.1016/0034-4257(91)90048-B.

Congalton, R.G. 2001. Accuracy assessment and validation of remotely sensed and other spatial data. Int. J. Wildland Fire, **10**: 321–328. doi:10.1071/WF01031.

Daniel, W.W. 1978. Applied nonparametric statistics. Houghton Mifflin. Boston, Mass.

Dieterich, J.H., and Swetnam, T.W. 1984. Dendrochronology of fire-scarred ponderosa pine. For. Sci. **30**: 238–247.

Everett, R.L., Schellhaas, R., Keenum, D., Spurbeck, D., and Ohlson, P. 2000. Fire history in the ponderosa pine/Douglas-fire forests on the east slope of the Washington Cascades. For. Ecol. Manag. **129**: 207–225. [Data archived with the International Multiproxy Paleofire Database, IGBP PAGES/World Data Center for Paleoclimatology Data. NOAA/NCDC Paleoclimatology Program, Boulder, Co. Available from www.ncdc.noaa.gov/paleo/impd/paleofire.html] doi:10.1016/S0378-1127(99)00168-1.

Falk, D.A., and Swetnam, T.W. 2003. Scaling rules and probability models for surface fire regimes in ponderosa pine forests. *In* Proceedings of the Fire, Fuel Treatments, and Ecological Restoration Conference, 16–18 April 2002, Fort Collins, Colorado. *Compiled by* P.N Omi and L.A. Joyce. U.S. For. Serv. Proc. RMRS-P-29. U.S. Forest Service, Fort Collins, Co. pp. 301–317.

Fraser, R.H., Hall, R.J., Lynham, T., Raymond, D., Lee, B., and Li, Z. 2004. Validation and calibration of Canada-wide coarse-resolution satellite burned-area maps. Photogramm. Eng. Remote Sens. **70**: 451–460.

Fulé, P.Z., Heinlein, T.A., Covington, W.W., and Moore, M.M. 2003. Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. Int. J. Wildland Fire, **12**: 129–145. doi:10.1071/WF02060.

Gibson, C.E. 2006. A northern Rocky Mountain polygon fire history: accuracy, limitations, strengths, applications, and recommended protocol of digital fire perimeter data. Master's thesis, University of Idaho, Moscow, Idaho.

Grissino-Mayer, H.D. 2001*a*. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res. **57**: 205–221.

Grissino-Mayer, H.D. 2001*b*. FHX2-Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Res. **57**: 115–124.

Hessl, A.E., McKenzie, D., and Everett, R. 2004. Fire and climatic variability in the inland Pacific Northwest. Ecol. Appl. **14**: 425–442. [Data archived with the International Multiproxy Paleofire Database, IGBP PAGES/World Data Center for Paleoclimatology Data. NOAA/NCDC Paleoclimatology Program, Boulder, Colorado, USA. Available from www.ncdc.noaa.gov/paleo/impd/paleofire.html]

Hessl, A.E., Miller, J., Kernan, J., Keenum, D., and McKenzie, D. 2007. Mapping paleo-fire boundaries from binary point data: comparing interpolation methods. Prof. Geogr. **59**: 87–104.

Holden, Z.A., Smith, A.M.S., Morgan, P., Rollins, M.G., and Gessler, P.E. 2005. Evaluation of novel thermally enhanced spectral indices for mapping fire perimeters and comparisons with fire atlas data. Int. J. Remote Sens. **26**: 4801–4808. doi:10.1080/01431160500239008.

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. **43**: 69–78.

Jenson, J.R. 1996. Introductory digital image processing. 2nd ed. Prentice-Hall, Inc., Upper Saddle River, N.J.

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

Keeley, J.E., Fotheringham, C.J., and Morals, M. 1999. Reexamining fire suppression impacts on brushland fire regimes. Science (Wash., D.C.), **284**: 1829–1832. doi:10.1126/science.284.5421.1829. PMID:10364554.

Key, C.H., and Benson, N.C. 2006. Landscape assessment (LA): sampling and analysis methods. U.S. For. Serv. Gen. Tech. Rep. RMRS-164-CD.

Lentile, L.B., Holden, Z.A., Smith, A.M.S., Falkowski, M.J., Hudak, A.T., Morgan, P., Lewis, S.A., Gessler, P.E., and Benson, N.C. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. Int. J. Wildland Fire, **15**: 319–345. doi:10.1071/WF05097.

López Garcia, M.J., and Caselles, V. 1991. Mapping burns and natural reforestation using Thematic Mapper data. Geocarto Int. **1**: 31–37.

Lynch, T.B., and Wittwer, R.F. 2003. *n*-Tree distance sampling for per-tree estimates with application to unequal-sized cluster sampling of increment core data. Can. J. For. Res. **33**: 1189–1195. doi:10.1139/x03-036.

McKelvey, K.S., and Busse, K.K. 1996. Twentieth-century fire patterns on Forest Service lands. *In* Sierra Nevada Ecosystem Management Project: final report to Congress. Vol. II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis, Calif. pp. 1119–1138.

Minnich, R.A. 1983. Fire mosaics in southern California and northern Baja California. Science (Wash., D.C.), **219**: 1287–1294. doi:10.1126/science.219.4590.1287.

Morgan, P., Aplet, G.H., Haufler, J.B., Humphries, H.C., Moore, M.M., and Wilson, W.D. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. J. Sustain. For. **2**: 87–111.

Morgan, P., Hardy, C., Swetnam, T.W., Rollins, M.G., and Long, D.G. 2001. Mapping fire regimes across time and space: understanding coarse and fine-scale patterns. Int. J. Wildland Fire, **10**: 329–342. doi:10.1071/WF01032.

Ott, R.L., and Longnecker, M. 2001. An introduction to statistical methods and data analysis. 5th ed. Duxbury Press, Pacific Grove, Calif.

Rehfeldt, G.E. 1986. Adaptive variation in *Pinus ponderosa* from intermountain regions. I. Snake and Salmon River Basins. For. Sci. **32**: 79–92.

Rollins, M.G., Swetnam, T.W., and Morgan, P. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Can. J. For. Res. **31**: 2107–2123. doi:10.1139/cjfr-31-12-2107.

Rollins, M.G., Morgan, P., and Swetnam, T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecol. **17**: 539–557. doi:10.1023/A:1021584519109.

Roy, D.P., Boschetti, L., and Trigg, S.N. 2006. Remote sensing of fire severity: assessing the performance of the normalized burn ratio. IEEE Geosci. Remote Sens. Lett. **3**: 112–116. doi:10.1109/LGRS.2005.858485.

SAS Institute Inc. 2003. SAS 9.1.3: help and documentation. SAS Institute Inc., Cary, N.C.

Schmidt, K.M., Menakis, J.P., Hardy, C.C., Hann, W.J., and Bunnell, D.L. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. U.S. For. Serv. Gen. Tech. Rep. RMRS-GTR-87.

Shapiro, L.B. 2006. Historical fire records: comparison of fire scars, fire atlases, and satellite data in the northwestern United States. M.S. thesis, University of Idaho, Moscow, Idaho. [Data archived with the International Multiproxy Paleofire Database, IGBP PAGES/World Data Center for Paleoclimatology Data. NOAA/NCDC Paleoclimatology Program, Boulder, Co. Available from www.ncdc.noaa.gov/paleo/impd/paleofire.html]

Smith, K.T., and Sutherland, E.K. 2001. Terminology and biology of fire scars in selected central hardwoods. Tree-Ring Res. **57**: 141–147.

Stephens, S.L., Skinner, C.N., and Gill, S.J. 2003. Dendrochronology-based fire history of Jeffrey pine – mixed conifer forests in the Sierra San Pedro Martir, Mexico. Can. J. For. Res. **33**: 1090–1101. doi:10.1139/x03-031.

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

Swetnam, T.W., and Betancourt, J.L. 1990. Fire-southern oscillation relations in the southwestern United States. Science (Wash., D.C.), **249**: 1017–1020. doi:10.1126/science.249.4972.1017.

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

Teske, C. 2002. Changing landscape-scale fire regimes in the upper Selway River basin, Idaho. Master's thesis, University of Idaho, Moscow, Idaho.

Upton, G.J., and Fingleton, B. 1985. Spatial data analysis by example. Vol. 1. Point pattern analysis and quantitative analysis. John Wiley & Sons, New York.

USDA Forest Service. 1993. National Interagency Fire Management Integrated Database (NIFMID) reference manual. USDA Forest Service, Fire and Aviation Management, Washington, D.C.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science (Wash., D.C.), **313**: 940–943. doi:10.1126/science.1128834. PMID:16825536.

Western Regional Climate Center. 2006. Western U.S. historical climate information [online]. Available from www.wrcc.dri.edu [cited 10 April 2006].