Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases[1]

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Abstract: Changes in fire size, shape, and frequency under different fire-management strategies were evaluated using time series of fire perimeter data (fire atlases) and mapped potential vegetation types (PVTs) in the Gila – Aldo Leopold Wilderness Complex (GALWC) in New Mexico and the Selway–Bitterroot Wilderness Complex (SBWC) in Idaho and Montana. Relative to pre-Euro-American estimates, fire rotations in the GALWC were short during the recent wildfire-use period (1975–1993) and long during the pre-modern suppression period (1909–1946). In contrast, fire rotations in the SBWC were short during the pre-modern suppression period (1880–1934) and long during the modern suppression period (1935–1975). In general, fire-rotation periods were shorter in mid-elevation, shade-intolerant PVTs. Fire intervals in the GALWC and SBWC are currently longer than fire intervals prior to Euro-American settlement. Proactive fire and fuels management are needed to restore fire regimes in each wilderness complex to within natural ranges of variability and to reduce the risk of catastrophic wildfire in upper elevations of the GALWC and nearly the entire SBWC. Analyses of fire atlases provide baseline information for evaluating landscape patterns across broad landscapes.

Résumé : Les changements dans la fréquence, la forme et la dimension des feux suite à l'application de différentes stratégies de gestion du feu ont été évalués à l'aide de séries temporelles de données sur le périmètre des feux (atlas des feux) et des types de végétation potentielle cartographiés dans les complexes sauvages de Gila – Aldo Leopold (GAL) au Nouveau-Mexique et de Selway–Bitterroot (SB) en Idaho et au Montana. Relativement aux estimés de la période pré-euroaméricaine, la périodicité des feux dans le complexe de GAL était courte au cours de la période récente d'utilisation du feu (1975–1993) et longue au cours de la période pré-moderne de suppression (1909–1946). Au contraire, la périodicité des feux dans le complexe de SB était courte au cours de la période pré-moderne de suppression (1880–1934) et longue au cours de la période moderne de suppression (1935–1975). De façon générale, la périodicité des feux était plus courte dans les types végétaux intolérants à l'ombre situés à une altitude intermédiaire. Les intervalles entre les feux dans les complexes de GAL et de SB sont présentement plus longs qu'ils l'étaient avant la colonisation euroaméricaine. La gestion proactive du feu et des combustibles est nécessaire pour ramener le régime des feux dans chaque complexe sauvage à l'intérieur d'une gamme naturelle de variabilité et pour réduire les risques de feux catastrophiques aux altitudes plus élevées dans le complexe de GAL et dans presque tout le complexe de SB. L'analyse des atlas des feux fournit une information de base pour détecter différents paysages sur de vastes étendues.

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Introduction

The extent and rate of burning has decreased markedly since the late 19th century in both wilderness and non-wilderness forests of the Rocky Mountains (Leopold 1924; Weaver 1951; Wellner 1970; Arno 1980; Arno and Peterson 1983; Swetnam and Dieterich 1985; Brown et al. 1994; Swetnam and Baisan 1996*a*; Barrett et al. 1997). Reduction in the rate of burning in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests, for example, has been accompanied by increases in fuel amounts and continuity as vegetation that would previously have been consumed in fire remains unburned (Arno 1976; Gruell et al. 1982; Covington and Moore 1994; Covington et al. 1994; Fulé and Covington 1995; Grissino-Mayer et al. 1995; Swetnam and Baisan 1996*b*). Decreased fire frequencies and associated increases in the amount of fuels and structural homogeneity will likely lead to larger, more severe fires in these forests than oc-

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curred in the past several centuries (Covington et al. 1994). Twentieth-century changes in fire frequency are directly related to the current extreme fire hazard forests of the western United States (Van Wagtendonk 1985; Barrett 1988; Covington et al. 1994; Quigley and Arbelbide 1997; GAO 1999). The 2000 fire season directly demonstrated this unprecedented fire hazard across landscapes of the western United States. Historical information on the timing and extent of burning can empirically increase our understanding of dynamic fire–climate–landscape interactions and improve current management efforts to return fire regimes to within natural ranges of variation (Morgan et al. 1994; Landres et al. 1999; Swetnam et al. 1999).

In this paper we compare the timing and extent of 20th century fires for two large Rocky Mountain wilderness complexes: the 486 673-ha Gila – Aldo Leopold Wilderness Complex (GALWC) in New Mexico and the 785 090-ha Selway–Bitterroot Wilderness Complex (SBWC) in Idaho and Montana. The GALWC and the SBWC factor heavily in the history of wildland fire in the United States (Pyne 1982). By 1950, two of the first centres for aerial fire detection and suppression were operating within 50 miles (1 mile = 1.609 km) of each area. Aggressive fire suppression continued through the mid-1970s, when each wilderness complex implemented policies allowing certain naturally ignited fires to burn (Garcia et al. 1978; Frost 1982; Swetnam 1983; Webb and Henderson 1985). Under these fire-management strategies (currently referred to as wildland fire use) lightning-ignited fires in particular areas were allowed to burn within specific fuel and weather conditions. The main goals of these programs were restoring natural fire processes and mitigating fire hazard at broad scales in remote areas (Garcia et al. 1978; Frost 1982). Comparison of 20th-century fire histories between each wilderness complex provides empirical, historical information for assessing the extent and rate of change of fire regimes in both the northern and southern Rocky Mountains.

Different approaches for evaluating fire history are needed in areas with different forest types and fire regimes (e.g., fire scar evidence may be completely consumed in a stand-replacing fire regime). Comparisons of fire history research between areas are sometimes invalid because of different sampling strategies, methods, and statistical analyses. Confusion results when the appropriate spatial extent for ecological interpretations and fire-management implications are spatially and temporally ambiguous. This uncertainty causes problems when interpretations from multiple sources of fire-history research are applied in fire and forest management. The historical role of fire is often characterized using mean fire intervals, fire rotations, or fire cycles (Johnson 1992; Swetnam and Baisan 1996*a*; Agee 1993; Minnich and Chou 1997). Mean fire intervals, based single fire-scarred trees, often provide incomplete estimates of fire frequency at any given point on a landscape. Fire-frequency estimates from multiple trees are usually aggregated or composited to estimate mean fire intervals at broader landscape or even regional scales (Heinselman 1973; Arno 1980; Dieterich 1980; Swetnam and Baisan 1996*b*; Swetnam et al. 1999). Fire rotation and fire cycle are examples of area fire frequencies, defined as the number of years required to burn an area equivalent to a specific study area (Agee 1993). These metrics can be calculated by estimating burned areas over time from mapped age-structure data, sometimes combined with fire-scarred trees, to compile time-since-fire maps. As an alternative, we calculated fire rotation for the GALWC and SBWC using archived sets of fire-perimeter maps.

Fire histories based on fire-scarred trees alone are explicitly spatial, with annual temporal precision in dating. However, representations of the spatial extent of individual fires over time are relativistic estimates, because fire perimeters usually cannot be reliably determined from fire-scarred trees alone (Agee 1993; Swetnam and Baisan 1996*a*; Pyne et al. 1996). Moreover, the quantitative extrapolation of spatial patterns is limited, because sites and trees are often opportunistically sampled and nonrandomly distributed (but see Arno et al. (1993), Fulé and Covington (1995), Niklasson and Granstrom (2000) for examples of systematic sample design).

Fire-history methodologies based on age-structure distributions or time-since-fire data assume that stand boundaries represent past fire perimeters. In these approaches, subsequent fires censor the evidence of past fires; only the most recent fires are represented in their entirety. This is most valid where stand-replacing fires dominate fire regimes but is less so in forests with less severe understory or mixed fire regimes, because stand boundaries do not correspond in any simple or clearly observable manner with past fires. Nonfire forest disturbances and local ecological gradients contribute to uncertainty in re-constructions of past fire perimeters in areas with low-severity fire regimes. In time-since-fire approaches, fire frequencies and fire rotations are estimated based on fitting statistical distributions to the distribution of areas represented by age polygons (Van Wagner 1978; Johnson and Gutsell 1994; Reed et al. 1998). Truncated time series, nonstationary fire hazard, different approaches to curve fitting, and the difficulty of re-constructing fire perimeters are the main limitations to this approach (Finney 1995, Reed et al. 1998). Historical interpretations of long fire chronologies define pre-Euro-American fire regimes for specific areas and provide important baseline data that ecologists and landscape managers may use for assessment of ecosystem change at broad temporal scales (Landres et al. 1999). However, discrepancy in results and interpretations contributes to an overall lack of knowledge of the spatial patterns of fire regimes at landscape scales (i.e., 1000s to 100 000s of ha).

Spatial patterns of past fires may be accurately reconstructed from time series of aerial photographs or satellite imagery. While the temporal extent of such re-constructions is limited, early aerial photographs and satellite imagery can provide accurate fire perimeter and severity information for reasonably long periods (Minnich 1983; Chou and Minnich 1990; Minnich and Chou 1997). The temporal extent of imagery, the length of the interval between the time of the fire and the acquisition date of the imagery, and the difficulty of accurately representing moderate- and low-severity fires are the main limitations on re-constructing historical fires using remotely sensed data.

Compilations of mapped observations of past fires provide spatially explicit time series of area burned. In these databases, fires are usually represented as sets of points (fire-occurrence databases) or perimeters (fire atlases). Fire atlases represent visual estimates of the shape and extent of actual fires over time and are well suited for estimation and evaluation of area frequencies over broad areas (Van Wagner 1988; Pickford et al. 1980; McKelvey and Busse 1996; Minnich and Chou 1997). The spatially explicit representation of fire perimeters in fire atlases provides an advantage over fire-history methods based purely on dendroecological or remotely sensed evidence of past fires. Information in fire atlases is usually limited to fire perimeters rather than burn-severity patterns within fire perimeters. Fire atlases represent a subset of the total number of fires from an area, because many small fires are not recorded. However, fire atlases usually include the largest fires and impart a unique spatial and temporal perspective for analyzing historical fire patterns at landscape scales (Strauss et al. 1989). Mapping methodologies and precision change over time within fire atlases; thus, it is impossible to completely assess the spatial accuracy of these data bases. Standard methods for mapping the extent and severity of fires do not exist, and the strategies for archiving fire information vary widely for different areas and different government agencies. In contrast with a time-since-fire approach, fire atlases implicitly represent areas that have burned multiple times. Area frequencies may be calculated from mapped fire perimeters, instead of estimated from a statistical distribution (e.g., Johnson and Gutsell 1994; Reed et al. 1998). The natural fire-rotation method (Agee 1993) explicitly incorporates re-burned areas from time series of fire perimeters. This method, while not as useful for empirical modeling of fire frequency, implicitly evaluates rotation period for a specific period of record. Calculations of area frequencies based on fire atlases provide spatially continuous, landscape-scale information that fire-scar composites, time-since-fire, and remote-sensing approaches lack.

Fire atlases from the GALWC and the SBWC encompassed three main periods of fire management strategies: pre-modern suppression, modern suppression, and wildfire-use periods. Rationale for these delineations is described later in the methods section. We were able to compare fire patterns among time periods within and between the two climatically distinct wilderness complexes used as study areas. By choosing large wilderness areas we minimized the effect of roads, timber harvest, and anthropogenic ignition on our interpretations of fire patterns.

We tested hypotheses that fire patterns differed statistically among time periods defined by different fire-management strategies (H_0: no difference in fire size, frequency, or shape over time). We expected fires would be larger, more frequent, and have more complex shapes in the early pre-modern suppression period and less frequent, smaller, and less complex during the modern suppression period. Further, we expected that the wildfire-use period, from 1975 to the end of the period of record, would be characterized by an increase in fire frequency and fire size relative to fires during the modern suppression period. Different fire-suppression policies affected the strategies for fire suppression through the 20th century. Anthropogenic suppression of fires implicitly tends to make individual fires smaller and less frequent. Suppression of fires may also impart less complex fire shapes by containing flaming fronts within control lines (sensu Krummel et al. 1987). Mosaics created by fires over time contribute to heterogeneity in landscape structure. Landscape heterogeneity is directly related to ecosystem function and affects the flow of resources, the spread of disturbance, and the migration of species (both plant and animal) across landscapes (Forman and Godron 1986; Turner et al. 1989; Waring and Running 1998).

This research is the first attempt to compare landscape-scale evaluations of fire patterns in two, climatically distinct areas. Statistical analyses provide spatially explicit, quantitative evidence of changes in fire rotations throughout the 20th century. Results improve understanding of the effects and consequences of different fire-management strategies and may be used to identify settings where fires have been more influenced by fire suppression than others. Relationships between landscape variables and climate patterns are investigated in a separate paper. Similarities in results between study areas provide converging lines of evidence that both aggressive modern fire suppression and prescribed natural fire have affected fire regimes in the Rocky Mountains. Such data are crucial as baselines for evaluating the degree to which climate change, land use, fire suppression, and topography contribute to changing fire regimes.

Methods

Study areas

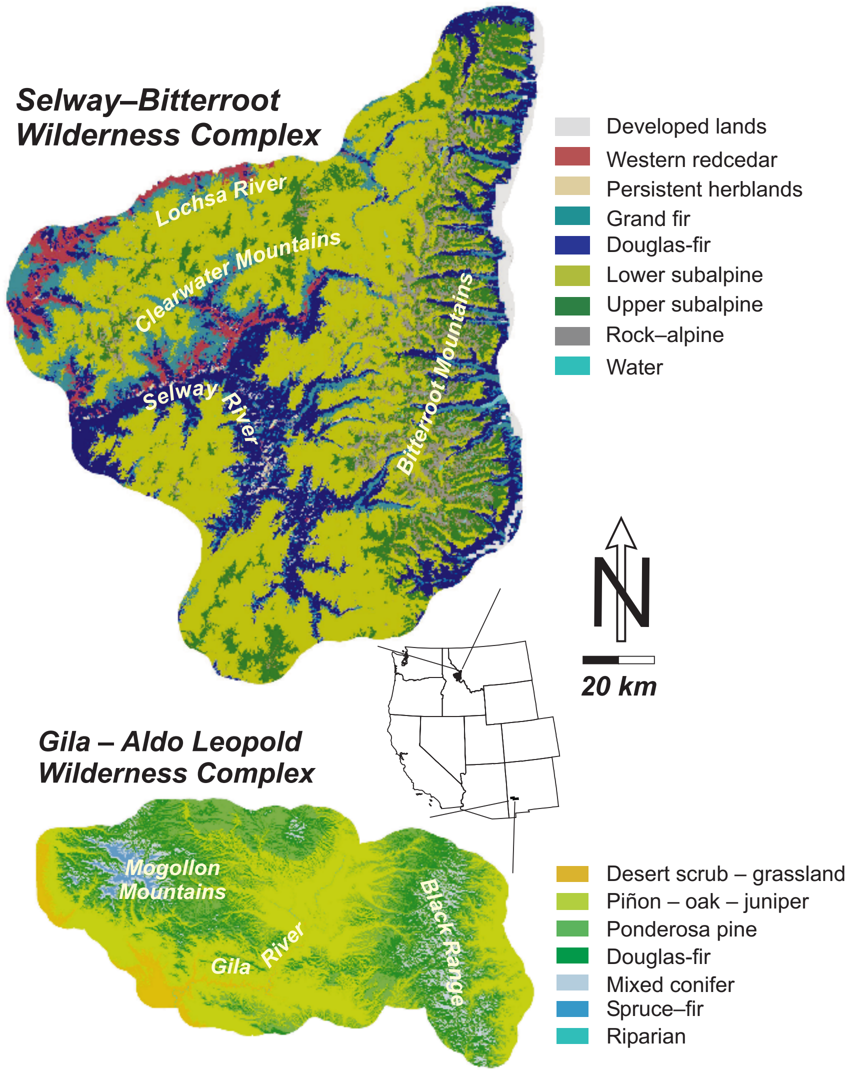
Gila – Aldo Leopold Wilderness Complex

The GALWC is a 486 673-ha area in west-central New Mexico (Fig. 1). The complex is composed of the Gila Wilderness Area, the Aldo Leopold Wilderness Area, Gila Cliff Dwellings National Monument, and some nonwilderness portions of the Gila National Forest. The Gila Wilderness Area, established in 1924, was the first officially designated wilderness in the United States. The GALWC encompasses the headwaters of the Gila River, the Mogollon Mountains, and the Black Range 70 km north of Silver City, N.M. The Gila Wilderness Area is phyisiographically diverse and is characterized by deep, narrow river canyons; broad, flat mesa tops; and steep, heavily forested mountains. Elevations range from 1300 m near the mainstem of the Gila River to 3300 m on top of the Mogollon Mountains. The Aldo Leopold Wilderness Area is rugged, with elevations ranging from 1500 m near the Mimbres River to 3000 m on McKnight Mountain in the Black Range.

The basin and range topography supports desert scrub (*Ceanothus*, *Artemisia*, and *Yucca* spp.) in broad valleys at the lowest elevations. As elevation increases, piñon pine – juniper woodlands (*Pinus edulis* Engelm., *Juniperus deppeana* Steud., *Juniperus monosperma* (Engelm.) Sarg., and *Quercus* spp.) gain dominance. Extensive stands of ponderosa pine are found at middle elevations with a shift to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at 2300 m. At upper elevations, forests are composed of mixed conifer forests of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), southwestern white pine (*Pinus strobiformis* Engelm.), white fir (*Abies concolor* (Gord. & Glend.) Lindl.), and trembling aspen (*Populus tremuloides* Michx.).

The geologic substrate of the GALWC was formed during volcanic events in the late Cretaceous (USGS 1965). The Gila Conglomerate, a tertiary sedimentary formation, is exposed in tall, pinnaclelike rock formations along the Middle and East Forks of the Gila River (Ratte et al. 1979). Annual precipitation varies from 250 to 760 mm in the mountain ranges (Beschta 1976). Mean daily temperatures vary from below freezing in the winter to 30°C in the middle of summer. Thunderstorms are common in the summer months, resulting from orographic lifting of moist, air masses moving north from the Gulf of Mexico.

Fig. 1. Study areas: the Gila – Aldo Leopold and Selway–Bitterroot wilderness complexes. Colors show the different potential vegetation types (PVTs). The PVT data were provided by the USDA Forest Service Fire Science Laboratory in Missoula, Mont.



The fire season in the GALWC begins as early as April and extends through September. Spring conditions are usually dry, with thunderstorm activity increasing in June and July after the onset of the summer monsoon. Historically, the GALWC was dominated by low-severity (i.e., low forest mortality) surface fire regimes with mixed-severity fire regimes found at upper elevations (Swetnam and Dieterich 1985; Abolt 1996). During dry years of the 20th century, fire behavior has been extreme with stand-replacing fire across all elevations (Swetnam and Dieterich 1985). The Gila Wilderness Area has one of the highest levels of lightning-caused fire occurrence in the nation, with an average of five lightning-caused fires per 10 000 ha per year. There are no temporal trends in lightning strike density or lightning-ignited fires over the period of record (Barrows 1978; M.G. Rollins, unpublished data).

Selway–Bitterroot Wilderness Complex

The SBWC in Idaho and Montana (Fig. 1) is a 785 090-ha wilderness complex, second in size (in the conterminous United States) only to the adjacent Frank Church River-of-No-Return Wilderness in Idaho. The area is characterized by extremely rugged terrain with over 2500 m of relief. Portions of the wilderness are found on the Bitterroot, Clearwater, Lolo, and Nez Perce National Forests.

Three main topographic regions exist within the wilderness complex. The eastern portion of the wilderness consists of the north–south oriented Bitterroot Range. These mountains begin in the northeastern corner of the wilderness, extend 70 km to the southeastern corner, and are characterized by large granitic mountain peaks as high as 3050 m. East–west oriented glacial valleys dissect the Bitterroot Mountains to valley bottoms as low as 1000 m. The Clearwater Mountains are found in the central and southern portions of the wilderness. This portion of the wilderness comprises the majority of the Selway River basin. This area consists of rugged terrain with complex high ridges dissected by steep canyons as low as 500 m. Large river valleys (the Lochsa River drainage) with over 1500 m of relief characterize the northwestern portion of the wilderness.

The upper portions of the Lochsa and Selway River basins (located in the north-central and northwestern portion of the wilderness) are distinguished by diverse, Pacific maritime forests with assemblages of western redcedar (*Thuja plicata* Donn. ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western white pine (*Pinus monticola* Dougl. ex D. Don), and Douglas-fir ranging from 500 m to 1500 m of elevation. At elevations near 1000 m, forests in the central, southern, and eastern portions of the SBWC are dominated by ponderosa pine, Douglas-fir, and western larch

(*Larix occidentalis* Nutt.). As elevation increases, these assemblages convert to mixed Douglas-fir – Engelmann spruce – grand fir (*Abies grandis* (Dougl.) Lindl.) forests followed by subalpine forests containing assemblages of Engelmann spruce and subalpine fir with lodgepole pine (*Pinus contorta* Dougl. ex Loud.) dominant in stands with more recent disturbance. Many stands of lodgepole pine are extensive and have homogenous stand structure and ages (Arno et al. 1993). Mixed whitebark pine (*Pinus albicaulis* Engelm.) and alpine larch (*Larix lyallii* Parl.) forests characterize the highest subalpine elevations. Subalpine forests cover 70% of the SBWC.

Mountainous geology in this region is characterized by granitic rock that is part of the Central Idaho Batholith. Lower elevations are dominated by substrate formed in a series of volcanic events during the Mesozoic and Cenozoic periods (Habeck 1972). The canyons and valleys of the central Selway and Clearwater River drainages were dissected prior to the eruption of the Columbia River basalt (Greenwood and Morrison 1973; Habeck 1972).

Along the Selway River, close to 1000 mm of precipitation falls annually with values as high as 1800 mm in the central and Bitterroot portions of the wilderness. Over 50% of this precipitation falls as snow (Finklin 1983). In general, snowpack persists in the high country of the SBWC through late June. January is usually the wettest month with average precipitation ranging from 75 to 250 mm (Finklin 1983). Late summer is the driest time of year with average monthly precipitation between 20 and 30 mm. Large thunderstorms are frequent in the SBWC, with a peak in activity during the early summer. Dry thunderstorms are common in the late summer and early fall. Monthly mean, daytime temperatures range from –10°C in January to around 30°C in July and August.

The fire season in the SBWC begins in the early summer and may extend through September. Fire regimes are mixed, with infrequent, patchy stand-replacement fire dominant in upper elevation forests and frequent, lower severity, surface fires at lower elevations (Brown et al. 1994). During years with extreme weather, stand-replacement fires are common across all elevations (Brown et al. 1994; Barrett and Arno 1991).

Compilation and analysis of spatial data

Potential vegetation

Potential vegetation types (PVT) uniquely describe the biophysical characteristics of sites. PVT classifications provide a direct method for integrating the biophysical characteristics that are important to plant distribution across landscapes (Keane et al. 1999). This landscape classification methodology is rooted in succession theory (Clements 1936) and is based on logic developed by Daubenmire (1968) and Pfister and Arno (1980) for describing the distribution of plant habitat across landscapes. PVTs are named for the climax plant association presumed to exist in the absence of disturbance (Cooper et al. 1991). Although originally based on single-pathway succession, the concept remains valid for multiple pathway succession models (e.g., Noble and Slayter 1980; Fastie 1995). PVTs are well suited for historical analyses, because they are based on well-described classification schemes and remain relatively constant over time. In contrast, maps of existing vegetation represent a single moment in time. Instead of estimating area frequency for existing landscape composition and structure we estimated area frequencies for unique permutations of biophysical characteristics of the two study areas (i.e., PVTs). Classification schemes for PVT are usually based on variables describing biophysical setting and site potential rather than plant associations. Methods for characterizing existing vegetation differ widely based on the goals and potential use of the classification. For example, a classification for an existing vegetation map used for characterizing elk habitat may differ widely from a map used for describing the distribution of fuel structure across a landscape, while the PVT classification for each study would be identical.

The USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Mont., provided maps of PVTs for both wilderness complexes. These classifications were based on geographic and topographic settings using a heuristic, rule-based approach (Keane et al. 1998, 2000). Rules for mapping PVTs in each wilderness were based on five geographic information system (GIS) layers: geographic zone, existing vegetation, elevation, slope, and aspect. Using these layers, area ecologists and scientists formulated series of rules to assign different permutations of location and topography to PVTs. These rules, along with field data, were incorporated into a classification model within a GIS to create raster maps of PVTs for each wilderness with a 30-m grid cell resolution. For example, in the northwestern portion of the SBWC, the western redcedar PVT was mapped in areas with elevations less than 1219 m on aspects from 280 to 120° and slopes less than 40% (Keane et al. 1998).

Our only modifications of the provided data were to group the subalpine forest PVT classes for the SBWC to form two new classes (lower subalpine and upper subalpine) and to subset PVT data to the extent of the each wilderness complex. Ponderosa pine occurs as a PVT in the GALWC but not in the SBWC; however, ponderosa pine may occur as a dominant seral tree in the Douglas-fir PVT in either study area. We excluded areas of development and water bodies from our analyses; these were insignificant portions of each study area (less than 3%). Thematic accuracy of these layers was determined by comparison with field data. Accuracies of PVT maps were 57% in the SBWC and 89% in the GALWC (Keane et al. 1998, 2000). Extensive fieldwork for other research projects showed that qualitatively, the PVT classes adequately represented the range of plant habitat and site conditions across each wilderness complex

Fire atlases

Twentieth-century fire perimeters were obtained in digital form (or digitized) from archival fire data at the Gila National Forest Supervisor's Office for the GALWC and from the Bitterroot, Clearwater, and Nez Perce National Forest Supervisor's Offices for the SBWC. Archives were compiled from old fire reports or operational fire perimeter maps. Although it is impossible to completely assess the accuracy of these data, mapped fire perimeters are based on information intended to spatially represent the location, size, and shape of fire events. Fires that are the most important financially, ecologically, and socially are the most likely to be mapped (McKelvey and Busse 1996). This may bias the data toward large, high-severity events that were easily mapped; however, the large fires usually comprise a very large proportion of the area actually burned (Strauss et al. 1989; Moritz 1997).

Fire perimeters for the GALWC were digitized from one of two 1 : 126 000 "master" fire atlases. The perimeters were compiled as "regions" (ESRI 1998) within a 5-km buffer around the Gila National Forest Wilderness District, forming the boundary of the atlas. A 5-km buffer around the wilderness boundary was used for each study area. This insured inclusion of the majority of fires that burned over the wilderness boundary. Most of the area included in the 5-km boundary was not densely roaded or harvested. "Regions" are a data architecture, specific to ARC/INFO GIS software (ESRI 1998), that are ideal for manipulating fire atlas data as overlapping fire perimeters are stored in a single database, while analyses involving areas of reburned areas or individual fires are still possible.

Archival data for the SBWC were obtained as ARC/INFO GIS coverages from the Bitterroot, Clearwater, and Nez Perce National Forests. Where duplicate fire perimeters existed, we included fires from the Nez Perce National Forest data base because the Nez Perce National Forest administers the largest portion of the wilderness. This minimized error resulting from compiling data mapped with different strategies. In all cases, perimeters that were truncated by National Forest boundaries were discarded in favor of perimeters (for the same fire) that were mapped across National Forest boundaries. A consequence is that large portions of the 1910 and 1919 fires (two of the largest fire years) were based on Clearwater National Forest maps instead of Nez Perce National Forest Maps. The areas for both study areas, including the 5-km buffers, were 486 673 ha for the GALWC and 785 090 ha for the SBWC.

The extent of fires included in the fire atlases were compared with the National Interagency Fire Management Integrated Database (NIFMID) to determine the proportions of large and small fires and proportions of lightning and human caused fires were included in the fire atlases. We calculated fire rotations by PVT for three time periods in each area: (*i*) the pre-modern suppression period (1909–1946 for the GALWC and 1880–1934 for the SBWC), (*ii*) the modern suppression period (1947–1974 for the GALWC and 1935–1974 for the SBWC), and (*iii*) the wildfire use period (1975–1993 for the GALWC and 1975–1996 for the SBWC). The USDA Forest Service is currently updating archives in each wilderness complex to include fires through 2001. Temporal extents for different time periods were based on different fire suppression strategies in each area over time. Anthropogenic ignitions, fire suppression, and land use (e.g., mining and grazing) affected fire patterns far before the beginning of fire occurrence archives in our study areas.

Time periods and data analysis procedures

We defined the pre-modern suppression period as the period before aerial operations greatly increased the ability to detect and suppress fires. The period during and after World War II was characterized by a shift in fire policy in the U.S. Forest Service, where new tactical emphases included mechanization and aerial operations (Pyne 1982). Aerial retardant and smokejumpers were permanently established at the Gila National Forest for the first time in 1947. This date delineated the beginning of the modern suppression period in the GALWC. Modern fire-suppression technologies were implemented successfully for the first time in the northern Rockies in 1935 (Pyne 1982; Brown et al. 1994; Moore 1996). This year marked the beginning of the modern suppression period in the SBWC. The smokejumper base at Nine Mile, Mont. (100 km from the SBWC), began official operations in 1939, and the aerial fire depot in Missoula, Mont., has been in operation since 1954. Aerial detection and suppression technologies gave fire managers a nearly immediate advantage in fire suppression (Pyne 1986). During the mid-1970s, fire policies in the U.S. Forest Service reflected an understanding of the importance of fire as an ecosystem process. Management-ignited fire and wildland fire use joined fire suppression at the forefront of fire policy in the United States (Pyne 1982). In both wilderness complexes, prescribed natural fire (PNF) management (now referred to as wildland fire use for resource benefit) was implemented in 1975 (Garcia et al. 1978; Frost 1982); this date delineates the beginning of the wildfire-use period in each area. The GALWC and SBWC wilderness complexes were among the earliest large areas with active PNF plans and have served as templates for fire-management plans on both government and private lands through the present. Federal changes in wildland fire policy at the agency level affect fire occurrence and spread gradually (Pyne et al. 1996). While the transition between periods was probably not perfectly discrete, by choosing local changes in suppression technology and policy implementation we reduced delays inherent in policy implementation at the National Forest level. Our goal was to illustrate changes in fire frequency and pattern based on rapid local improvements in fire-suppression technology and policy changes at the level of individual wilderness complexes, where policy was implemented quite rapidly (Garcia et al. 1978; Frost 1982). We assumed that there was a lack of overall trend in variability in weather and ignition potential over the period of record defined by the temporal extent of the fire atlases. Relationships between climate variability and landscape characteristics and fire patterns are analyzed in another paper (Rollins et al., in review[3]).

Statistics compiled and reported include number of fires, fire size (mean, median, minimum, and maximum), the largest fire years, and fire-rotation periods. Size and area-weighted mean shape index (AWMSI, a measure of shape complexity; McGarigal and Marks 1995) of fires were computed to assess possible trends in fire size or shape. Two-sided Kolmogorov–Smirnov tests were used to assess differences in size distributions between time periods. AWMSI was calculated for every fire perimeter as

$$[1] \qquad \mathrm{AWMSI} = \sum_{j=1}^{n}\left[\left(\frac{p_{ij}}{2\sqrt{\pi a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right]$$

where p is the perimeter and a is the area of the individual fires i in year j (McGarigal and Marks 1995). We considered every individual polygon in the fire atlas as a separate fire. We used Kruskal–Wallis nonparametric ANOVAs to determine if size or fractal dimension of fires were significantly different among time periods.

Cumulative distributions of area burned were plotted to identify changes in the rates of burning over time in both wilderness complexes. We used annual area burned to calculate fire rotation by PVT and by time period. Fire rotation is based on the actual annual area burned (i.e., maps of complete fire perimeters). We used the following formula to calculate fire rotation (FR) from the complete perimeter fire atlases:

$$[2] \qquad \mathrm{FR} = \frac{T}{P}$$

where T is the temporal extent of the fire atlas and P is the proportion burned for each PVT within the study area.

Results and discussion

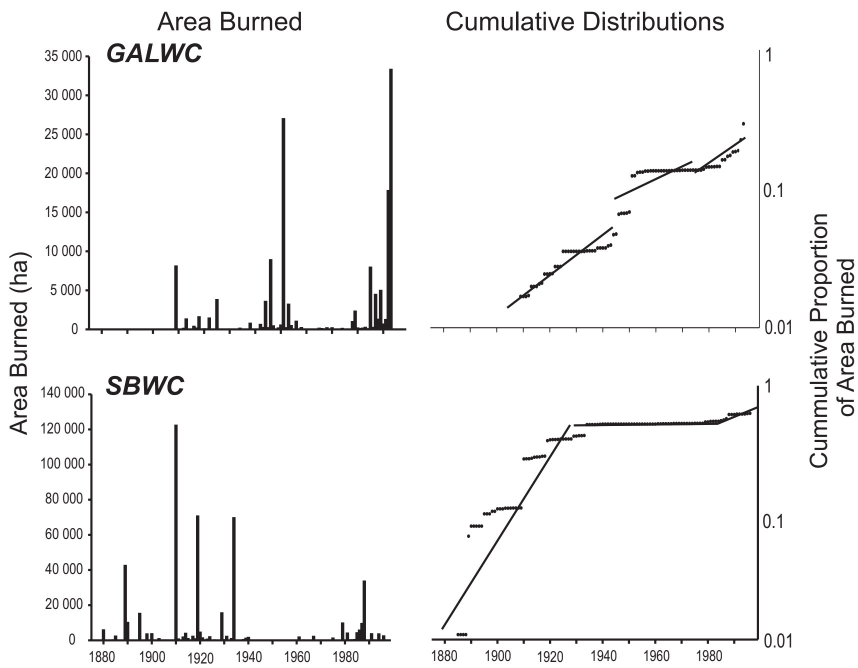
Fire rotations in each area differed between time periods defined by different fire suppression strategies. In the GALWC, fire rotations were long during the pre-modern suppression period, short during the modern suppression period, and shorter still in the wildfire-use period. In the SBWC, fire rotations were short in the pre-modern suppression, very long in the modern suppression period, and short in the wildfire-use period (Table 1). Fire frequencies were low for the entire 20th century relative to estimates of pre-Euro-American fire frequency from each area (eg. Arno 1976; Swetnam 1983; Swetnam and Dieterich 1985; Barrett and Arno 1991; Brown et al. 1994; Abolt 1996). Fire-perimeter data extended from 1909 to 1993 in the GALWC and from 1880 to 1996 in the SBWC (Fig. 2). Mapped data indicated that 142 700 ha burned in 220 fires in the GALWC, and 545 229 ha burned in 524 fires in the SBWC. Including areas burned multiple times, 30% of the GALWC

[3] M.G. Rollins, P. Morgan, and T.W. Swetnam. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain wilderness areas. Landsc. Ecol. In review.

Table 1. Fire rotation, fire cycle, area, and percent reburned for each time period.

Time period	Fire rotation (years)	Fire cycle (years)	Area of reburn (ha)	Area burned that reburned (%)
Gila – Aldo Leopold Wilderness Complex				
All years	289	290	39 559	28
Pre-modern suppression 1909–1946	580	659	4 693	15
Modern suppression 1947–1974	396	395	285	1
Wildfire use 1975–1993	121	117	13 850	18
Selway–Bitterroot Wilderness Complex				
All years	194	197	103 973	22
Pre-modern suppression 1880–1934	110	102	75 502	20
Modern suppression 1935–1974	3888	3883	29	0.5
Wildfire use 1975–1996	218	214	3 546	4

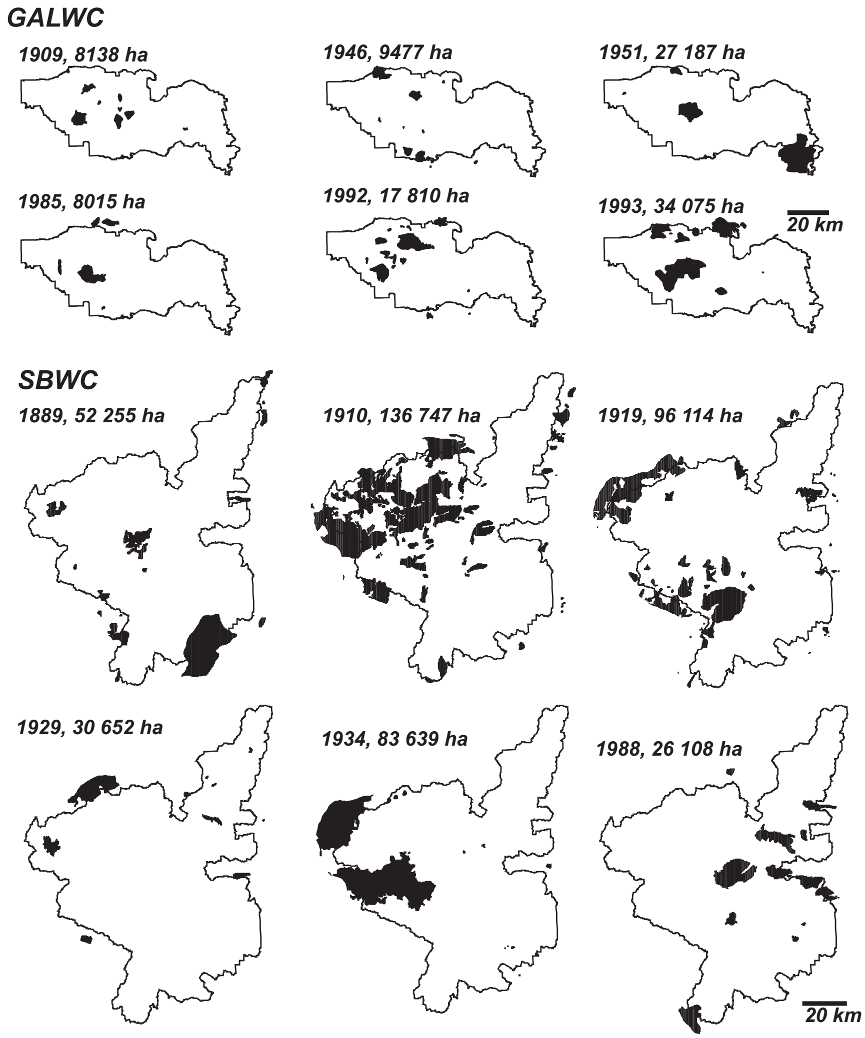
Fig. 2. Area burned and cumulative distributions of area burned over time for each study area. Cumulative distributions were based on proportion of area burned during each year relative to the area of the wilderness complex. Lines were fit to indicate different rates of burning for each time period. Steeper slopes represent faster rates of burning.



and 70% of the SBWC burned during the period of record. In the GALWC, 1909, 1946, 1951, 1985, 1992, and 1993 were the years with the most extensive areas burned (Figs. 2 and 3) and accounted for 72% of the total area burned in the 94-year record. In the SBWC, the years with the largest areas burned were 1889, 1910, 1919, 1929, 1934, and 1988 (Figs. 2 and 3) accounting for 75% of the total area recorded in the 116-year fire atlas.

Archived fire perimeter data represented only a small proportion of the small fires that actually occurred. Fire atlases usually represent the most ecologically and sociologically important fires (Strauss et al. 1989; McKelvey and Busse 1996). Comparison of the fire atlases from each wilderness complex with the NIFMID fire occurrence data indicated that 0.13 and 0.32% of the fires less than 10 ha were accounted for in the fire atlases from the GALWC and SBWC, respectively. However, nearly 80% of the small fires not accounted for in each fire atlas burned less than 1 ha. While these small fires are ecologically significant at fine scales, fire atlases from each wilderness complex account for a large proportion of area burned in landscape-scale fires. In the GALWC, 85% of the fires over 100 ha were included in the fire atlas. The fire atlas from the SBWC contained 76% of the fires over 100 ha recorded in the NIFMID data. Number of fires is not as important as total area for the fire-frequency analyses presented in this paper. In the GALWC and SBWC, 99 and 93% of the total area burned in the NIFMID data was included in the corresponding fire atlases. Large proportions of the fires in the NIFMID data were lightning ignited (90% in the SBWC and 94% in the GALWC). Low correspondence in small fires between the fire atlas and the NIFMID may result from a lack of specific policies or guidelines for including fire perimeters in fire-history databases. Low correspondence may also result from

Fig. 3. Six largest fire years in each study area. These fires were responsible for 72 and 75% of the area burned in the GALWC and SBWC, respectively, during the period of record.



the exclusion of particularly remote fires or the sole inclusion of fires that were actively suppressed. While correspondence between these two independent fire-occurrence databases is not as high as might be desired, our mapped time series of fire perimeters are at least as good as other sources of fire-history data (e.g., stand age based estimates), particularly for large, landscape-scale fires (Morgan et al. 2001). Additionally, our data provide spatially explicit fire perimeters for all of the largest individual fires.

Fire size and shape

The extent and shape complexity of fires directly affect landscape heterogeneity and ecosystem diversity and are key characteristics of natural fire regimes (Agee 1993). Size and shape of fires vary naturally and are directly related to fire frequency and behavior (Pickett and White 1985; Clark 1991; Agee 1993; Minnich and Chou 1997). Shifts in the size distribution of fires and rates of burning over long periods of time can change the patch dynamics of landscapes (Pickett and White 1985; Clark 1991). During the latter half of the 20th century, reduction in fire size without corresponding increases in fire frequency has created more homogenous landscape structure across in large wilderness areas of the western United States and has increased the potential for future disturbance and reduced ecosystem diversity (Quigley and Arbelbide 1997; McKelvey et al. 1996). Reducing the complexity of fire perimeters can increase ecosystem homogeneity as well, reducing the amount of edge and effectively reducing the width of ecotones between adjacent patch types (Pickett and White 1985; Forman and Godron 1986). In the forests of the Rocky Mountains, differential exploitation of fire-generated patches by available plant and animal species increases the potential number of coexisting species across landscapes (Pickett and White 1985).

Size distributions of fires in both wilderness complexes were heavily skewed, with few large and many small fires (Fig. 4), similar to fire patterns described in the Sierra Nevada Mountains in California (McKelvey and Busse 1996); Baja California, Mexico, and southern California (Minnich and Chou 1997); Olympic National Park, U.S.A. (Pickford et al. 1980); and Canada (Van Wagner 1988). Each perimeter in the fire atlases was considered as an individual fire. Variability in fire size was highest during the modern suppres-

Fig. 4. Size distribution of individual fires in each study area. Note the log scale and the infrequent large events in each area.

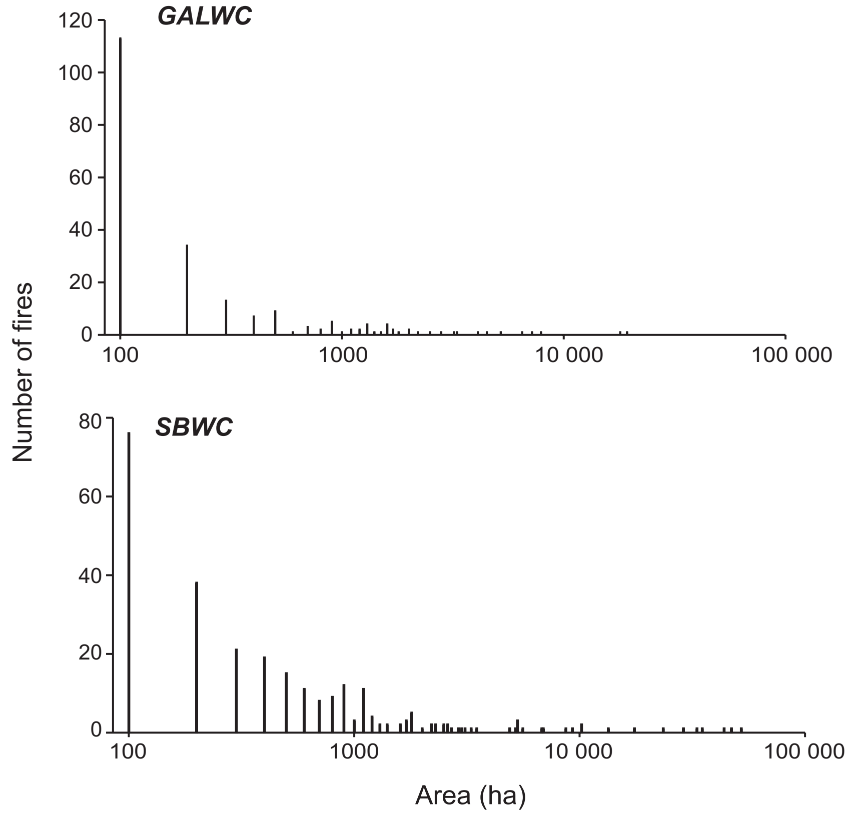


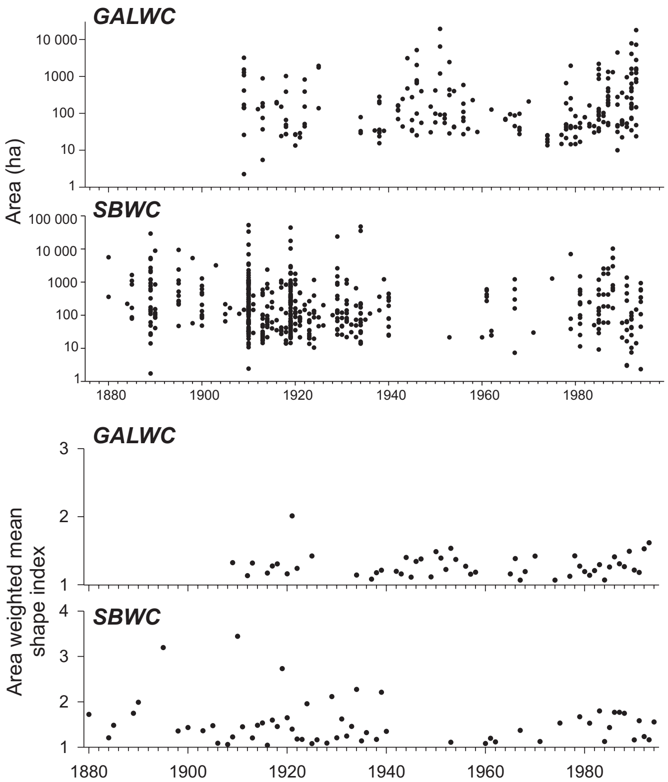
Table 2. Mean, median, minimum, and maximum fire sizes (ha) and area-weighted mean shape index (AWMSI) for all years and for pre-suppression, wildfire-use, and fire-management time periods for each study area.

	Mean fire size (ha)	Median fire size (ha)	SE	Minimum fire size (ha)	Maximum fire size (ha)	AWMSI
Gila – Aldo Leopold Wilderness Complex						
All years	648	939	137	2	19 446	1.27
Pre-modern suppression 1909–1946	441	133	101	2	5 166	1.27
Modern suppression 1947–1974	769	68	457	14	19 446	1.27
Wildfire use 1975–1993	744	110	208	10	17 945	1.29
Selway–Bitterroot Wilderness Complex						
All years	1153	136	224	2	52 223	1.51
Pre-modern suppression 1880–1934	1321	133	288	2	52 223	1.57[a]
Modern suppression 1935–1974	269	159	55	7	1 209	1.28
Wildfire use 1975–1996	730	154	1819	2	10 219	1.57

[a]Fire shapes in the pre-modern suppression period were significantly more complex than fire shapes during modern suppression period (Kruskal–Wallis Test, $P < 0.05$), but no other pairwise comparisons were statistically significant.

sion period in the GALWC and during the wildfire-use period in the SBWC (Table 2). These periods were each dominated by one or two large fire years. In the GALWC, large fires in 1951 and 1953 burned 89% of the total area burned during the modern suppression period, and the maximum fire size occurred during this time period. The mid-1950s were characterized by the most severe drought in the southwestern United States since 1580 (Swetnam and Betancourt 1998). Large fires during the extremely dry summer of 1988 were responsible for 44% of the area burned during the wildfire-use period in the SBWC. The largest fire in the wildfire-use period was one fifth the size of the largest fire in the pre-modern suppression period in the SBWC. In both wilderness complexes, large fires during periods with the highest variability in fire size burned primarily in upper elevation forests. This probably results from a combination of dry conditions during these years and the difficulty of suppressing fires in subalpine and mixed conifer forests during extreme fire weather (Rollins et al., in review[3]). Although size distributions between time periods and between areas were not significantly different (two-sample Kolmogorov–Smirnov tests, $P > 0.05$), it is important to

Fig. 5. Size and area-weighted mean shape index (AWMSI) of fires over time. With a few exceptions, fires under 20 ha in size are not included. AWMSI ranges from one to infinity and is a description of shape complexity. Neither fire size nor shape showed an overall trend with time.



note that the period of record in the fire atlases was probably too short to fully assess the effect of shifting size distributions on landscape patterns or ecosystem processes.

Fire shape and size showed little evidence of trend over the period of record (Fig. 5). While mean fire sizes between each area were quite different, Kruskal–Wallis tests for differences in medians between fire sizes in different time periods indicated no significant difference in either wilderness complex ($P > 0.05$; Table 2). In the GALWC, fires were large in both the modern suppression and wildfire-use periods and small during the pre-suppression period. In the SBWC, fires were large in the pre-modern suppression period, small during the modern suppression period, and relatively larger during the wildfire-use period (Table 2). In the GALWC there were no significant differences in fire shape between the different time periods. Fire shape was significantly more complex in the pre-modern suppression period compared with the less complex modern suppression period in the SBWC. Lack of an overall trend in fire shape does not support the assertion that mapping technology has changed the ability to map the patchiness of fires. For recent periods, this fine-grain information is documented in databases of remotely sensed imagery (i.e., aerial photos and satellite data).

We expected that a trend toward less complex fire perimeters (i.e., a lower AWMSI) would occur with higher levels of fire suppression. We hypothesized that fire shape would be most complex in the pre-modern suppression period and least complex during the modern suppression period. This pattern was evident in the SBWC, indicating that fire suppression may reduce the complexity of landscape patterns created by fire. Increases in fire shape complexity between time periods may suggest that fires were burning in more complex patterns or that the spatial patterns of fires were mapped more precisely. There was an overall lack of a trend in the shape of fires in the GALWC, but this may be a bias of the digitizing process. As mapped data are digitized, there is a reduction of precision from the original data. As data are manipulated and re-projected, mapping precision decreases. However, this effect is small if users pay careful attention while digitizing or re-projecting spatial data. Polygons in each fire atlas went through several undocumented stages of manipulation prior to compilation for this paper. Landscape-scale variability of fuel composition and structure may override fire suppression in determining the shape complexity of fires.

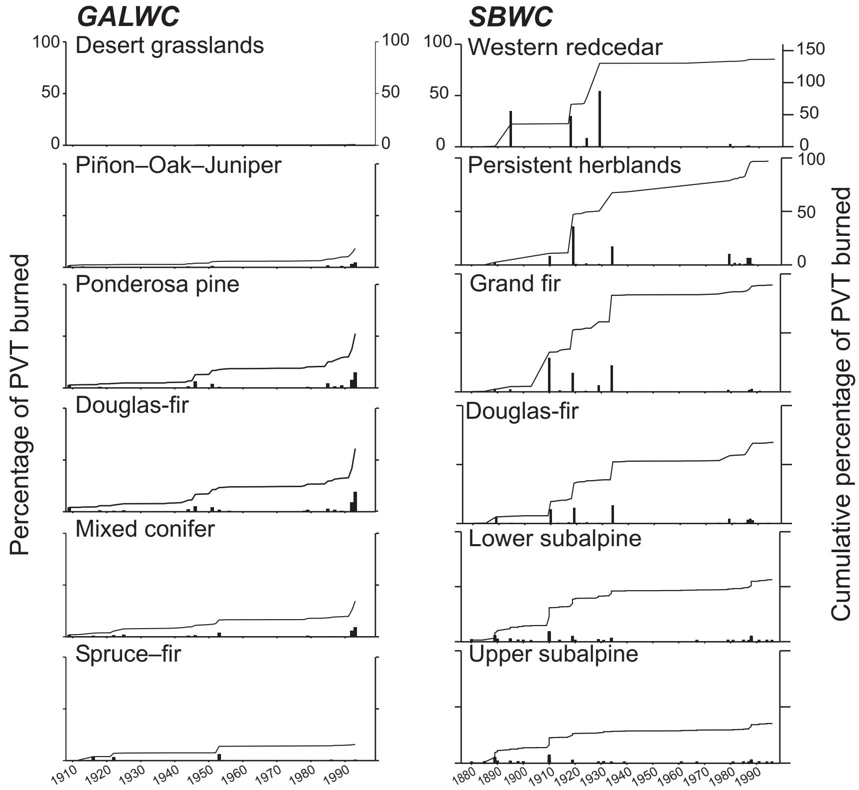
Temporal patterns of fire

Pre-modern suppression period

Six percent of the 486 673-ha GALWC burned during the pre-modern suppression period. In contrast, fires burned 49% of the 785 090-ha SBWC. Relative to estimates of pre-Euro-American fire frequencies, fire rotations were long in the GALWC and short in the SBWC (Tables 1 and 2). Area burned between 1909 and 1942 was low in the GALWC compared with estimates of pre-Euro-American area burned made by Swetnam and Dieterich (1985) and Abolt (1996). This was very probably due to a reduction of fine fuels by intense overgrazing by sheep and cattle in the late 19th century through the middle 20th century (Swetnam and Dieterich 1985, Savage and Swetnam 1990; Abolt 1996). At the turn of the century, Rixon (1905) reported that the area encompassing the current Gila National Forest was very heavily grazed. Swetnam and Dieterich (1985) suggest that fires over 1200 ha burned with 10- to 15-year fire return intervals in the ponderosa pine and Douglas-fir forests of the Gila Wilderness during the 17th, 18th, and 19th centuries and have suggested this as a goal for fire management in this wilderness area. This goal is within current Federal Wildland Fire Management Policies (U.S. Government 2001) but not allowed for in the wildland fire use policy of the Gila National Forest (Garcia 1978).

Area burned in the SBWC was high in the late 19th and early 20th centuries. Grazing was not as prevalent in the SBWC as in the GALWC. The east-facing slopes of the Bitterroot Mountains and low-elevation benches along the Selway River experienced domestic grazing from the mid-1800s to the mid-1900s, but the majority of the SBWC was so remote that little if any grazing occurred (Gruell et al. 1982). There is little evidence that grazing affected fire frequencies in these areas to the same extent as in the southwestern United States. Anthropogenic ignitions, both before and after Euro-American settlement, were important factors in fire frequencies of lower elevation forests in the northern Rocky Mountains and the SBWC (Barrett and Arno 1982; Pyne 1982; Gruell 1985; Phillips 1985; Moore 1996). Estimates of 17th-, 18th-, and 19th-century fire intervals for the SBWC have ranged from 17 years for surface fires in ponderosa pine dominated forests (contained within the Douglas-fir PVT) to 197 years for stand-replacing fire in western redcedar forests (Barrett and Arno 1991; Brown et al. 1994).

Fig. 6. Proportional distributions (bars) and cumulative distributions (lines) of area burned over time. Area is given as percentages to facilitate comparison between potential vegetation types (PVTs) and between study areas. Note that the percent of area burned in western redcedar PVT in the SBWC exceeds 100% as a result of extensive reburned areas.



During the pre-modern suppression period, low-elevation PVTs burned far more often than expected based on previously published, pre-Euro-American fire histories (Fig. 7). These results are similar to results from Heyerdahl et al. (2001) and McKelvey and Busse (1996). Only 3463 ha of the western redcedar PVT remained unburned (13% of the entire western redcedar PVT), while 40 and 44% of this PVT burned once and twice, respectively. A fire rotation of 41 years is an extremely rapid rate of burning in this type relative to fire-frequency reconstructions for previous centuries (Barrett and Arno 1991, Brown et al. 1994). Indeed, many of these Pacific maritime forests that burned and reburned in 1910 and 1919 show little sign of returning to a forested condition, even after 80 years. In subalpine forests (70% of the area of SBWC), fire rotations for the pre-modern suppression period ranged from 117 to 191 years. These rotation periods are short relative to mean fire-return intervals reported in previous research in the SBWC (Barrett and Arno 1991; Brown et al. 1994). The entire SBWC experienced a great deal more fire in the early 20th century than would be expected based on previously published fire regime descriptions. Very large fires in this period are likely due to a combination of increased rates of anthropogenic ignition, seasonal droughts, and lack of modern suppression technology (Larsen and Delaven 1922; Pyne 1982; Moore 1996).

Modern suppression period

The modern suppression period was characterized by an almost complete lack of fire in the SBWC and reduced burning in the late 1950s and 1960s in the GALWC (Figs. 2, 6, and 7). High-elevation fires burned 7% of the 486 673-ha GALWC, a larger proportion than burned during the pre-modern suppression period. Proportions of PVTs burned were shifted toward high-elevation forests in the GALWC (Figs. 6 and 7). Less than 1% of the 785 090-ha SBWC burned during the modern suppression period. Fire rotations were long during the modern suppression period in both wilderness complexes with the exception of the mixed-conifer PVT in the GALWC. Reductions in area burned during the modern suppression period correspond with dramatic increases in levels of fire suppression and fire-suppression technology in the western United States (Pyne et al. 1996).

The modern suppression period in the GALWC was characterized by large fluctuations in annual area burned. Rates of burning were rapid during the first half of the modern suppression period and slow during the last half (Fig. 2). Advances in fire-suppression technology following World War II (Pyne 1982) were first implemented in the GALWC in 1947, with reconnaissance and aerial suppression operating from an aerial fire depot in Silver City, N.M. These improved suppression efforts appeared to reduce the amount and rate of burning in the GALWC from 1958 through 1978 (Fig. 2).

The fire atlas for the SBWC showed an almost total lack of mapped fire from 1935 through 1979. In the SBWC, fire rotations ranged from 1967 years in high-elevation rock–alpine to 396 498 years in the western redcedar PVT in the SBWC (Table 3). This was likely due to a lack of personnel for observing remote fire events during World War II, and an extended period of modern and aggressive fire suppression after World War II (Pyne et al. 1996). After 1948 there were

Fig. 7. Proportion of potential vegetation types (PVTs) burned in each time period. These distributions parallel the distributions of fire rotations for each time period.

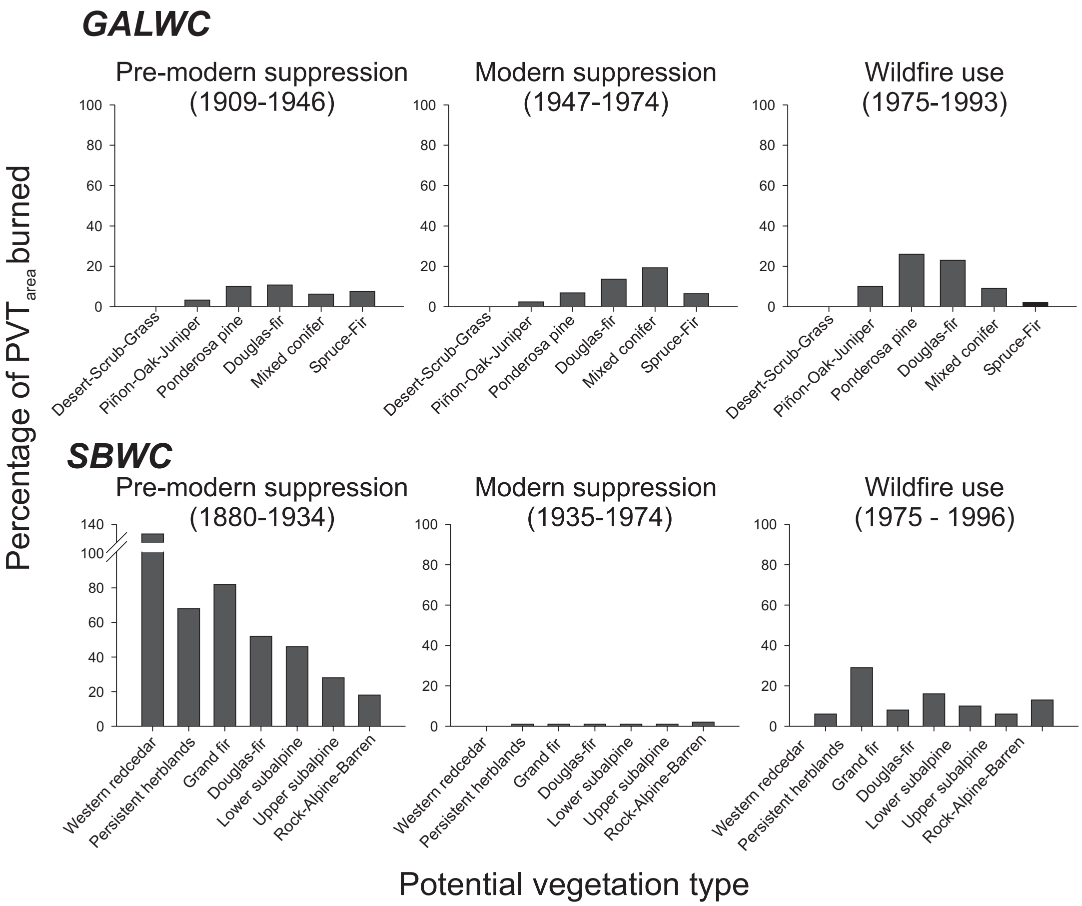


Table 3. Fire rotations for potential vegetation types for the entire period of record and three different time periods representing different fire-management scenarios.

Potential vegetation type	Entire time period 1909–1993	Pre-modern suppression 1909–1946	Modern suppression 1947–1975	Wildfire use 1976–1993
Gila – Aldo Leopold Wilderness Complex				
Desert scrub – grassland	15 753	120 514	40 782	4324
Piñon pine – oak – juniper	540	1 156	1 182	188
Ponderosa pine	200	382	410	74
Douglas-fir	180	353	205	84
Mixed conifer	245	612	145	207
Spruce–fir	537	508	435	998
Selway–Bitterroot Wilderness Complex				
Western redcedar	368	41	396 498	359
Persistent herblands	80	79	4 167	77
Grand fir	384	66	7 380	267
Douglas-fir	169	104	4 704	140
Lower subalpine	519	117	3 651	230
Upper subalpine	852	191	3 361	361
Rock–alpine–barren	371	295	1 957	164

two major aerial fire depots on either side of the SBWC that served as headquarters for smokejumpers, aerial reconnaissance, and aerial fire retardant application (Pyne 1982).

Wildfire-use period

After the implementation of prescribed natural fire management in 1975, each study area showed moderately increased rates of burning relative to the preceding modern suppression period (Fig. 2). During the wildfire-use period, 16% of the GALWC and 10% of the SBWC burned. Overall fire rotations were 121 and 218 years, respectively, for the GALWC and SBWC (Table 1). With the exception of the upper elevation PVTs in the GALWC, the proportional area of PVTs burned increased (Figs. 6 and 7), and fire rotations decreased relative to the modern suppression period (Table 3). Fire rotations ranged from 74 years in the ponderosa pine PVT to 4324 years in the desert–shrublands PVT in the GALWC. Fire rotations in the SBWC ranged from 77 years in the persistent shrublands along the main stems of the Lochsa and Selway Rivers to 361 years in upper subalpine PVTs (Table 3).

The amount and rate of burning in the GALWC increased in Douglas-fir and ponderosa pine PVTs during the wildfire-use period (Figs. 2, 6, and 7, Table 3), even though the two decades from about 1976 to 1993 were the wettest in the 20th century (Swetnam and Betancourt 1998). Fires were large, with 10 fires over 1000 ha in the ponderosa pine and Douglas-fir PVTs. These fires were primarily managed as low-intensity, prescribed natural fires. Fires were largely absent at higher elevations with a fire rotation of 998 years in the spruce–fir PVT. The fire rotation during the wildfire-use period in the spruce–fir PVT was the longest of any time period. Fire management focused on restoring natural fire processes has reduced the length of fire rotations in mid-elevation forests. Fire rotations have lengthened, however, at high elevations of the GALWC relative to the previous time periods. These longer fire rotations could be due to the lack of occurrence of fires resulting from continued, effective fire suppression in these high elevation forests. During the wildfire use period, 13 850 ha (3%) of the GALWC burned multiple times (Table 1).

The wildfire-use period in the SBWC was characterized by more fire than in the modern suppression period, particularly in subalpine forest PVTs (Figs. 2 and 7, Table 3). Fire rotations during this period were an order of magnitude shorter than during the modern suppression period. Further, as Brown et al. (1994) found, less area has burned during recent years than would be expected under pre-Euro-American fire regimes, especially at upper elevations. It is important to note that the recent period includes 1988 and 1994, where several large wildfires burned extensive areas in upper elevation forests despite attempts to suppress them.

Fire–climate patterns

In both study areas, close to 70% of the total area burned was attributed to the six largest fire years (Fig. 2). In general, large fire years corresponded with regional drought periods (Larsen and Delavan 1922; Arno 1980; Swetnam and Baisan 1996*b*; Barrett et al. 1997; Swetnam and Betancourt 1998; Rollins et al., in review[3]). Median fire sizes were much lower than mean fire sizes indicating the heavily skewed size distributions in each area (Table 2). This indicates that at least during the 20th century, total area burned at landscape scales was heavily dominated by large, relatively infrequent fire events that appear to correspond with seasonal climate patterns at regional scales.

Climate was variable during the 1960s and 1970s in the southwestern United States (Swetnam and Betancourt 1998; Cook et al. 1999). From 1942 through 1958, however, New Mexico experienced the worst period of prolonged drought since 1580 (Swetnam and Betancourt 1998). This period was associated with a large increase in the amount and rate of burning in upper elevations of the GALWC (Figs. 2 and 6) and across the American Southwest (Swetnam and Betancourt 1998). Several of the largest large fire years in the GALWC (1946, 1951, 1953, and 1956) correspond to notable drought years (Swetnam and Betancourt 1998). This period included the 1951 McKnight fire, the largest fire in the 20th century. The McKnight fire and the 1953 Lookout Canyon fire burned 19% of the mixed conifer forests in the GALWC. Based on pre-Euro-American fire interval reconstructions by Abolt (1996), the amount and rate of burning in upper elevation forests in the GALWC during the 1950s drought was more rapid than at any time during the last three centuries. The large fires during the modern suppression period were high-severity fires that burned primarily in upper elevation forests and correspond with the most severe period of drought in the American Southwest since 1580 (Swetnam and Betancourt 1998).

The largest and third largest fire years (1993 and 1992) in the GALWC were two of the wettest years in the 20th century (Swetnam and Betancourt 1998; Rollins et al., in review[3]). However, the summers during these years were relatively dry, and the largest fires were actively managed as prescribed natural fires. Most of the large fires in 1992 and 1993 were surface fires that burned with generally low severities over most of the burned area (L. Garcia, Gila National Forest Wilderness, fuels technician, personal communication). Aggressive attempts failed to suppress the large fires in 1946, 1951, and 1953 (L. Garcia, personal communication).

In the northern Rocky Mountains, the great fires of 1910 burned in August and September and were the result of a wet winter followed by an abnormally dry spring and summer (Larsen and Delavan 1922). Large areas of the 1910 fires re-burned in subsequent years (Table 2). Large fire years in 1917, 1919, 1929, 1934, and 1988 correspond to dry summers (Larsen and Delavan 1922; Barrett et al. 1997; Rollins et al., in review[3]).

Fire regime metrics

Fire atlases are valuable for evaluating fire patterns at broad spatial and temporal scales despite limitations imposed by spatial error, limited temporal extent, and limited thematic data (i.e., no information on internal unburned areas or fire severity patterns or unobserved fires). Mean fire intervals and area frequencies estimated from dendroecological reconstructions and calculated from fire-perimeter data are difficult to quantitatively compare. In dendroecological analyses involving only fire-scarred trees, only the relative spatial extent of wildfires may be estimated from spatial and temporal arrays of point locations. Time-since-fire maps, estimated from stand age (and sometimes also fire-scarred trees) provide very coarse estimates of fire perimeters (e.g., because patchy mortality patterns and disturbance interactions obscure historical fire perimeters). Where they exist, digital fire atlases provide explicit estimates of the actual extent of past fires.

In this paper, fire-rotation periods were calculated based on directly observed extents of fires across broad landscapes.

For an equivalent spatial extent, fire rotations calculated using a relatively short time series of digital fire-atlas data will tend to be longer than dendroecological estimates of mean fire interval because of the spatial characteristics of dendroecological sampling and the short temporal extent of fire atlas data. We find this to be true in the GALWC, where we have several fire-history sites within the area (Swetnam and Dieterich 1985; Abolt 1996) from which we can estimate fire intervals in the ponderosa pine and mixed conifer PVTs.

Problems with precision in mapping fire perimeters are not limited to fire-history reconstructions based solely on arrays of fire-scarred trees. Approaches based on stand-age estimates and (or) remotely sensed fire patterns are also prone to error. In dendroecological research where fire perimeters are relativistic estimates and provide only coarse spatial resolution, time-since-fire approaches and age structure analyses are only useful to the extent that reconstructed stand boundaries and stand ages represent the patterns of historical fires (more likely in stand-replacing fire regimes). Stand boundaries in forests with stand-replacing fire regimes are not solely the effect of fire severity. Microclimate, disturbance interactions, and local- to landscape-scale ecological gradients contribute significantly to indistinct stand boundaries. This problem in delineating past fire perimeters is amplified in forests with extensive low-to-moderate or mixed high- and low-severity fires. In forests where stand boundaries do not represent past fires, time-since-fire maps cannot be accurately constructed using tree-ring based or remote sensing approaches. For these reasons, fire-atlas data are a valuable source of historical information about past fires and have been used throughout North America to evaluate 20th-century fire patterns.

Using a fire atlas from federal lands in California, U.S.A., McKelvey and Busse (1996) found large areas burned in the Sierra Nevada prior to 1948 and after 1988 but found little evidence of trend or pattern when fires were considered for the entire 20th century. Minnich and Chou (1997) found changes in fire intensity, shape, and seasonality because of suppression by comparing fire atlases from Baja California, Mexico, and southern California, U.S.A. However, using the same database for southern California, U.S.A., Keeley et al. (1999) found no change in patterns of burning when fires before and after 1950 were compared. Using a fire-occurrence database, Van Wagner (1988) found a gradual decline in area burned in Canada through the 20th century, with decadal cyclicity from low to high area burned. However, area burned increased dramatically in Canada during the early 1970s and 1980s and was attributed to increases in extreme fire weather (Van Wagner 1988). This increase in extreme fire weather was not evident in the GALWC and SBWC (Rollins et al., in review[3]).

In the GALWC, 20th-century fire rotations would be much longer without the large areas burned during the 1950s drought and large prescribed fires in 1992 and 1993. At this reduced rate of burning, ponderosa pine forests are likely to convert toward more shade-tolerant species in PVTs that support shade-tolerant species (e.g., Douglas-fir, mixed conifer, and spruce–fir PVTs). Fuel build-up and stand homogeneity are likely to increase across the entire area. Our data only include 18 years of prescribed natural fire management in the GALWC, and fire rotations, at least in certain forest types, have become much shorter in recent years. In mixed conifer and spruce–fir forests, however, fire was largely absent from 1953 to 1993. Because of fuel accumulation across large areas, these high-elevation forests may be at the highest risk of unusually large, severe fires without some kind of proactive management to alleviate the effects of 50 years of fire suppression. On the other hand, stand-replacement fires at long intervals are within the natural range of variability of the higher elevation mixed-conifer and spruce–fir PVTs of this region (Abolt 1996).

Fire rotations for the entire period of record in the SBWC are largely based on the 49% of the study area that burned between 1880 and 1934, an indication of how area frequencies are affected by extreme events that occur during a specific period. During the recent wildfire-use period, fire rotations increased relative to the modern suppression period. However, if 1988 is dropped from the record, fire rotations for the wildfire use period increase dramatically, especially in subalpine PVTs (70% of the SBWC). In lower subalpine forest PVTs during the wildfire-use period, fire rotation is 230 years with 1988 in the record. Without 1988, fire rotation increases to 520 years in this PVT. The pattern is the same in upper subalpine PVTs with fire rotations of 361 with 1988 included and 852 with 1988 excluded. While wildfire use management has met goals at local scales. The influence of the 1988 fire year, where attempts were made to suppress nearly every fire, suggests a need for increased proactive fire management in the SBWC. Middle- and high-elevation forests on mesic sites are probably at the highest risk of future fire. The temporal extent of the fire atlas in the SBWC may be too short to accurately depict fire regimes in these forests, which typically exhibit low fire frequencies. As with high elevations in the GALWC, lower and upper subalpine forests in the SBWC are characterized by infrequent, moderate-to-high severity fires. The general lack of mapped fires since 1935 in the SBWC does not necessarily imply that fire regimes in the wilderness complex are outside of natural ranges of variation. There have been long fire-free periods in forests of the SBWC in the past (Brown et al. 1994). However, if the trends in rate and extent of fires from 1935 through 1996 continue, the forests of the SBWC will become more densely stocked and landscapes will become more homogeneous, leading to higher risks of fire and other large disturbances in all forest types.

Conclusions

Twentieth-century fire atlases show large variations in the areal extent and rates of burning across different forest types in both study areas. In some cases, the size and extent of fires were reduced relative to pre-Euro-American estimates (e.g., the pre-modern suppression period in the GALWC). In others, fire occurred at a much more rapid rate compared with pre-Euro-American estimates (e.g., the pre-modern suppression period in the SBWC). The 2000 fire season in the western United States has illustrated that landscape-to-regional scale fire events are returning to ecosystems in both the northern and southern Rocky Mountains that have experienced reduced fire frequencies in the 20th century.

Despite the lack of overall statistically significant differences in fire size and shape, fire atlases from each wilderness complex show that the amount and rate of burning changed dramatically with different fire-management strategies and a variable climate. Fire atlases are extremely useful for evaluating fire patterns across broad landscapes. In the SBWC and the GALWC, differences and similarities in fire rotations among and between PVTs increase knowledge of how fire regimes have changed over the 20th century. Despite limitations in spatial and temporal resolution, digital fire atlases are a valuable tool for providing historical information on fire patterns for use in efforts to re-introduce fire as an ecosystem process in both wilderness complexes and managed landscapes. Fragmentary historical records are a common limitation of fire-history research, emphasizing the need for better record keeping and documentation of fires in the future. Our analyses of fire patterns in two large, disparate wilderness complexes provide contextual information on fire patterns in both areas. These data may be used to assess the successional status of forests within each wilderness and to gauge the effects of continued fire suppression on adjacent or similar landscapes without fire-management programs based on wildfire use.

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