

RESEARCH ARTICLE

NORTHERN ROCKIES PYROGEOGRAPHY: AN EXAMPLE OF FIRE ATLAS UTILITY

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ABSTRACT

We demonstrated the utility of digital fire atlases by analyzing forest fire extent across cold, dry, and mesic forests, within and outside federally designated wilderness areas during three different fire management periods: 1900 to 1934, 1935 to 1973, and 1974 to 2008. We updated an existing atlas with a 12070086 ha recording area in Idaho and Montana, USA, west of the Continental Divide, 81% of which is forested. This updated atlas was derived from records maintained locally by 12 national forests and Glacier National Park. Within the cold, dry, and mesic forests that encompass 45%, 44%, and 11% of the fire atlas recording area, respectively, we analyzed 3228 fire polygons (those ≥ 20 ha in extent and $\geq 75\%$ forested). We discovered that both fire extent and the number of fire polygons were greater in the north during the

RESUMEN

Demostramos la utilidad de los atlas digitales de incendios analizando la cobertura de incendios forestales en bosques fríos, secos y mésicos, dentro y fuera de áreas silvestres designadas por el gobierno federal durante tres diferentes periodos de tiempo de manejo del fuego: 1900 a 1934, 1935 a 1973 y 1974 a 2008. Actualizamos un atlas existente con una superficie con registro de incendios de 12070086 ha en Idaho y Montana, EUA, al oeste de la divisoria de aguas continental; 81% de esta superficie tiene cobertura forestal. Este atlas actualizado se derivó de registros locales generados por 12 bosques nacionales y el Parque Nacional Glacier. Dentro de los bosques fríos, secos y mésicos que abarcan, respectivamente, el 45%, 44% y 11% del área de registro del atlas, analizamos 3228 polígonos de incendios (aquellos con ≥ 20 ha de extensión y cobertura forestal $\geq 75\%$). Encontramos que la extensión de los incendios y el número de polígonos de incendios fueron mayores en el norte du-

early period and greater in the south during the late period, but in all cases burned in proportion to land area. Over the 9 731 691 ha forested fire-atlas recording area, 36% of 10 000 randomly located points burned at least once, 7% burned twice, and fewer than 1% burned three or more times. Of these same points, disproportionately more burned inside wilderness than outside. These points burned in proportion to land area by forest type and generally by slope, aspect, and elevation. Analysis revealed that despite extensive fires early and late in the twentieth century, area burned was likely still low relative to prior centuries, especially at low elevations and outside large wilderness areas. The fire atlas includes few fires <40 ha, and its perimeter accuracy is uncertain and likely historically inconsistent; even so, the perimeters are georeferenced and, because they include the entire twentieth century, can serve to bridge past and future fire regimes. Fire atlases are necessarily imperfect, but they remain useful for exploring the pyrogeography of modern fire regimes, including how the spatial distribution of fire varied through time with respect to landscape controls, fire management, and climate.

rante el primer periodo, mientras que en el sur fueron mayores durante el último periodo, pero en todos los casos afectaron a una superficie proporcional al área total. La superficie total con cubierta forestal y registro de incendios fue de 9 731 691 ha; de 10 000 puntos distribuidos al azar, el 36% se quemó al menos una vez, el 7% se quemó dos veces y menos del 1% se quemó tres veces o más. De estos mismos puntos, un número desproporcionadamente mayor se quemó dentro de las áreas silvestres que fuera. Estos puntos se quemaron en proporción a su superficie por tipo de bosque y generalmente por pendiente, exposición y altitud. Los análisis mostraron que a pesar de los grandes incendios registrados a principios y finales del siglo XX, el área quemada sigue siendo baja en relación a siglos anteriores, especialmente en elevaciones bajas y fuera de las áreas silvestres. El atlas de fuego incluye algunos incendios <40 ha, aunque la precisión de los perímetros es incierta y probablemente históricamente inconsistente; aun así los perímetros están geo-referenciados y como incluyen todo el siglo XX, pueden servir para enlazar los regímenes de fuego pasados y futuros. Los atlas de fuego son imperfectos, pero siguen siendo útiles para explorar la pirogeografía de los regímenes de fuego modernos, así como entender cómo varía la distribución espacial del fuego a través del tiempo con respecto a los controles del paisaje, el manejo del fuego y el clima.

Keywords: fire atlas, fire history, fire regimes, northern Rocky Mountains, wildfires

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INTRODUCTION

Fire atlases, also called digital polygon fire histories, are compilations of annual fire perimeter records. On many federal lands in the western United States, historical fire perimeters have been digitized from hand-drawn

maps and from fire incident reports. More recently, they have been inferred from satellite imagery (e.g., the Monitoring Trends in Burn Severity project; www.mtbs.gov), infrared sensing, or hand-held global positioning system (GPS) receivers, and integrated into a geographic information system (GIS). These digi-

tized records contain georeferenced fire perimeters; thus, they differ from point records of fire occurrence and size (e.g., those used by Westerling *et al.* 2006), as well as from records of annual area burned compiled for national forests or regions (e.g., those used by Littell *et al.* 2009). When combined with other georeferenced records such as topography and vegetation type, georeferenced fire perimeters can be used to describe fire patterns over all parts of the landscape through time, thus better informing our understanding of what determines those fire patterns (Rollins *et al.* 2001, 2002). Both ignition and area burned are influenced by complex, multiscale interactions among fuels, climate, weather, topography, and human action (Krawchuk *et al.* 2009, Parisien and Moritz 2009, Parisien *et al.* 2011). Characterizing this variation, termed pyrogeography, is critical to understanding both the causes and consequences of fire, and how these vary in response to climate, topography, land use, and vegetation—all of which interact at multiple scales. Parisien and Moritz (2009) lamented the paucity of analyses of the “habitat” of fire across environmental gradients, while highlighting its value in understanding and predicting the response of fire to changing climate and fire management.

Topography is a strong driver of fire behavior and likely affects the spatial distribution of area burned. If fires burn randomly, then the distribution of area burned by landscape characteristics (e.g., its topography or forest type) should be similar to the distribution of land area by those same characteristics. If, however, some locations are predisposed to burning, the patterns of distribution can highlight potential mechanisms driving past fire regimes. Many possibilities exist. For example, the spatial distribution of fire across parts of the western US was found to be controlled by different factors (Barrett *et al.* 1991; McKelvey and Busse 1996; Rollins *et al.* 2001, 2002; Falk *et al.* 2007; Kellogg *et al.* 2008) and at regional to local scales (Parisien and

Moritz 2009). In Spain, fires burned preferentially in some landscape positions (Moreno *et al.* 2011), whereas in the western US, spatial variation in vegetation, weather, and ignitions affected burn probability (Moritz *et al.* 2005, Parisien and Moritz 2009, Parisien *et al.* 2011). Rollins *et al.* (2002) found that elevation and aspect influenced twentieth century fire frequency in large wilderness areas, but Podur and Martell (2009) and Bessie and Johnson (1995) found that fire extent was little influenced by landscape characteristics. Patterns of fire likelihood in the western US have also been found to be significantly influenced by people (Parisien *et al.* 2012).

The US northern Rockies are unusual in having a forest fire atlas that includes the entire twentieth century (Morgan *et al.* 2008). Regional and historical variation in both fire management and climate resulted in a changing pyrogeography—fires were more extensive, for example, to the north early in the twentieth century and more extensive to the south late in the century (Morgan *et al.* 2008). These patterns may reflect the distribution of landscape characteristics throughout the region, differences in fire management, spatial variations in climate (such as distribution of lightning storms), or a combination of these factors.

Fire management in the US northern Rockies can be separated into three consecutive time periods (Rollins *et al.* 2001, Hessburg and Agee 2003). Early in the century (1900 to 1934), fire suppression was limited and poorly organized until fires in 1910 and in the decades following galvanized funding and training for fire suppression (Hessburg and Agee 2003). In the mid twentieth century (1935 to 1973), fire suppression became increasingly effective, fueled by military technology and the 10 AM policy implemented in 1935, which emphasized aggressive fire suppression everywhere (Pyne *et al.* 1996). Aerial fire detection and fire suppression by smokejumpers were initiated in 1950 at bases in the region, and local

crews were numerous and well equipped (Pyne *et al.* 1996). Late in the century (1974 to present), as part of intentional land management, some fires were not aggressively suppressed, particularly in federally designated wilderness and adjacent remote areas (Pyne *et al.* 1996).

Fire management in the region varies locally, by land management designation of wilderness versus nonwilderness and by forest type. Wilderness areas now account for 17% of the area covered by the northern Rockies fire atlas. The greater part of these wilderness areas were federally designated in the second half of the twentieth century—either in 1964, with the passage of the Wilderness Act (Bob Marshall Wilderness and Selway-Bitterroot Wilderness: 408 646 ha and 542 748 ha, respectively) or in 1980 (Frank Church-River of No Return Wilderness: 958 230 ha). Managers of many, but not all, of the wilderness areas in the region have the option to allow lightning-caused fires to burn under prescribed conditions for ecological benefit, an option employed to varying degrees. Even before designation as wilderness, these areas, being remote, experienced less effective initial attack and other fire suppression efforts than did areas with roads, especially early in the century before aerial fire detection and delivery of smokejumpers to remote fires became more common (Pyne *et al.* 1996). Further, these areas have had a lower priority for fire suppression resources, especially in years of many simultaneous large fires. Because of differences in physical environments and fire suppression efforts, fire size distributions inside large wilderness areas differ from those outside them (Haire *et al.* 2013). Additionally, outside wilderness boundaries, fire management has been less intensive in cold forests than in either dry or mesic forests (Agee 1993, Hessburg and Agee 2003, Baker 2009). In dry and mesic forests, road building, domestic livestock grazing, and timber harvesting were more intense and began earlier than in the higher elevation, more remote cold forests (Hessburg and Agee 2003). As a consequence, fires had become

rare in dry forests in this region by the end of the 1800s, before fire record keeping began in the northern Rockies (Hessburg and Agee 2003).

Climate also varied over time in this region, which may have affected pyrogeography. Fires in each of the forest types in the northern Rockies fire atlas are influenced differently by climate, with fires in cold forests more likely to be more climate-limited than fuel-limited (Schoennagel *et al.* 2004). Cold forests dominate both the higher elevations where fires burn less frequently (Schoennagel *et al.* 2004), and wilderness areas where fire suppression is less aggressive. Litschert *et al.* (2012) found that in the southern Rockies, on average, nine times more fires burned from 1991 to 2006 than from 1930 to 1950. In the northern Rockies, fires were more extensive in later decades of the twentieth century than in the middle of the century; the century's first decades had numbers similar to this later period (Morgan *et al.* 2008). Westerling *et al.* (2006) attributed the western US's longer late-century (1987 to 2003) fire seasons (with many large fires), relative to those of mid-century (1970 to 1986), to earlier snowmelt and warmer summers. Especially sensitive were forests at middle elevations in the northern Rockies. The middle period of the twentieth century was relatively cool and had fewer extremely dry fire seasons (Morgan *et al.* 2008). Analyzing fire records from the full century can help us understand whether recent trends are unusual, and how they might vary geographically.

The method of recording fire perimeters also changed during the twentieth century and could have influenced records of pyrogeography. Early fire atlas records were derived from hand-drawn maps of fire perimeters and fire incident reports, whereas recent perimeters are derived from field mapping with GPS receivers, remote sensing, or, during some large fires, infrared mapping.

Our objective was to describe twentieth century pyrogeography—the spatial distribution of fire by wilderness status and topogra-

phy—in forests of the northern Rockies and to determine whether that pyrogeography was different in the early (1900 to 1934) versus the late (1974 to 2008) fire management periods. We also highlight the utility of fire atlas records for understanding where fires occur and why. Finally, we make recommendations to address some of the inherent limitations of those records.

METHODS

Study Area

The fire atlas recording area is in Idaho and Montana west of the Continental Divide (Figure 1). Most of the atlas lies within climate divisions 4 in Idaho and 1 in Montana (NOAA 2012). The climate is continental with cold winters (-6°C mean January temperature 1900 to 2008; climate division average) and warm summers (17°C mean July temperature 1900 to 2008). Mean annual precipitation is 58 cm (1900 to 2003), much of which falls as snow in winter (62% from 1963 to 1996, Serreze *et al.* 1999).

The Fire Atlas

We updated an existing atlas of the dates and locations of fire perimeters, which had been assembled from digital polygon fire histories maintained locally by 12 national forests and one national park for the period 1900 through 2003 (Gibson 2006, updated through 2003 by Gibson and Morgan 2009, then updated through 2008 by Gibson *et al.* 2014). The atlas does not document unburned patches within fire polygons or indicate if a single polygon results from more than one ignition. For our analysis, we excluded polygons less than 20 ha in extent because small polygons were not consistently recorded and some small polygons were artifacts of combining records from different land management units. This excluded 1129 fire polygons with a total extent of 8790 ha. We further limited our analysis to

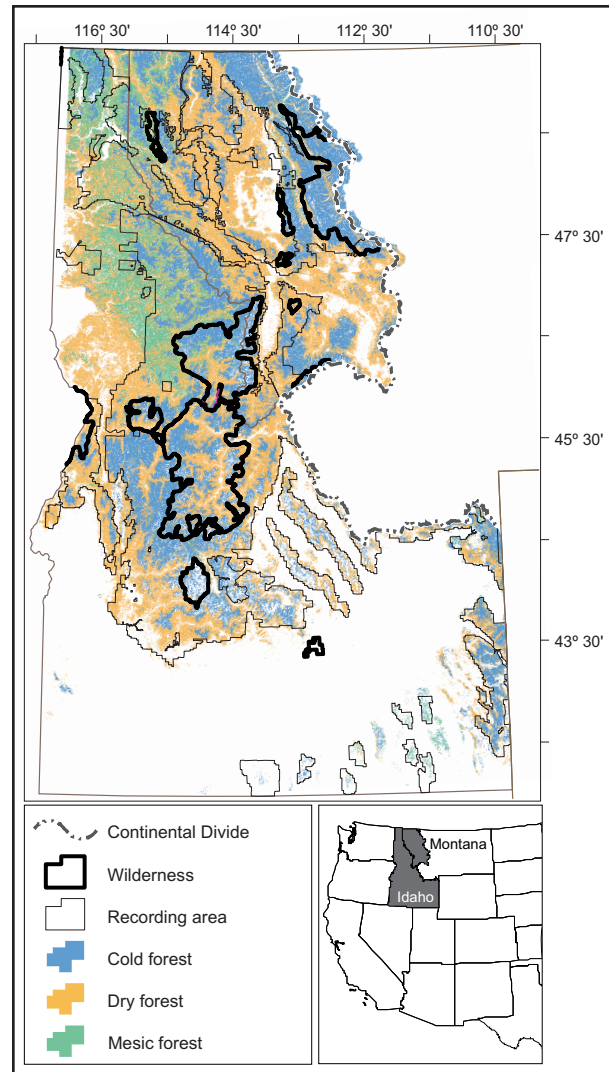


Figure 1. The study area includes cold, mesic, and dry forests in Idaho and Montana west of the Continental Divide. We analyzed forested area within a fire atlas recording area derived from records maintained by Glacier National Park and 12 national forests from 1900 to 2008, within and outside federally designated wilderness areas.

the 9 731 691 ha that were forested, equivalent to 81% of the 12 070 086 ha recording area. We defined forested polygons as those with $\geq 75\%$ of pixels classified as forested (generally $>10\%$ forest cover; LANDFIRE 2012). This excluded 603 fire polygons in non-forest vegetation types with a total extent of 835 805 ha. We conducted our analyses on the remaining 3228 fire polygons with a total extent of 5 326 687 ha.

To infer the possible influence of changing methods of recording fire over the twentieth century, we visually examined the perimeter-to-area ratio of fire polygons over time, dividing the ratio of each polygon by the area of a circle of the same area to remove the bias of patch size. If satellite imagery had captured more of the complexity in fire boundaries late in the century than hand mapping of fires did early in the century, we would expect the perimeter-to-area ratio to increase correspondingly. In addition, if detection and mapping of small fires improved later in the century, this index would presumably also increase over time.

Pyrogeography

To characterize pyrogeography, we compared (1) polygons by forest type, wilderness status, elevation, aspect, and slope; and (2) the distribution of a set of randomly selected points to the distribution of subset of these points that had burned. All spatial data had a 30 m resolution.

We assigned forest types using environmental site potential (ESP; Rollins 2009; public communication, <http://www.landfire.gov/NationalProductDescriptions19.php>). The ESP is a potential vegetation classification indicating the vegetation an area could support based on biophysical site characteristics such as climate, topography, and substrate. Although they are named for forest types, ESPs reflect the biophysical template (e.g., a mesic forest is found where both climate and site conditions are moist, although many different tree species could dominate depending on disturbance history). We grouped ESPs into three broad categories (Morgan et al. 2008): cold forests, mesic forests, and dry forests. All three forest types occur across a broad range of aspects. Cold forests primarily occur above 1500 m, typically on shallow, poorly developed soils and are often dominated by lodgepole pine (*Pinus contorta* Douglas ex Loudon),

subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and other cold-tolerant tree species. Dry forests are usually found both above and below 1500 m on well-drained, often poorly developed soils and are dominated by ponderosa pine (*Pinus ponderosa* P.C. & Lawson) and Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco). Mesic forests are usually found below 1500 m in areas with high annual (and growing season) precipitation and well-developed soils. Mesic forests are dominated by a mixture of conifer species, including grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), Douglas-fir, western larch (*Larix occidentalis* Nutt.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). Cold, mesic, and dry forests occupy 45%, 11%, and 44% of the 9731691 ha forested part of the fire atlas recording area (Morgan et al. 2008). Although portions of some fire polygons were not forested, 90% of the fire extent recorded as burned in the atlas occurred in these three forest types. In addition, many fire polygons included more than one forest type. In those cases, we subdivided polygons accordingly for analyses including forest type as a variable.

One fifth (17%) of the fire atlas recording area currently lies either in federally designated wilderness areas or in Glacier National Park (USDI 2010; Figure 1). Most of the forest within wilderness is cold forest (63%; Figure 1); the remainder is mostly in dry forest (34%) with a small amount in mesic forest (3%). In contrast, outside wilderness areas, nearly half the forest is dry (47%), with the rest cold (40%) or mesic (13%).

We randomly selected 10000 points from the forested portion of the fire atlas recording area that were separated by at least 42 m (the length of the hypotenuse of a 30 m pixel, in the digital elevation and ESP data). We chose this distance to avoid selecting more than one point in any 30 m pixel. Of the 3738 points that burned between 1900 and 2008, 17%

burned more than once (to a maximum of 5 times), and thus we included them in our analysis more than once. The distribution of points according to topography (slope, aspect, and elevation from a 30 m digital elevation model) and forest type varied latitudinally in our study area; during the early period, almost all of the burned pixels (95%) were north of 45° 30' N, whereas in the late period, more than half the burned pixels were south of this latitude (58%; Figure 2). Therefore, we separately analyzed areas north and south of 45° 30' N. Most of the fire atlas recording area (and our randomly selected points) lay north of this latitude (60% and 62%, respectively). We compared the distributions using Pearson's chi-squared test (SAS, Cary, North Carolina, USA). With large sample sizes, *P* values are small (Lin *et al.* 2013), so with our very large sample size of 10000 points, we assumed that the distributions differed significantly at $\alpha \leq 0.0001$.

We also compared fire polygon size distributions by wilderness status and time period, but not by topography. Individual fire polygons often span more than one topographic facet; that is, a single fire can burn on both

north and south slopes. Furthermore, the complex terrain of the northern Rockies results in relatively small topographic facets. In contrast, apportioning fire polygons by wilderness areas is less challenging because wilderness areas in this region are relatively large. We classified polygons as inside wilderness when $\geq 75\%$ of the polygon was within federally designated wilderness areas.

RESULTS

The Fire Atlas

In the forested fire atlas recording area between 1900 and 2008, total forest fire extent was 5326687 ha, as computed from polygons that were ≥ 20 ha and $\geq 75\%$ forested, including areas that burned more than once and unburned islands within fire perimeters. In a majority of years (90%), fewer than 75 fire polygons were mapped, even in years when total fire extent was high (Figure 3a, b). Fire extent during the early and late periods was much greater than during the middle period (Figure 3a), and a greater number of polygons also

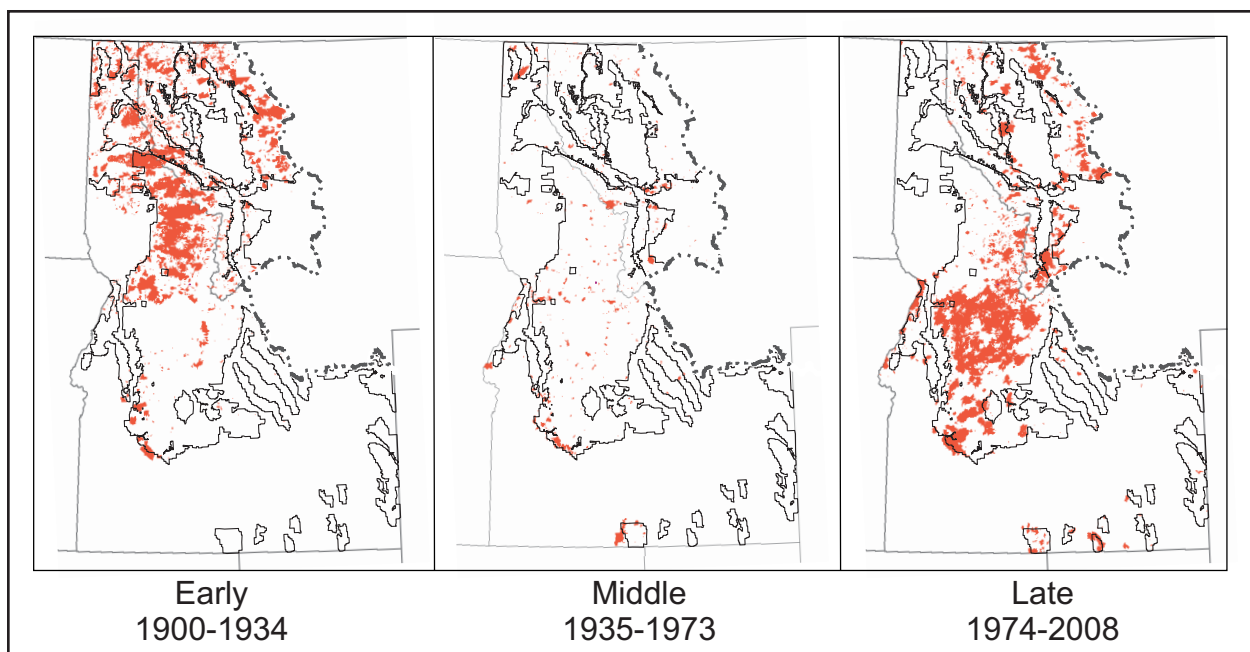


Figure 2. Total fire extent (red) and its spatial distribution varied among fire management periods.

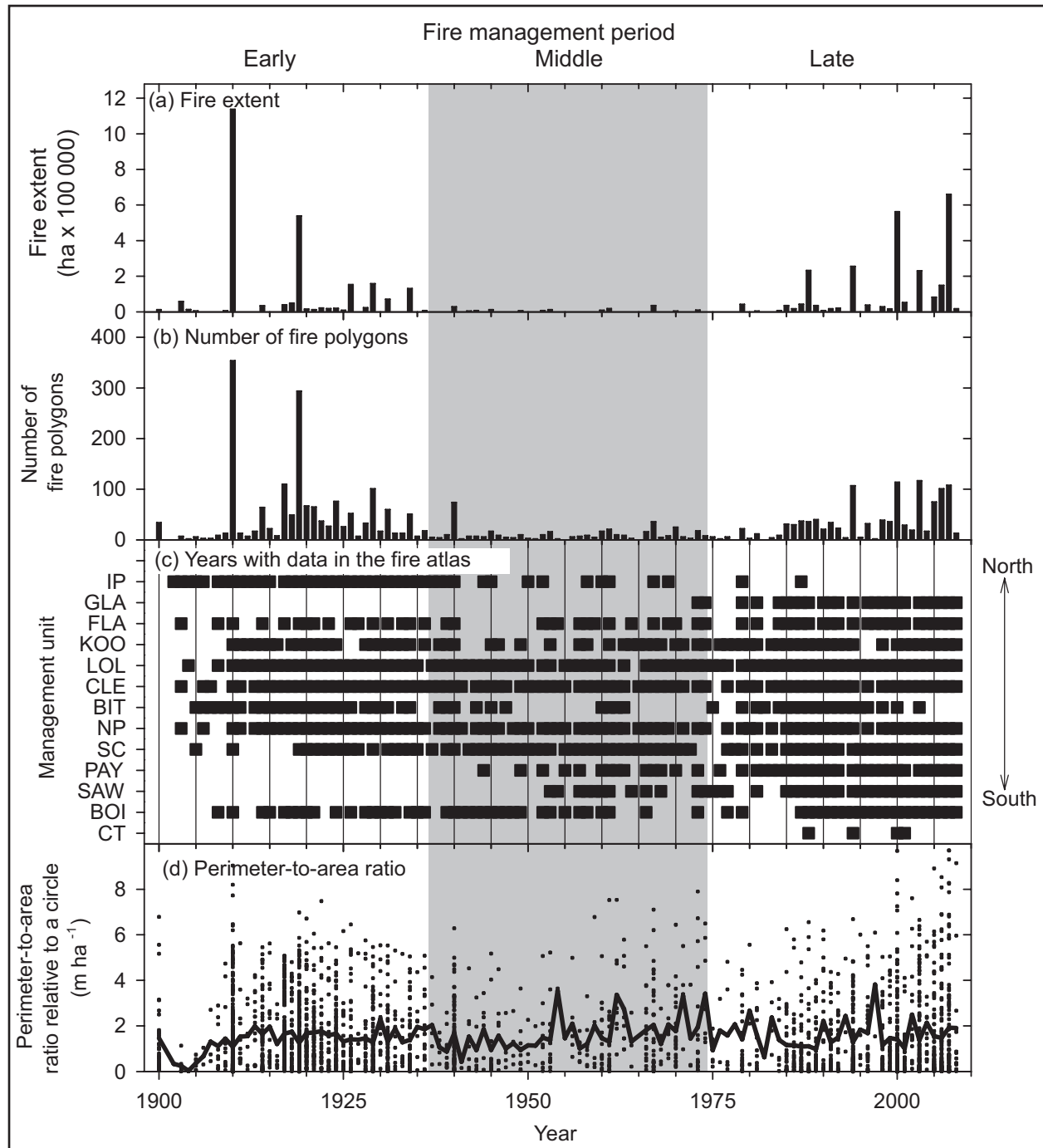


Figure 3. The northern Rockies fire atlas, showing fire polygons ≥ 20 ha in extent and $\geq 75\%$ forested. Fire polygons were recorded by 13 land management units: Idaho Panhandle (IP), Flathead (FLA), Kootenai (KOO), Lolo (LOL), Clearwater (CLE), Bitterroot (BIT), Nez Perce (NP), Salmon-Challis (SC), Payette (PAY), Sawtooth (SAW), Boise (BOI), and Caribou-Targhee (CT) national forests; and Glacier National Park (GLA)

burned early and late relative to middle. The annual number of fire polygons varied from 0 in 1901 and 1965 to 354 in 1910. The years

with the most burned polygons commonly but not always coincided with the years of greatest fire extent.

No management unit recorded fire during every year of the twentieth century (Figure 3c). The gaps in fire records do not always coincide among management units, but more than half of the management units recorded fire polygons in more than half of the years. Some records were nearly complete (e.g., Lolo National Forest) while others (e.g., Bitterroot National Forest) had long gaps.

The fire polygons had a broad range of perimeter-to-area ratios throughout the century, but there is no obvious long-term trend in the annual average of this metric (Figure 3d).

Pyrogeography

Points burned in proportion to the distribution of land area by forest type and aspect in both the northern and southern parts of the study area, and by elevation and slope in the north but not in the south (Figure 4). In the

southern part of the study area, low and middle elevations burned slightly more than expected and high elevations burned 4 less, and steeper (30% to 60%) slopes burned more than expected. Fires burned disproportionately more inside wilderness than outside wilderness areas, both in the north and in the south.

Fire polygon size distributions likewise varied by wilderness status (Figure 5a, b). A greater proportion of small burned polygons (20 ha to 100 ha) were recorded outside than inside wilderness, both in early (1900 to 1934) and late (1974 to 2008) periods. In contrast, proportionately more of the 101 ha to 1000 ha polygons burned inside than outside wilderness, both early and late in the record. Of fire polygons 1001 ha to 10000 ha and 10001 ha to 100000 ha, a higher proportion burned outside wilderness than inside late in the record in contrast to the early period (Figure 5a, b). Most of the recorded area burned was in large

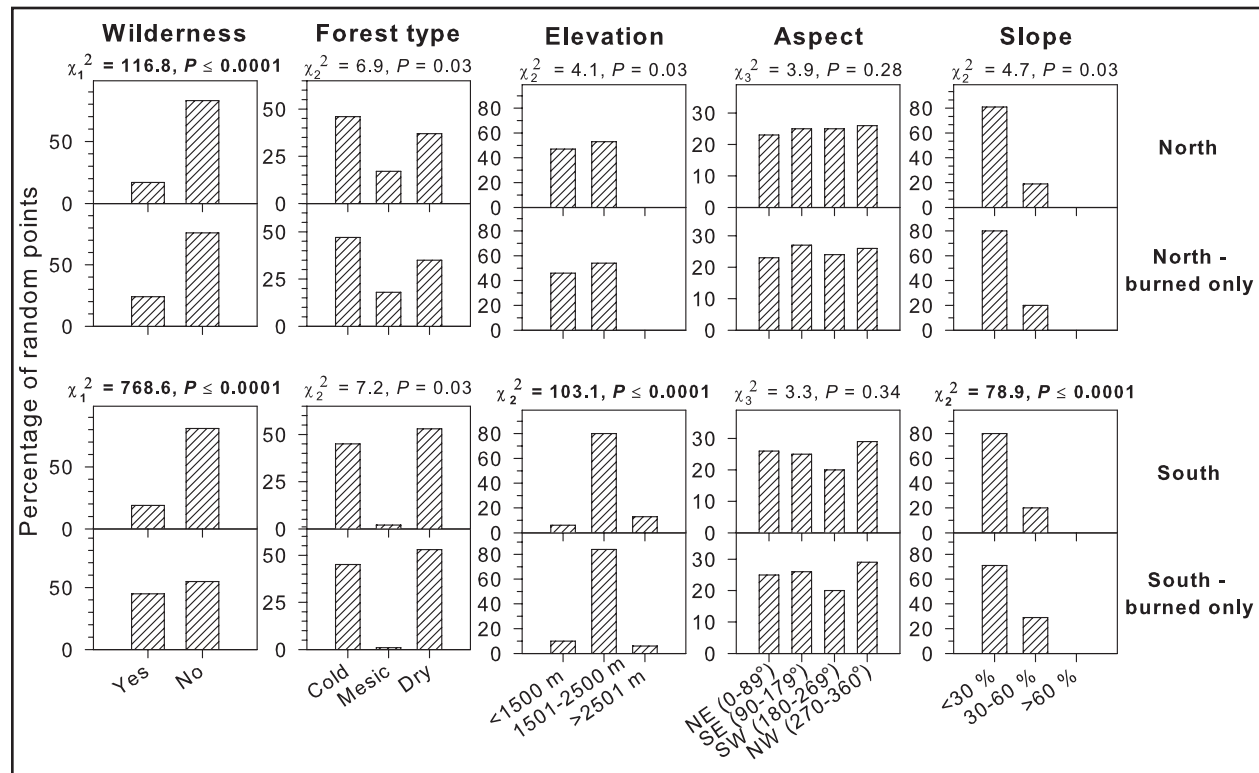


Figure 4. Proportion of land north and south of 45° 30' N latitude, compared to proportion burned at 10000 randomly located points within the forested fire atlas recording area (9731 691 ha). Statistically significant test statistics are indicated in bold ($\alpha \leq 0.0001$).

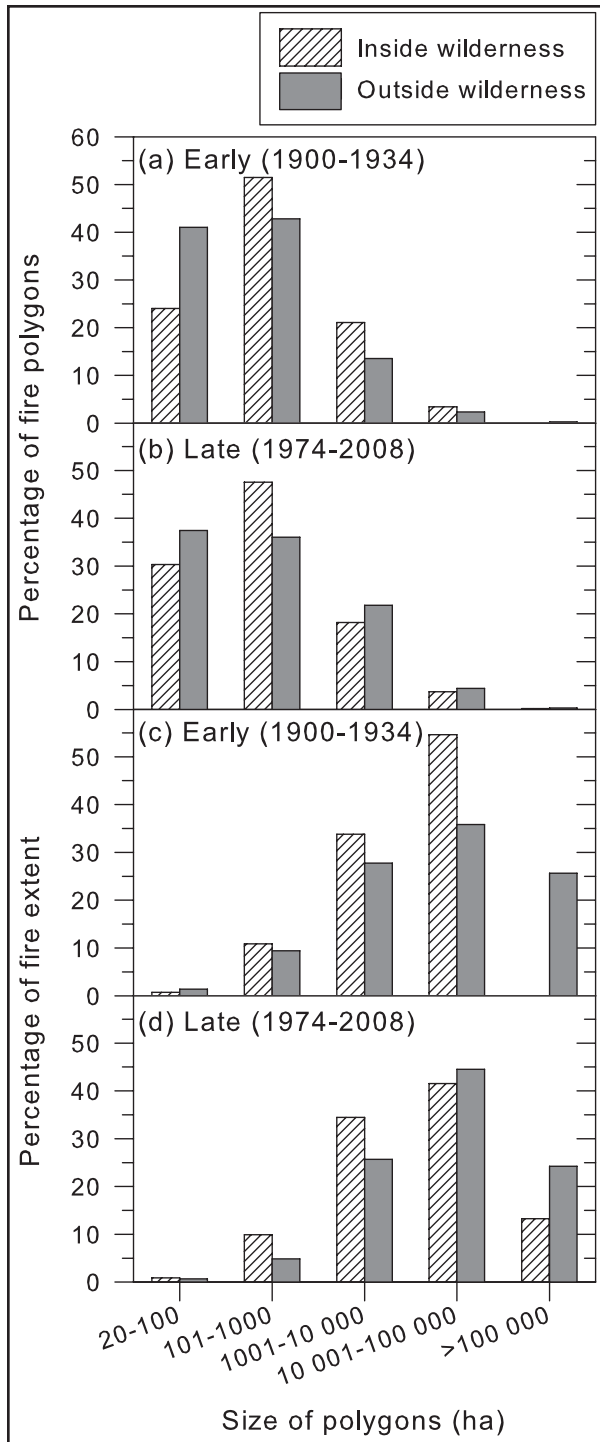


Figure 5. Size distribution of forested fire polygons (≥ 20 ha in extent and $\geq 75\%$ forested) by time period inside (shaded) versus outside (black) federally designated wilderness early and late in the fire atlas record.

polygons both inside and outside wilderness (Figure 5c, d). In the late period, the proportion of the largest polygons (>10000 ha) was higher outside than inside wilderness (Figure 5c, d).

DISCUSSION

Twentieth Century Pyrogeography

Burn probability and polygon size distribution from fire atlases can be analyzed across environmental gradients to inform our understanding of fire as a key disturbance process shaping vegetation distribution (Bond and Keeley 2005) and landscape dynamics. The 109-year record of the northern Rockies fire atlas enables evaluation of fire extent across complex terrain, contrasting fire management and varying climate (Rollins *et al.* 2001, 2002; Morgan *et al.* 2008; P. Higuera *et al.*, University of Idaho, unpublished report) in a region with a rich history of fire, influence on fire policy, and both recent (Westerling *et al.* 2006, Morgan *et al.* 2008) and projected future increase in fire extent (Littell *et al.* 2009, Spracklen *et al.* 2009).

If fire were an organism in the northern Rockies, we would declare it more a generalist than a specialist with respect to habitat. We expected fires to burn preferentially in some places on the landscape (e.g., on low-elevation, south-facing slopes), but found instead that the distribution of fire was not strongly controlled by topography. Parisien *et al.* (2011) concluded that environmental influences on fire vary regionally. Even though rugged topography dominates in the northern Rockies, it did not strongly influence the distribution of fire at the scale measured (in 30 m pixels and across broad classes of forest type and topography). It is possible that analysis at a different scale would yield different results (Parks *et al.* 2011), but this also could be related to the type of fires recorded in the atlas, most of which were large (>40 ha) and burned under

relatively extreme conditions during years of widespread fire (Morgan *et al.* 2008). Landscape characteristics are less influential during extreme fire weather (Turner and Romme 1994, Bessie and Johnson 1995, Mermoz *et al.* 2005, Haire *et al.* 2013), and Dillon *et al.* (2011) hypothesized that fire extent is more influenced by climate than by topography, especially in years of widespread fire when the most area burned.

We also expected fires to preferentially burn some forest types, but they did not. Historically, fires were more frequent in dry than cold forests (Schoennagel *et al.* 2004), leading us to expect that proportionately more area would have burned in dry forests than in cold forests in the twentieth century. Instead, the fire atlas reveals that modern fires burned both cold and dry forests in proportion to their distribution by land area and in roughly equal amounts (Figure 4). That dry forests burned as much as cold forests in the twentieth century likely reflects a change in dry forest fire regimes where fires have become less frequent as a consequence of fire exclusion (Hessburg and Agee 2003).

We stratified our analyses into north versus south because of the obvious differences in fire extent recorded in the fire atlas early versus late in the century (Figure 2). This geographic pattern may be due to both land management and landscape differences. Following the extensive fires of 1910 that burned in the north, fire suppression, logging, and road building were aggressive (Hessburg and Agee 2003), particularly where timber was harvested in the productive mesic and dry forests. Further, wilderness areas are more extensive to the south and it is likely that records of fires are less complete in wilderness and other remote terrain. Alternatively, the driver of temporal and spatial differences could be location of lightning storms or climate changes through time.

The fire atlas reflects modern patterns that may differ considerably from historical patterns, especially for dry forests. Tree-ring reconstructions of surface fire at 14 dry forest

sites in the fire atlas recording area averaged 8 fires per century from 1650 to 1900 (range 4 to 14 fires; Heyerdahl *et al.* 2008). The fire atlas record from the same locations and area sampled had a record of many fewer fires after 1900 (range 0 to 2 fires from 1900 through 2008; Heyerdahl *et al.* 2008). While these tree-ring data are from sites targeted for frequent fires, the contrast with the fire atlas data suggests that departures from historical fire regimes occurred before 1900 in dry forests and continue to the present.

We expected fire polygon size to be greater within than outside wilderness, but it was not (Figure 5). Although the proportion of fires 20 ha to 1000 ha in size within and outside wilderness was similar both early and late in the record, there were more large fires outside compared to inside wilderness (Figure 5). Late in the record, there were proportionately more large fires (1001 ha to 10000 ha and 10001 ha to 100000 ha) outside wilderness despite the typically longer response time and lower priority for fire suppression efforts within wilderness. This pattern could arise if small fires are less likely to be detected and mapped in wilderness areas, but could also be because non-wilderness contains proportionately more dry forests with their longer fire season and different fuels, or fire spread could be influenced by complex topography and previous fires (Teske *et al.* 2012, Parks *et al.* 2014; but see Haire *et al.* 2013).

Finally, we expected the quality of fire records to improve in recent decades as a consequence of improved technology, but it did not (Figure 3d). Fire management and climate likely influenced polygon size distribution. Fire suppression, with the help of roads and land uses outside of wilderness areas, likely resulted in smaller fire polygons, but under the more extreme climate of the regional fire years, fires may have burned irrespective of variations in vegetation, fuels, and topography. For these and perhaps other reasons, we did not find the differences in fire polygon size distribution we expected through time and space.

Multivariate analysis with continuous data may illuminate relationships that we did not detect with our analyses. In addition, analyses at other spatial and temporal scales might also be revealing (Falk *et al.* 2007).

*Atlases Are Valuable and Useful,
if Incomplete,
Records of Twentieth Century Fire*

The northern Rockies fire atlas proved useful in studying the pyrogeography of the region. However, the nature of the fire atlas data limits possible inferences. We offer several cautionary notes on completeness, consistency, and accuracy in using such data—cautions likely applicable to other fire atlases, including those of recent decades derived from satellite imagery or other remotely sensed data.

Although the northern Rockies atlas included 109 years, it was an incomplete temporal record, containing gaps. We must expect that other atlases contain similar gaps, and we caution against inferring absence of fire from absence of data. While long gaps in the record (e.g., the 1950s in the Bitterroot National Forest) are likely due to lack of recording or loss of records, shorter gaps, of one to several years, could be due to lack of reporting, lack of fire, or both. Although we suspected that shorter gaps probably reflect a relative lack of fire in those years, we did not assume it; consequently, we did not attempt to weight the data from the different management units.

Fire atlases also are likely incomplete because of a bias toward mapping large fires that are considered more economically and socially significant (McKelvey and Busse 1996). We recognize that small fires in the northern Rockies were less likely to be mapped than large ones, and that this bias would be even more pronounced if small fires were to go undetected in the remote wilderness areas making up a large portion of this region. This bias in the fire atlas data introduces uncertainty into any inferences that we can make about fire size

distributions. Inferences about size distributions are further limited by inconsistencies in the minimum mapping unit (i.e., the size of the smallest fire polygons mapped), which likely varied through time and by management unit (McKelvey and Busse 1996, Minnich and Chou 1997, Morgan *et al.* 2001, Rollins *et al.* 2001, Gibson 2006).

Inconsistent methods of mapping fire perimeters in the northern Rockies fire atlas are another source of uncertainty. Prior to the mid 1930s, fires in the atlas were primarily mapped from stand ages interpreted from aerial photographs (J.H. Logsdon, USDA Forest Service Idaho Panhandle National Forests, personal communication; Rollins *et al.* 2001), but fire reports and maps, newspaper accounts, journals, and interviews were also used (Gibson 2006). Mapping has improved through the century and perimeters are now often interpreted from satellite imagery. However, even today, mapping methods vary widely and range from satellite-derived data and airborne imagery (including infrared mapping of perimeters of actively burning fires) to hand-drawn perimeters. Depending on the method and the person employing it, simple or complex perimeters could result. We did not find a systematic bias in the northern Rockies atlas in shape complexity of the fire polygons through time. Other atlases may differ in this respect; this could be revealed with simple analyses of the complexity in mapped fire perimeters.

Perimeters in fire atlas data simplify reality. Unfortunately, unburned islands within fire perimeters are not mapped (Kolden and Weisberg 2007), and atlases like the one from the northern Rockies contain fire perimeters, but not burn severity. Because atlas perimeters do not discern unburned islands, they likely overestimate the area burned by any single fire, although the degree to which this is true is generally unknown (Kolden *et al.* 2012). The perimeters are approximate and ground truthing is necessary before relying on them for many applications. Accuracy of most perimeters is

unknown and likely varies through time and among management units. For example, Shapiro-Miller *et al.* (2007) found that the fire perimeters in the northern Rockies fire atlas agreed with fire scar records, and Farris *et al.* (2010) similarly found that fire atlas and fire scar records were in strong agreement. Yet Kolden and Weisberg (2007) found poor agreement between manually mapped fire perimeters (created through a number of different undocumented methods) and Landsat-derived perimeters, especially in areas of complex topography. Fire atlas data should be regarded with healthy skepticism and supplemented with other sources of information whenever possible.

Despite these weaknesses, atlas data can be very useful. These “wall-to-wall” georeferenced landscape fire histories complement remote sensing, and tree-ring and other fire proxies. While fire atlases typically do not include all small fires, they do capture the larger fires that account for the majority of fire extent (Shapiro-Miller *et al.* 2007, Farris *et al.* 2010) and provide one of the only sources of information about temporal change in fire polygon size distribution prior to the advent of remote sensing from satellite imagery and aerial photography. They are georeferenced, and so can be linked to other georeferenced data such as topography, vegetation type, climate, and weather. For instance, they are useful in evaluating where and why fire regimes change across time and space (Morgan *et al.* 2001, Rollins *et al.* 2002). They are also useful for elucidating the causes of temporal and spatial variation in twentieth century fire regimes (e.g., Morgan *et al.* 2008). They can also be used to identify sites for studying forest dynamics for conservation and restoration. In many regions, digital polygon fire histories are the only record of the location and extent of fires throughout the twentieth century, a time period that encompasses different fire management practices, multiple forest

vegetation types, and multiple land uses, all of which influence fire regimes.

Because they complement fire records from prior centuries such as charcoal and tree rings, fire atlas data form a bridge between the past and the future. Simulation models of landscape dynamics can be informed by, parameterized with, and tested against fire atlas data (Miller 2007). Models predicting burn probability also rely upon fire size distributions (e.g., Parks *et al.* 2011) and, despite the biases discussed above, fire atlas data can provide site-specific inputs to many of these models.

As a consequence, maintaining and improving fire atlas records is valuable and that value will only continue to increase. The National Wildfire Coordinating Group (2006) adopted national interagency standards for digital polygon fire histories, but did not include all of the fire descriptors we think are ecologically or methodologically significant, such as source of perimeter location (e.g., GPS, satellite, hand-drawn polygon), fire cause (lightning or human), fire start and end date, fire management actions, minimum mapping unit, assumptions made while gathering and developing the data, data dictionaries (i.e., definition of values in an attribute column), software used to digitize fire perimeters, and process steps used to assemble polygon fire histories. Ideally, they would also capture unburned islands within fire perimeters and daily fire progression.

Fire atlas data, although imperfect, offer opportunities for analyzing fire patterns, relative to spatially rich climate and weather data, to enrich our understanding of fire as a spatial process varying through time. Understanding the pyrogeography of fire across large, complex landscapes and through time periods of changing fire management and climate will inform the mapping of fire likelihood under future scenarios, and provide useful inputs and tests of simulation models.

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