RESEARCH ARTICLE

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Historical Surface Fire Frequency in Ponderosa Pine Stands in Research Natural Areas, Central Rocky Mountains and Black Hills, USA

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ABSTRACT: "Historical range of variability" and "reference conditions" are two concepts that attempt to characterize ecosystem conditions as they may exist in the absence of pervasive human impacts. However, to define reference conditions from reference landscapes, such as U.S. Forest Service Research Natural Areas, requires a long-term perspective by which to assess whether existing ecosystem conditions are driven by predominately natural rather than human factors. We used fire-scarred trees to reconstruct centuries-long chronologies of surface fires in four research natural areas (three established and one proposed) that contain ponderosa pine *(Pinus ponderosa* Laws.) forests in South Dakota, Wyoming, and Colorado. Fire frequency was variable among research natural areas, but recent fire-free periods in three of the four areas were up to approximately 2.5 times longer than any presettlement intervals. Loss of surface fires most likely is related indirectly to recent land and resource use in areas outside of the research natural areas and related directly to fire suppression and livestock grazing in the research natural areas themselves. Studies that attempt to define reference conditions for ponderosa pine ecosystems from existing conditions in these Research Natural Areas will need to consider changes that may have occurred in these areas as the result of loss of historical fire patterns. Determination of historical fire frequency also should provide useful information for the management or restoration of ecosystem processes and conditions in these or similar natural areas.

Index terms: fire chronologies, cross-dating, fire scars, historical range of variability, *Pinus ponderosa*

INTRODUCTION

While change is normal in all ecosystems, the rate or direction of ecological changes brought about by land and natural resource use during recent decades may be outside the range of what many ecosystems are able to sustain before they shift into new modes of behavior (Covington et al. 1994, Holling and Meffe 1996). A well-documented example is changes that have occurred in ponderosa pine *(Pinus ponderosa* Laws.) forests of the western United States over the past century (Cooper 1960; White 1985; Covington and Moore 1992, 1994; Mutch et al. 1993; Arno et al. 1995; Rile et al. 1997). Historically open forests with scattered trees and high understory biomass and diversity have shifted to forests dominated by closed-canopy stands with reduced understory production and species composition. Historical conditions were maintained by frequent, episodic surface fires that killed ponderosa pine seedlings and saplings before they were able to reach the forest overstory (Cooper 1960, White 1985). Livestock grazing, logging, geographical fragmentation caused by road and fence construction, and active fire suppression by land management agencies are among the factors that have disrupted surface fire regimes in ponderosa pine forests (Savage 1991; Covington and Moore 1992, 1994; Touchan et al. 1995; Brown and Sieg 1996; Swetnam and Baisan 1996; Rile et al. 1997). Shifts from historical patterns also have resulted in altered fire regimes, with high-severity crown-destroying fires replacing low-severity surface fires (Swetnam 1990, Covington and Moore 1994, Arno et al. 1995), and have led some researchers to question whether ponderosa pine ecosystems are sustainable under these new disturbance regimes (Covington et al. 1994).

For management of ecosystems, it is critical to know when human manipulation of ecosystem components may be compromising ecosystem function and resilience (Holling and Meffe 1996). Two concepts—"historical range of variability" (HRV; Morgan et al. 1994) and "reference conditions" (e.g., Kaufmann et al. 1994)—are used to characterize ecosystem processes and patterns in the absence of pervasive human impacts. HRV refers to long-term patterns of ecosystem conditions that prevailed before, generally, the middle to late 1800s, when widespread non-Native American—primarily Euro-American—settlement in the western United States began in earnest. Although Native Americans are known to have altered ecosystems to a limited extent prior to settlement, their effects do not match the predominance and ubiquity of impacts that have occurred during the recent century as a result of population increases and industrialization. Reference conditions are ecosystem conditions defined either from analysis of presettlement patterns or from present-day ecosystems that have been altered minimally by human impacts. Present-day ecosystems useful for defining reference conditions may be found in wilderness areas, many National Park Service landscapes, and Forest Service Research Natural Areas (RNAs; e.g., Ryan et al. 1994). RNAs are permanently protected landscapes that have been set aside principally for the purposes of maintaining certain aspects of biological diversity and conducting non-manipulative ecological research (Ryan et al. 1994).

While both of these concepts, HRV and reference conditions, are crucial for scientifically based ecosystem management (Kaufmann et al. 1994, Holling and Meffe 1996, Leslie et al. 1996), reference landscapes can be used to characterize reference conditions only if one uses a long-term perspective to assess whether present-day conditions in these landscapes represent predominately natural rather than human factors. Probably no ecosystem on Earth has escaped at least some minimal level of impact from industrial society (Swanson et al. 1993, Kaufmann et at. 1994, Vitousek et al. 1997). Although logging, road construction, or other landscape fragmentation may not have occurred in a reference landscape with a history of surface fires, fire cessation in adjacent landscapes may have excluded landscape-scale fires from the reference area. In addition, active fire suppression by land management agencies has occurred in virtually all ecosystems of the western United States. Exclusion of surface fires from a reference area may result in changes in ecosystem structure and function that are as pronounced as those in more directly impacted areas.

We reconstructed historical ranges of variability in surface fire frequency in ponderosa pine stands at four RNAs (three established and one proposed) in Colorado, Wyoming, and South Dakota. Fire frequency in the RNAs was reconstructed using fire-scar records in dendrochronologically cross-dated tree-ring series. These reconstructions were made to assess if fire frequency was different in these reference landscapes during the postsettlement period, or if recent fire frequency and likely associated ecosystem processes in the RNAs are within the HRV.

METHODS

Study Areas

Four study areas were selected in South Dakota, Wyoming, and Colorado. These included three established RNAs—Upper Pine Creek in the Black Hills National Forest of South Dakota (Ryan et al. 1994), Lone Pine in the Arapahoe-Roosevelt National Forest in northern Colorado, and Hot Creek in the Rio Grande National Forest in southern Colorado—and one pro-posed RNA, Ashenfelder Basin in the Medicine Bow National Forest in central Wyoming (Table 1). Each of the RNAs contained unroaded, old-growth ponderosa pine stands that have had a history of little or no logging or other significant human disturbances during the twentieth century. Native American impacts before the twentieth century probably occurred to some extent in each of the areas. How-ever, the RNAs are for the most part located in areas with difficult access and each is considered to be representative of conditions driven by predominately natural rather than human agents.

At three of the four study areas, we collected 10 to 13 fire-scarred ponderosa pine trees each from two stand-level sites to provide replication of both spatial and temporal patterns in fire frequency (Table 1; Brown and Sieg 1996, 1999). At the fourth study area (Hot Creek), we collected 18 fire-scarred ponderosa pine trees from one site (Table 1). Sites ranged in size from 10 to 20 ha and were selected based upon the presence of adequate old-age fire-scarred trees or remnant (dead) material. The goal of collection at each site was to obtain a comprehensive, long-term inventory of past fires using fire scar records from individual trees (Brown and Sieg 1996, Swetnam and Baisan 1996). Long-term sequences of fire scars often are recorded on individual trees. However, individual trees may be missing fire records because not all fires that burned in the vicinity of a tree may be recorded as scars, and scars may be burned off by subsequent fires or other-wise eroded from the scar record.

Upper Pine Creek was established as an RNA in 1931, the first in this region of the U.S. Forest Service (Ryan et al. 1994). The 482-ha RNA is in the rocky, isolated center range of the Black Hills and contained within the Black Elk Wilderness Area. As in many areas of the Black Hills, ponderosa pine regeneration in Upper Pine Creek has been heavy during the twentieth century, and there are many areas of dense, often suppressed trees (McAdams 1995).

Table 1. Fire history study sites in Research Natural Areas in South Dakota, Wyoming, and Colorado.

Site Name	Site Code	Elevation Range (m)	Latitude (N)/ Longitude (W)
Upper Pine Creek, S.D.	UPC	1660–1690	43° 53.0' / 103° 30.0'
Upper Pine Creek Middle, S.D.	UPM	1670–1720	43° 52.5' / 103° 30.5'
Ashenfelder Basin Lower, Wyo.	ASL	1920–1950	42° 20.0' / 105° 23.0
Ashenfelder Basin Upper, Wyo.	ASU	1930–1960	42° 20.0' / 105° 24.5'
Lone Pine, Colo.	LPI	2340–2400	40° 49.5' / 105° 27.5'
Lone Pine Upper, Colo.	LPU	2380–2410	40° 48.5' / 105° 27.0'
Hot Creek, Colo.	HCK	2590-2640	37° 17.5' / 106° 16.0'

We collected fire-scarred trees from two sites about 0.5 km apart in the main part of the Upper Pine Creek Basin (designated Upper Pine Creek [UPC] and Upper Pine Creek Middle [UPM]) (Table 1).

The proposed Ashenfelder Basin RNA is on the north side of Laramie Peak south of Douglas, Wyoming. The study area en-compasses ponderosa pine stands that grade into lodgepole pine *(Pinus contorta* Dougl.) forests on the higher flanks of Laramie Peak. The ponderosa pine forest experienced heavy impacts from an out-break of mountain pine beetle *(Dendroctonus ponderosae* Hopkins) that began in 1988 and ended in the early 1990s; there was extensive mortality of all size classes over much of the basin. We collected trees from two sites about 1 km apart in the lower end of the basin (designated Ashenfelder Upper [ASU] and Ashenfelder Lower [ASL]) (Table 1).

The 1200-ha Lone Pine RNA is in a steep, rugged area north of the North Fork of Lone Pine Creek near Red Feather Lakes in the northern Front Range of Colorado. Lone Pine was designated as an RNA in 1997. A high plateau that makes up much of the RNA supports a mixed-conifer forest consisting of Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco.), lodgepole pine, aspen *(Populus tremuloides* Michx.), and occasional limber pine *(Pinus flexilis* James), although ponderosa pine is the dominant species over the entire area. We collected trees from two sites, one centered in low-elevation ponderosa pine forest (designated LPI) and the other approx-imately 2 km southeast in the upland area (designated LPU; Table 1).

The 750-ha Hot Creek RNA is on the western edge of the San Luis Valley in southern Colorado at the ponderosa pine/ grassland ecotone. This area was designat-ed as an RNA in 1996. The landscape here is very steep and rugged, dissected by three deep canyons with two relatively flat pen-insulas of ponderosa pine forest between them, which form the lower end of the study area. Ponderosa pine forest at the low end changes to mixed-conifer forest with Douglas-fir, aspen, white fir *(Abies concolor* [Gord. & Glend.] Lindl. ex Hildeb), and ponderosa pine as elevation increases. We collected trees in one area from the lower end of the RNA (in ponde-rosa pine forest), which we designated HCK (Table 1).

Reconstruction of Fire History

Cross sections were collected from fire-scarred trees using chainsaws and, in the wilderness area, handsaws. We selected individual trees at each site based upon the numbers of fire scars visible in fire-created "cat-faces." Generally, full circumference cross sections were removed from logs while partial cross sections were re-moved from the vicinity of the fire-scarred surface on living or standing dead trees (snags). We concentrated our collections on logs and snags both to minimize impacts to living trees in the RNAs and to extend the fire chronologies as far back in time as possible. We also collected increment cores from living trees in the vicinity of the fire-scarred trees to aid in cross-dating of tree-ring series (Brown and Sieg 1996). All cross sections and increment cores were surfaced using a hand planer, belt sander, and hand sanding with 320- or 400-grit sandpaper.

We cross-dated cores and fire-scarred cross sections using standard dendrochronological procedures such as skeleton plotting (Stokes and Smiley 1968, Swetnam et al. 1985). Cross-dating involved matching of climatically controlled patterns of ring width or other ring parameters (e.g., late-wood widths or intra-annual latewood bands) between trees and sites. After cross-dating tree-ring series on all cross sections from a site, we assigned dates to fire scars. Intra-annual positions of fire scars also were noted when possible (Brown and Sieg 1996, Swetnam and Baisan 1996). Once we verified cross-dating on all trees, fire chronologies were compiled from all re-corded fire dates (Dieterich 1980). Com-pilation of fire chronologies minimized any potential incompleteness of scar records on individual trees. Historical fire variability for a period of analysis for each chronology was described using quartiles and range of fire intervals. These measures then were compared to recent fire-free periods at each site to determine if recent fire frequency is within the HRV.

RESULTS AND DISCUSSION Fire

Chronologies

Fire chronologies for the four RNAs are shown in Figure 1. The Upper Pine Creek fire chronologies (Figure la) show that most fire scars were highly synchronous on trees within and between the two sites, even though the area where trees were collected is dissected by numerous rocky outcrops and ridges that could have limited fire spread between stands. A number of fire years observed at Upper Pine Creek occurred over much of the Black Hills, notably 1580, 1668, 1753, 1785, 1807, 1822, 1864, and 1890 (Brown and Sieg 1996, 1999; RM. Brown, unpubl. data). While it is unlikely that single fires burned across vast areas during these years, mul-tiple ignitions during dry summers probably resulted in large areas burning during regional fire years *(sensu* Swetnam 1993, Swetnam and Baisan 1996). Also, as in the rest of the Black Hills, regular surface fires ceased in the late 1800s. Our collection at Upper Pine Creek concentrated on remnant material, with only four trees that extended into the twentieth century (Figure la); however, none of these trees re-corded fire scars after 1890. The Upper Pine Creek chronologies also recorded a long period without fire in the early 1700s, a pattern that is also seen in many areas *of* the Black Hills (Brown and Sieg 1996; RM. Brown, unpubl. data), and which was probably related to regional climate variability.

The fire chronologies we collected from the proposed RNA in Ashenfelder Basin also recorded many synchronous fire dates between the two sites from this area (Figure lb). Regular fire events were recorded by trees up to the early 1900s, with no fire scars recorded after 1909 and 1911. Most *of* the trees sampled from this area were snags or logs that had been killed by the mountain pine beetle outbreak that began in the late 1980s.

Individual fire-scarred trees at the Lone Pine RNA recorded at most three fire scars. The fire chronologies from this area (Figure lc) contained some of the longest intervals between surface fires yet seen in ponderosa pine forests in the Front Range of Colorado (e.g., P.M. Brown, W.D. Shepperd, T.W. Swetnam, unpubl. data; Brown et al. 1999). It also appears that there may have been stand-destroying fires in this area. Several of the fire-scarred trees recorded pith (center) dates between 1595 and 1620, with another cluster of pith dates on other trees between 1700 and 1720 (Figure lc). These pith dates occurred after fire scars recorded on other trees, in 1568 and 1578 and again in 1685, and suggest that stand-destroying fires during those years may have opened up space for tree establishment.

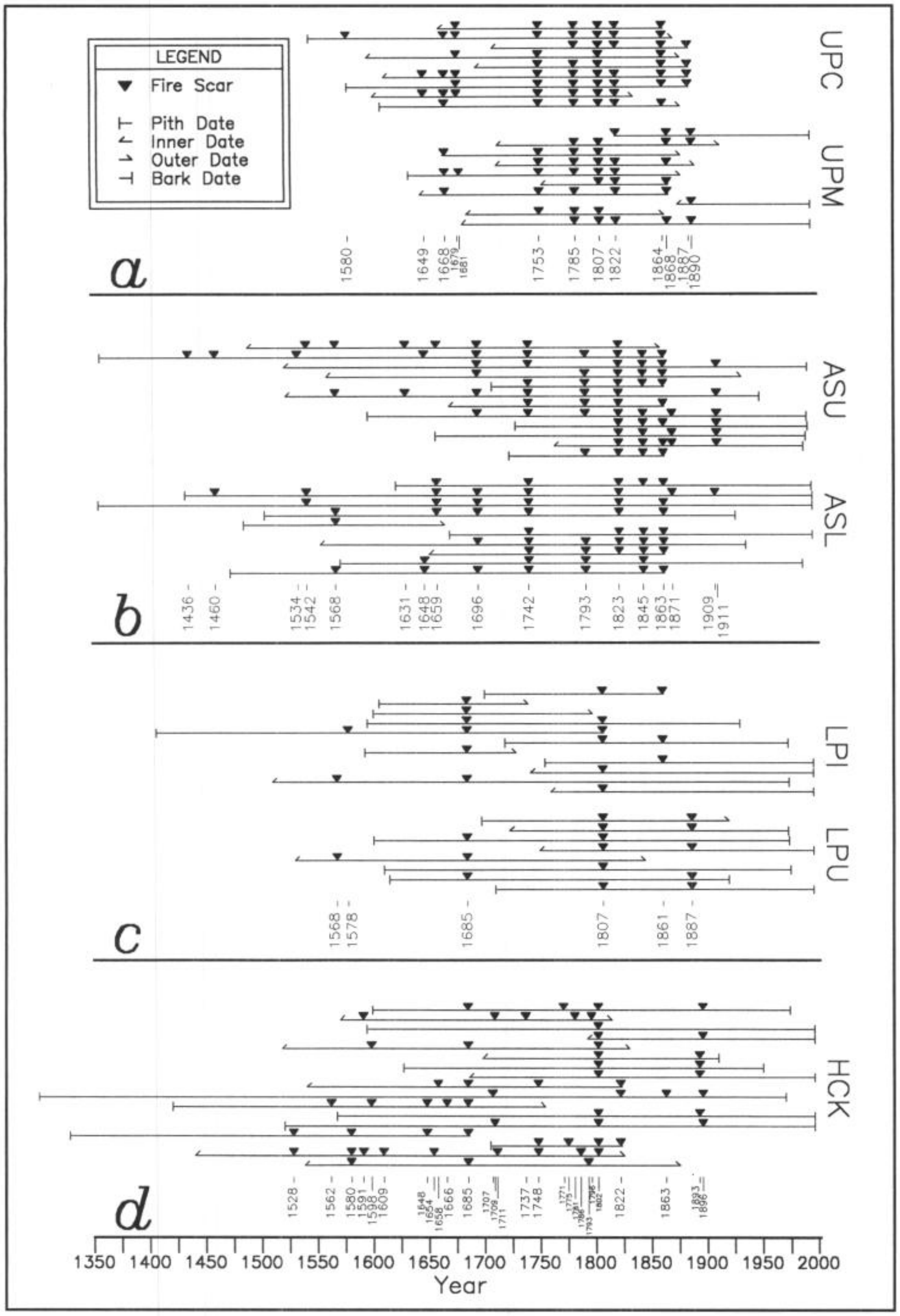

Figure 1. Fire chronologies from RNA study sites in Central Rocky Mountains and Black Hills, USA. Horizontal lines represent time spans of individual trees, with fire scars represented by inverted triangles at the dates they were recorded. Pith or bark dates indicate that pith or bark was present on cross sections removed for fire scar analysis, while inside or outside dates indicate that there were unknown numbers of years to pith or bark on cross sections. (a) Fire chronologies from two sites (UPC and UPM) at Upper Pine Creek RNA. (b) Fire chronologies from two sites (ASU and ASL) at the proposed Ashenfelder Basin RNA. (c) Fire chronologies from two sites (LPI and LPU) at Lone Pine RNA. (d) Fire chronologies from site (HCK) at Hot Creek RNA.

Trees at Hot Creek RNA recorded overall high numbers of fire years before about 1800, although fire scars were recorded very patchily on individual trees (Figure 1d). The fire scar record at HCK may be reflective of frequent but spatially patchy and generally small fires in the very rocky and broken landscape of this RNA. A shift in fire frequency was apparent after the 1802 fire, which was also the fire most extensively recorded on trees in this stand. After 1802 there was a relatively long period without fire, which is similar to temporal patterns seen in other fire chronologies from sites in Arizona and New Mexico (Grissino-Mayer 1995, Swetnam and Baisan 1996, Swetnam and Betancourt 1998). This shift in fire timing and frequency after the early 1800s may be related to a change in the magnitude and spatial position of subtropical moisture flow into the southwestern United States during this time (Grissino-Mayer 1995). After fires recorded in 1893 and 1896, no fire scars were recorded during the twentieth century.

Historical Variability in Fire Frequency

Measures for fire frequency were comparable between replicate sites at Upper Pine Creek, Ashenfelder Basin, and Lone Pine RNAs (Figure 2, Table 2). Similar statistics from replicate stands suggest that re-constructed central tendencies and variability in fire intervals are adequate measures of historical surface fire frequency in the ponderosa pine forests of these three areas. Variability in fire frequency between RNAs was the result of differences in climatic regimes between the regions and elevations where the sites are located, as well as differences in topography and fuels between forest types. With the exception of the long intervals between fires at the Lone Pine stands, fire frequen-

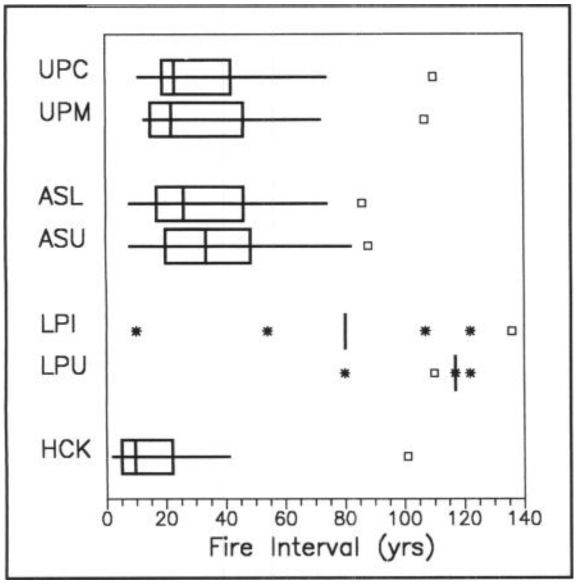

Figure 2. **Box plots of fire intervals for sites at Upper Pine Creek, Ashenfelder Basin, and Hot Creek. Horizontal lines for each site are ranges of intervals, boxes are the first and third quartiles, and vertical lines in boxes are median intervals. For sites LPI and LPU, presettlement fire intervals are denoted by asterisks with median intervals marked by vertical lines. Lengths of the most recent fire-free periods at sites (from date of the last fire recorded to 1997) are denoted by small squares (0).**

cies in Table 2 are within historical ranges found in many other ponderosa pine forests of the central Rockies or Black Hills (e.g., Brown and Sieg 1996, Swetnam and Baisan 1996, Fule et al. 1997, Brown et al. 1999).

With the exception of site LPU, recent postsettlement fire-free periods exceeded the longest presettlement fire intervals during the period of analysis of the fire chronologies (Figure 2; Table 2). At Hot Creek (HCK), the postsettlement fire-free period has been almost 2.5 times as long as the longest presettlement interval (101 years vs. 41 years) and over 10 times as long as the median fire interval for the period of analysis. At the Up-per Pine Creek sites, the post-settlement periods were approximately one-third longer than the longest interval in the period of analysis, and almost five times longer than the median fire intervals. At the Ashenfelder Basin sites, the post-settlement periods have been 12 years and 6 years longer than the longest presettlement intervals, and over three times as long as the presettlement median fire interval. Only at the Lone Pine sites are the re-cent fire-free periods within the presettlement range of intervals, although at site LPI the postsettlement interval has been almost twice as long as the median presettlement interval.

Implications for Reference Conditions in the RNAs

With the exception of the Lone Pine sites, current fire frequencies in these reference landscapes are outside historical ranges of variability when compared to median and maximum presettlement surface fire intervals (Table 2). Cessation of surface fires beginning at the end of the nineteenth or early twentieth centuries is similar to pat-terns seen in ponderosa pine ecosystems throughout the central Rockies and Black Hills (Cooper 1960; Savage 1991; Grissino-Mayer 1995; Touchan et al. 1995; Brown and Sieg 1996, 1999; Swetnam and Baisan 1996; Fule et al. 1997). Cessation of surface fires usually coincided with widespread, intensive livestock grazing in these or surrounding landscapes and usually preceded, often by several decades (Savage 1991, Touchan et al. 1995), the beginnings of direct fire suppression efforts by land management agencies. Livestock grazing contributed indirectly to a reduction in surface fires since herbivory removed grasses and other fine fuels necessary for fire spread (Zimmerman and Neuenschwander 1984, Archer 1994, Touchan et al. 1995, Swetnam and Baisan 1996, Brown and Sieg 1999). Fire cessation and livestock grazing also often coincided with geographical fragmentation caused by road and fence construction and logging, which limited fire spread across landscapes. Disruption of historical patterns of Native American ignitions also may have had a limited impact in some areas. Road construction and logging may not have occurred in the RNAs but these factors in surrounding landscapes must have contributed to lack of fires spreading into the study areas. Grazing and direct fire suppression efforts in the RNAs also contributed to the loss of fires from these ecosystems.

Often dramatic changes in tree densities and forest structure are related to fire exclusion in ponderosa pine forests (Cooper 1960; White 1985; Covington and Moore 1992, 1994; Arno et al. 1995; Covington et al. 1997; Fule et al. 1997). Frequent surface fires tended to reduce tree regeneration and maintained open, multi-aged forest stands. Both known and hypothesized changes in ecosystem structure and function also occurred at the same time (e.g., White 1985, Mutch et al. 1993, Covington and Moore 1994). These changes included losses of understory species and biomass, reduction in rates of nutrient cycling, degradation of wildlife habitat, reduction in surface and subsurface hydrological flows, and an increase in both fuel loading and creation of "ladder fuels" in forest canopies, leading to more prevalent large-scale

Table 2. **Measures** of **fire frequency calculated for period** of **analysis** at **RNA study sites.** All **measures** of **fire frequency are for sites** of < 20 ha in size.

Site	**Period of Analysis**	**No. of Intervals**	**Median Fire Interval (y)**	**Range** of **Intervals (y)**	Years Since Last Fire
UPC	1580–1887	9	23	11 to 74	110 (1887 to 1997)
UPM	1668–1890	7	22	13 to 72	107 (1890 to 1997)
ASL	1436–1911	15	26	8 to 74	86 (1911 to 1997)
ASU	1460–1909	12	33.5	8 to 82	88 (1909 to 1997)
LPI	1568–1861	4	80.5	10 to 122	136 (1861 to 1997)
LPU	1568–1887	3	117	80 to 122	110 (1887 to 1997)
HCK	1528–1896	26	9.5	2 to 41	101 (1896 to 1997)

crown fires (Swetnam 1990, Covington and Moore 1994).

Changes in forest structure and tree density probably have occurred in at least some of the RNAs because of the disruption of historical patterns of surface fires. In the Black Hills, increases in ponderosa pine tree density and landscape coverage have been documented using repeat photographs (Progulske 1974) and analysis of tree age and stand structure (McAdams 1995). Dense, sup-pressed stands of young small-diameter trees are present in the Upper Pine Creek RNA (Ryan et al.1994; Lundquist 1995a, 1995b). Surface fires would have killed many of these younger trees before they became established, and present-day forest conditions are probably outside the HRV in stand conditions for this area.

Further assessments of present forest conditions in the RNAs are needed before these landscapes can be used to define reference conditions for comparable ecosystems. At Ashenfelder Basin, the recent mountain pine beetle epidemic killed many trees, and the remaining ponderosa pine forest is very open with a well-developed grass and herbaceous understory. The mountain pine beetle may have fulfilled the "role" that fire used to play in this landscape, and present forest structure may well be within a range of historical conditions. At Hot Creek, which recorded the most frequent fires of any of the study areas, the existing ponderosa pine forest is very open with no evidence of denser, younger stands established after fire exclusion. Hot Creek is a very dry landscape with low productivity, and the patchy nature of the presettlement fire regime at this site (Figure 1d) may reflect a high level of ignition but very poor grass and herbaceous fuel production and continuity during most fire years in the past. Density of the ponderosa pine forest here may be controlled more by climate regime rather than by fire regime.

At sites LPI and LPU, as at most of the other sites, no fires were recorded during the twentieth century. However, this long period with-out fire does not appear to be far outside the HRV in fire frequency for this area. There is tentative evidence that crown fire may have been a component of the fire regime in the LPU stand (Figure 1 c). Although our study concentrated on reconstructing HRV of surface fire regimes in the RNAs, catastrophic stand-destroying fires may have been a component of the HRV of this ponderosa pine forest (and possibly of the other RNAs), though on different temporal and spatial scales than surface fires (Brown et al. 1999). Nevertheless, even at the Lone Pine sites, lengths of recent periods with no recorded surface fires have equaled or slightly exceeded the longest intervals between surface fires recorded at the stands over the last few centuries. At Lone Pine, as at Hot Creek and Ashenfelder Basin, forests were generally open, with no widespread denser stands of trees seen during reconnaissance for the collection of the fire history material.

Holling (1992) has called fire a "keystone" ecosystem process that structures and en-trains other ecosystem processes analogous to the manner in which a keystone species may do so with other species in a community. Historical changes in ponderosa pine forests throughout the western United States are well-documented and usually attributed to loss of or reductions in surface fires in these ecosystems (Coo-per 1960; White 1985; Covington and Moore 1992, 1994; Mutch et al. 1993; Arno et al. 1995; Fule et al. 1997; Covington et al. 1997). Results from this study suggest that a historical perspective is critical to defining ecosystem patterns as they might exist in the absence of pervasive human impacts and to developing appropriate goals for ecosystem management (Kaufmann et al. 1994). Knowledge of differences in historical and current fire regimes also should be useful in the development of fire and other management plans in these and similar areas.

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