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MULTI-SEASON CLIMATE SYNCHRONIZED FOREST FIRES THROUGHOUT THE 20TH CENTURY, NORTHERN ROCKIES, USA

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Abstract. We inferred climate drivers of 20th-century years with regionally synchronous forest fires in the U.S. northern Rockies. We derived annual fire extent from an existing fire atlas that includes 5038 fire polygons recorded from 12 070 086 ha, or 71% of the forested land in Idaho and Montana west of the Continental Divide. The 11 regional-fire years, those exceeding the 90th percentile in annual fire extent from 1900 to 2003 (>102 314 ha or ~1% of the fire atlas recording area), were concentrated early and late in the century (six from 1900 to 1934 and five from 1988 to 2003). During both periods, regional-fire years were ones when warm springs were followed by warm, dry summers and also when the Pacific Decadal Oscillation (PDO) was positive. Spring snowpack was likely reduced during warm springs and when PDO was positive, resulting in longer fire seasons. Regional-fire years did not vary with El Niño–Southern Oscillation (ENSO) or with climate in antecedent years. The long mid-20th century period lacking regional-fire years (1935–1987) had generally cool springs, generally negative PDO, and a lack of extremely dry summers; also, this was a period of active fire suppression. The climate drivers of regionally synchronous fire that we inferred are congruent with those of previous centuries in this region, suggesting a strong influence of spring and summer climate on fire activity throughout the 20th century despite major land-use change and fire suppression efforts. The relatively cool, moist climate during the mid-century gap in regional-fire years likely contributed to the success of fire suppression during that period. In every regional-fire year, fires burned across a range of vegetation types. Given our results and the projections for warmer springs and continued warm, dry summers, forests of the U.S. northern Rockies are likely to experience synchronous, large fires in the future.

Key words: climate variability; digital polygon fire history; ENSO; fire atlas; Idaho; Montana; PDO; precipitation; season; temperature.

Introduction

Regionally synchronous fires like those that occurred in the U.S. northern Rockies in 1910, 1988, 1994, 2000, and 2003 can account for the majority of area burned in a region (Strauss et al. 1989, Bessie and Johnson 1995, Rollins et al. 2001, 2002). During such years, the threats to people and their property are highest because fires during these years can quickly overwhelm our ability to suppress them. They are also likely to "reset" ecological succession over large areas (Turner et al. 1998) and thus potentially contribute to a positive feedback whereby extensive fires become more likely in the future (Veblen et al. 1999). The cumulative effect of extensive fires could greatly alter regional forest carbon budgets (Running 2006), water and nutrient cycles (Agee 1993), as well as habitats of many species of conservation concern (McKenzie et al. 2004). Understanding the complex interactions between fire, land use, vegetation type, and climate is critical to predicting the effects of climatic variability and climatic change on future fire extent and severity (Swetnam and Betancourt 1998, Morgan et al. 2001, Westerling et al. 2006) and to help land managers in their forecasting and strategic planning for regionally extensive fires.

Climate and fire in the northern Rockies

Interannual extremes in climate synchronized fires across large regions of western North America late in the 20th century (Gedalof et al. 2005, Collins et al. 2006, Westerling et al. 2006) and before (e.g., Swetnam and Betancourt 1998, Veblen et al. 2000, Heyerdahl et al. 2002, Kitzberger et al. 2007). Repeatedly during the 20th century, extensive fires in the northern Rockies have prompted revisions of national fire management policy, yet relatively little is known about the climate drivers of regional-fire years here. Among western U.S. forests, mid-elevation forests of the northern Rockies are predicted to have the highest risk of climate-induced increase in fire (Westerling et al. 2006) and therefore fire–climate relationships in this region are important to understanding the effects of climate and climatic change on fires across North America (Whitlock et al. 2003, Brown et al. 2004, McKenzie et al. 2004, Westerling et al. 2006). Large forest fires occur in areas with

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abundant, dry fuel, low relative humidity, high ambient temperature, and wind (Agee 1993, Bessie and Johnson 1995). Therefore, much fire–climate research has focused on summer drought extremes and the duration of these droughts during and preceding years of extensive fire. However, the potential influence of spring climate in synchronizing regional fires in the northern United States has been suggested for modern and historical fires but only recently confirmed for the 20th century in the western United States through its effect on duration of snowpack and hence length of the fire season (Balling et al. 1992, Heyerdahl et al. 2002, Hessl et al. 2004, Collins et al. 2006, Westerling et al. 2006). Large-scale climate patterns are partly responsible for variation in spring climate in the northern Rockies. For example, interannual variations in PDO, sometimes interacting with ENSO, account for roughly one-third of the variance in modern spring snowpack in the region (Gershunov and Barnett 1998, Harshberger et al. 2002, McCabe and Dettinger 2002). However, spring snowpack declined in the late 20th-century regardless of variation due to PDO (Hamlet et al. 2005) so that the effect of snowpack on fire cannot be identified with the relatively short late-20th-century record of fire occurrence that is readily available. Given the importance of snowpack duration on regionally synchronous fires, the effect of climate on fire may vary across vegetation types and elevation.

Fire atlases as fire history

Fire atlases, also termed digital polygon fire histories, are compilations of fire perimeters maintained in some locations by land managers as hard copy maps or digitally in a geographic information system (GIS). While fire atlases typically do not include all fires, they encompass extensive areas across diverse vegetation types and topographic settings, capture the large fires that account for the majority of area burned (McKelvey and Busse 1996, Morgan et al. 2001, Rollins et al. 2001, 2002), and may include the entire 20th century. Fire atlases have only recently been used in fire science in North America (McKelvey and Busse 1996, Minnich and Chou 1997, Morgan et al. 2001, Rollins et al. 2001, 2002, Stocks et al. 2002, Gillett et al. 2004, Gibson 2006, Luazon et al. 2007). Using atlases to identify regional-fire years takes advantage of their strengths while minimizing the influence of their limitations (the locations of perimeters may be inaccurate and may include unburned areas, and small fires may not be recorded). We use a fire atlas for the northern Rockies recently compiled for the entire 20th century to identify years of extensive fires (Gibson 2006).

Our objective

Our objective was to infer the climate drivers of 20th-century regional-fire years in the northern Rockies using annual fire extent from 1900 to 2003 derived from an existing fire atlas covering 12 070 086 ha in 12 national forests and one national park (Gibson 2006). We explored the influence of multi-season climate (temperature and precipitation) and large-scale climate patterns that affect spring temperature and snowpack in the region (ENSO and PDO). We did this for the region, through time, and by vegetation type to help us understand if the occurrence of regional-fire years in recent decades is the result of climate, fire exclusion (due to fire suppression and land-use change), or a combination. Our study is unique for its long, high-resolution modern record of fire (1900–2003), links to past fire (Heyerdahl et al. [2008] for 1650–1900), and focus on the U.S. northern Rockies.

Study Area

Regional climate

Most of the fire atlas lies within five climate divisions (1, 4, 8, and 10 in Idaho and 1 in Montana; data *available online*).[4] The climate is continental with cold winters and warm summers. Mean temperature in January ranges from −3 to −8°C and in July from 18 to 19°C (1900–2003). Mean annual precipitation ranges from 24 to 72 cm (1900–2003), much of which falls as snow in winter (62%, 1963–1996 [Serreze et al. 1999]). Snow water equivalent at elevations averaging 1905 m (range 960–2790 m) peaks in mid-April and drops to zero by early July (Serreze et al. 1999). Fires occur during spring, summer or fall and are often ignited by lightning as dry, cold fronts pass (Larsen and Delavan 1922).

Vegetation types and biophysical settings

The fire atlas recording area, 81% of which is forested, is in Idaho and in Montana west of the Continental Divide (Fig. 1). As integrators of biophysical setting, we used groups of environmental site potential types (ESP, Comer et al. 2003) as mapped by LANDFIRE (project description *available online*).[5] ESP is a stratification of biophysical environment identified by the vegetation that could potentially occupy a site in the absence of disturbance. We grouped like ESP types together and refer to them by the associated vegetation types. Cold forest covers 36% of the fire atlas (Fig. 1). It occurs at high elevations (median 1980 m, range 545–3502 m) on all aspects, typically with shallow, poorly developed soils and is often dominated by lodgepole pine (*Pinus contorta* Dougl. Ex Loud.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and other cold-tolerant tree species. Dry forest covers 36% of the fire atlas. It occurs at low elevations (median 1474 m, range 244–3142 m) on all aspects, typically with well-drained, often poorly developed soils and is dominated by ponderosa pine (*Pinus ponderosa* P.C. & Lawson) and Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco). Mesic forest covers 9% of the fire atlas. It occurs at low elevations

[4] ⟨lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html⟩
[5] ⟨www.landfire.gov⟩

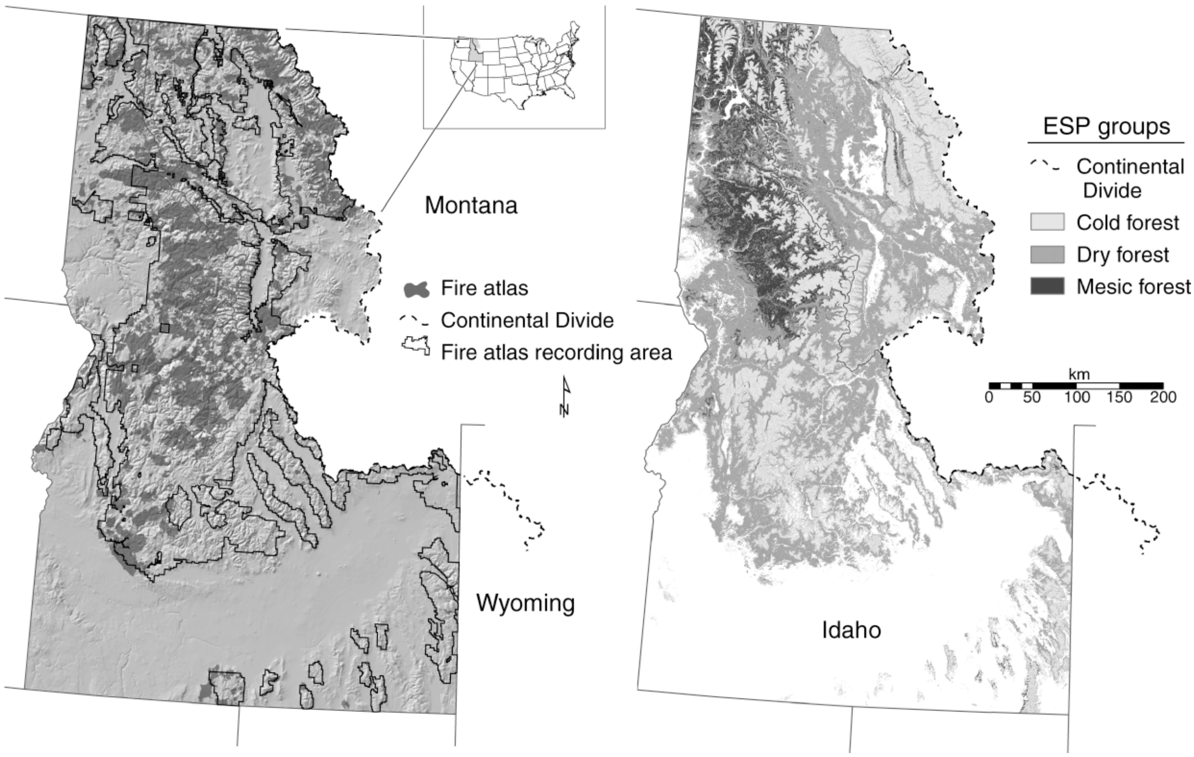

FIG. 1. The U.S. northern Rockies study area in Idaho and Montana west of the Continental Divide. Our 12 070 086-ha fire atlas recording area (left) is reported from 12 national forests and one national park. Burned polygons (1900–2003) are shown in dark gray against a background of elevation. The three most extensive types of potential vegetation (identified by environmental site potential [ESP], right) cover 81% of the fire atlas recording area. A small amount of the total fire extent (657 983 ha, 5% of the fire atlas recording area) lies outside the boundaries of the fire atlas recording area.

(median 1139 m, range 318–2974 m), often on north-facing slopes or other locations with high annual and growing season precipitation and well-developed soils. Mesic forest is dominated by a mixture of conifer species, including grand fir (*Abies grandis* [Dougl. Ex D. Don] Lindl.), Douglas-fir, western larch (*Larix occidentalis*), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western redcedar (*Thuja plicata* Donn Ex D. Don). Woodlands cover 4% of the fire atlas recording area and are dominated by juniper (*Juniperus* L. spp), aspen (*Populus tremuloides* Michx.), or other vegetation with trees of short stature. Woodlands in the northern Rockies are found from 231 to 3556 m (median 1779 m). The mesic shrub vegetation type covers 6% of the fire atlas recording area and includes riparian areas often dominated by willow (*Salix* spp.) and other shrub communities along streams and on hillsides from 233 m to 3571 m in elevation (1378 m median). The dry shrub vegetation type covers 5% of the fire atlas recording area and includes shrublands dominated by sagebrush species (*Artemisia* L. spp.) found from 229 m to 3030 m elevation (1524 m median). The grassland vegetation types include meadows and prairies dominated by perennial cool-season grasses mixed with many different herbaceous and shrub species, as well as grass-forb meadows commonly found in valley bottoms and forest openings. The grassland vegetation type covers 1% of the fire atlas recording area and is found from 231 m to 3531 m in elevation (1036 m median). The other environmental site potential group includes rock, barren and water and covers 3% of the fire atlas recording area over 231 m to 3593 m elevation (1660 m median).

METHODS

Regional-fire years

The fire atlas includes perimeters, dates, and locations of large (>40 ha) and some smaller fires recorded by year for 12 national forests and one national park from 1900 to 2003 (Gibson 2006). We summed the area within fire perimeters over each year into annual fire extent and over all years into total fire extent. We also computed these extents by vegetation type (i.e., ESP group). We identified regional-fire years as those exceeding the 90th percentile in annual fire extent from 1900 to 2003 (102 314 ha; Fig. 3). The time series of annual fire extent by vegetation type is available in the Supplement, while the GIS files and related metadata are available from the Fire Research and Management Exchange System (information *available online*).[6]

[6] ⟨http://frames.nbii.gov⟩

To evaluate whether fires were more geographically widespread in regional-fire years than in other years, we divided the fire atlas recording area into 17 grid cells, each 1.5° longitude by 1.5° latitude and counted the number of grid cells containing fire polygons in each year. We report the median and range of number of these 17 grid cells with fire for the 11 regional-fire years and the 93 other years.

Climate drivers of regional-fire years

We used instrumental temperature, which we normalized (i.e., subtracted the mean and divided by the standard deviation) and averaged across the five climate divisions covered by the fire atlas (divisions 1, 4, 8, and 10 in Idaho and 1 in Montana, data *available online*).[7] Annual fire extent was significantly correlated with seasonal precipitation only during prior winter (Spearman rank correlation $r = -0.33$, December–February) and summer ($r = -0.49$, June–August). Annual fire extent was significantly correlated with seasonal temperature only during spring ($r = 0.30$, March–May) and summer ($r = 0.59$). Among these four climate series, significant correlations ($P < 0.001$) occur only between summer precipitation and temperature ($r = -0.47$) and spring and summer temperature ($r = 0.33$).

As indices of large-scale climate patterns that affect spring climate in the northern Rockies, we used an index of instrumental spring PDO (MAM [Mantua et al. 1997]). We also used an index of winter ENSO ([Trenberth 1997] December–February (DJF); Niño-3.4 sea-surface temperature anomalies; data *available online*).[8] The Niño-3.4 index is computed from a slightly different area than the tree-ring-reconstructed Niño-3 index used in Heyerdahl et al. (2008). However, the two indices are highly correlated (Trenberth 1997).

To identify the influence of interannual climate on fire, including climate during antecedent years, we used superposed epoch analysis (Baisan and Swetnam 1990, Grissino-Mayer 2001) to assess whether climate during regional-fire years was significantly different from climate during the preceding and following years (±3 years). We calculated departures from average of five parameters: spring and summer temperature, prior winter and summer precipitation, and Niño-3.4. We identified significant departures as those exceeding 99% confidence intervals determined by bootstrapping (1000 trials [Mooney and Duval 1993, Grissino-Mayer 2001]). We repeated these analyses for each of the three forest types individually (cold, mesic, and dry forest). We visually assessed interactions between climatic indices (spring and summer temperature and prior winter and summer precipitation) and also between large-scale climate patterns (ENSO and PDO) in driving the occurrence of regional-fire years.

[7] ⟨www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp⟩

[8] ⟨ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/nino34.long.latest⟩

Vegetation types and regional-fire years

To evaluate whether vegetation types burned in proportion to their extent on the landscape in regional-fire years, we used nonparametric multi-response permutation tests (Mielke and Berry 2001). We used the same approach to compare proportion burned by vegetation types in regional-fire years early and late in the 20th century, with a Bonferroni adjustment to maintain type I error for tests of differences for individual vegetation types.

We repeated these analyses using fire extent only in the four national forests with the longest records (Clearwater, Kootenai, Lolo, and Nez Perce). We sought to make sure that the changing patterns of forest type burning that we detected from the entire fire atlas was not due to relatively short records in the southern portion of the atlas.

Results

Regional-fire years

We identified eleven regional-fire years between 1900 and 2003, during which fire extent was 1% to 10% of the recording area (1910, 2000, 1919, 1994, 2003, 1988, 1926, 1929, 1992, 1934, and 1931, in order of decreasing fire extent; Fig. 2). The 11 regional-fire years account for 74% of total fire extent from 1900 to 2003; in this 104-year record every year except 1901 recorded fires >40 ha. Regional-fire years were concentrated early and late in the 20th century (Fig. 3). They occurred from 1910 to 1934 and 1988 to 2003 but not in the mid 1900s.

Fires were geographically widespread during regional-fire years (Fig. 2). During such years, fire polygons occurred in an average of 12 (range 11–15) of the 17 grid cells whereas during all other years, they occurred in an average of only seven (range 0–13).

Climate drivers of regional-fire years

Both early and late in the 20th century, regional-fire years were ones of significantly warm springs followed by significantly warm, dry summers ($P < 0.01$; Figs. 3–5), with climate departures near one standard deviation from average. During regional-fire years, average divisional spring temperature was 1.1–1.7°C above average, divisional summer temperature was 0.4–1.2°C above average, and summer precipitation was −1.1 to −1.6 cm below average. Prior winter precipitation did not depart significantly during regional-fire years. Consistent with its strong influence on spring temperature in the northern Rockies, the PDO index was positive during nine of the 11 regional-fire years (all except 1910 and 1919, both at −0.08; Fig. 5). Consistent with its relatively weak influence on spring climate in the region, Niño-3.4 was not significantly different during regional-fire years (Fig. 4), but rather regional-fire years occurred during both El Niño and La Niña years (Fig. 5). Furthermore, ENSO and PDO did not interact in their effect on the occurrence of regional-fire years

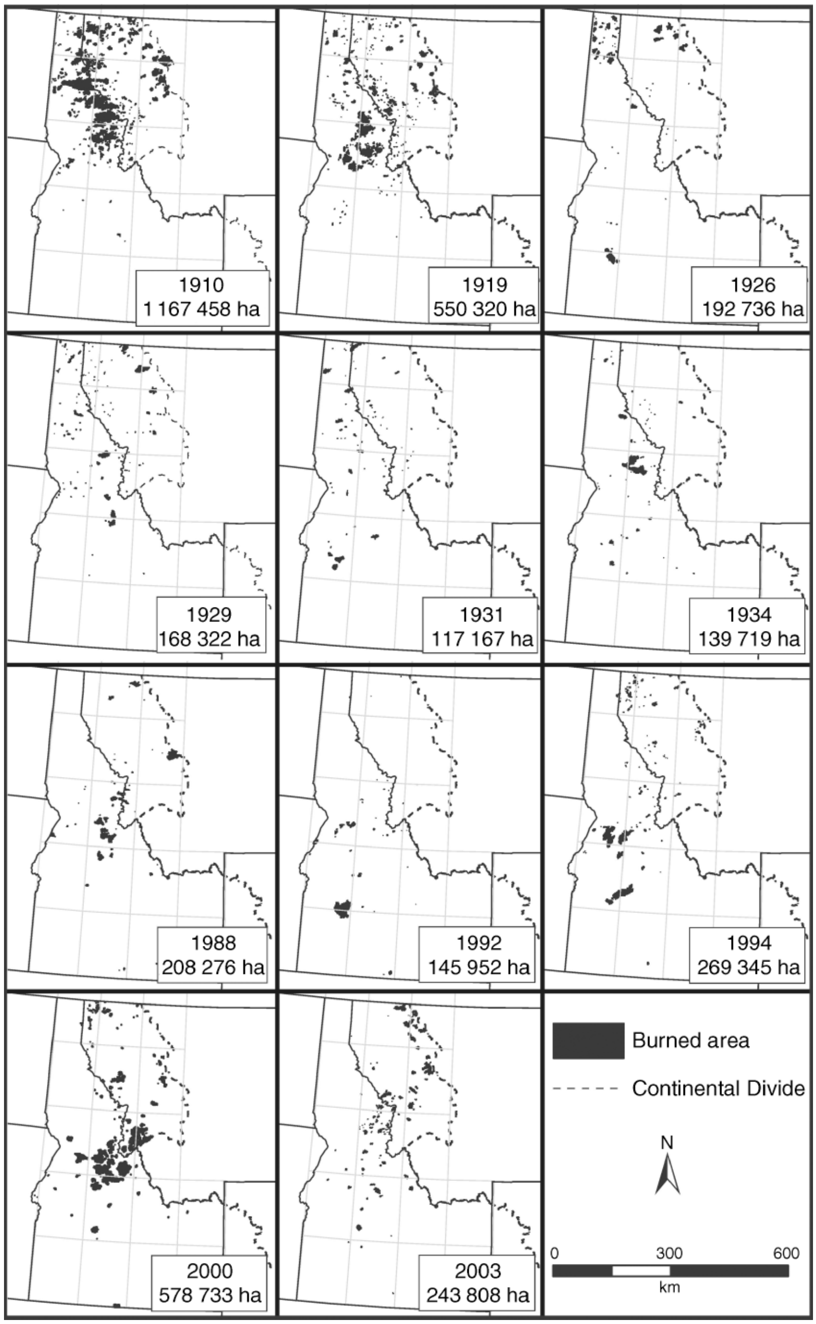

FIG. 2. Fires were widespread during each of the eleven 20th-century regional-fire years identified for the northern Rockies. The grid cells are 1.5° latitude by 1.5° longitude, and all 17 grid cells shown had burned polygons in them in at least one year, though not necessarily in one of the regional-fire years shown here.

(Fig. 5). There were no significant departures in temperature (spring or summer), precipitation (prior winter or summer), or Niño-3.4 during years prior to regional-fire years. Non-regional-fire years, those with fire extents below the 90th percentile, occurred under any combination of spring and summer climate and a variety of ENSO and PDO phase combinations (Fig. 5). The mid-20th-century period lacking regional-fire years (1935–1987) was characterized by generally cool springs, generally negative PDO, and a lack of extremely dry summers (Fig. 3). Climate results were similar for each of the three forest types (not shown).

Vegetation types and regional-fire years

Most of the area recorded as burned during the 20th century was in the cold and dry forests (67%, Fig. 6).

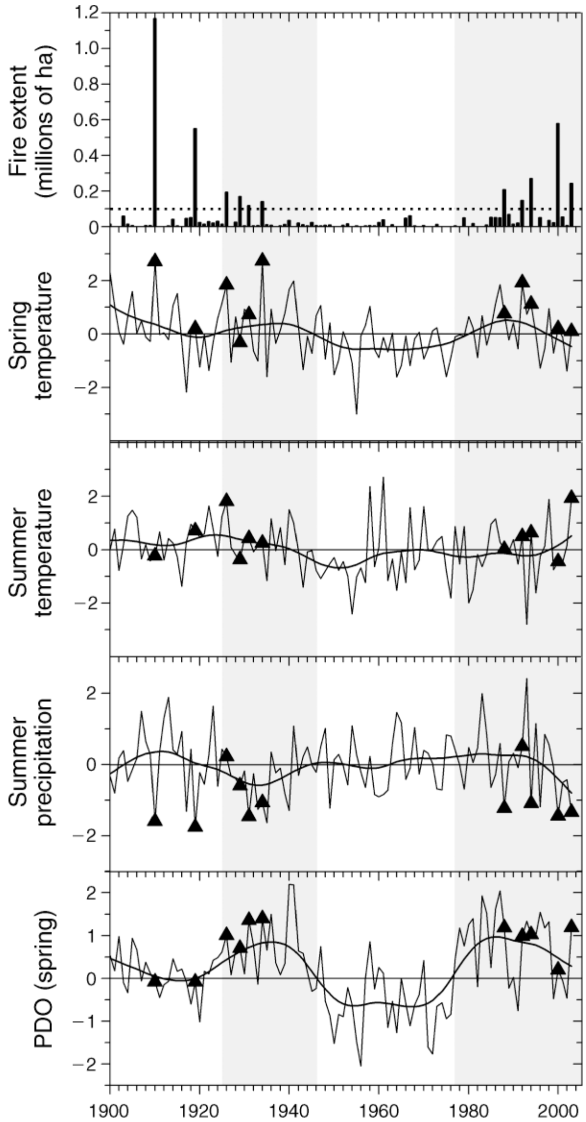

FIG. 3. Annual fire extent and 20th-century climate in the northern Rockies. The 11 years exceeding the 90th percentile in annual fire extent (102 314 ha, horizontal dotted line) were identified as regional-fire years (top) and indicated with triangles in the other plots. Spring temperature (March–May), summer temperature (June–August), and summer precipitation were normalized then averaged over the five climate divisions covered by the fire atlas (1900–2003; see *Methods: Climate drivers of regional-fire years* for details). Heavy lines are climate data smoothed with cubic smoothing splines that retain 50% of the variance at periods of 25 years. Positive phases of the Pacific Decadal Oscillation (PDO) are shaded (Mantua et al. 1997).

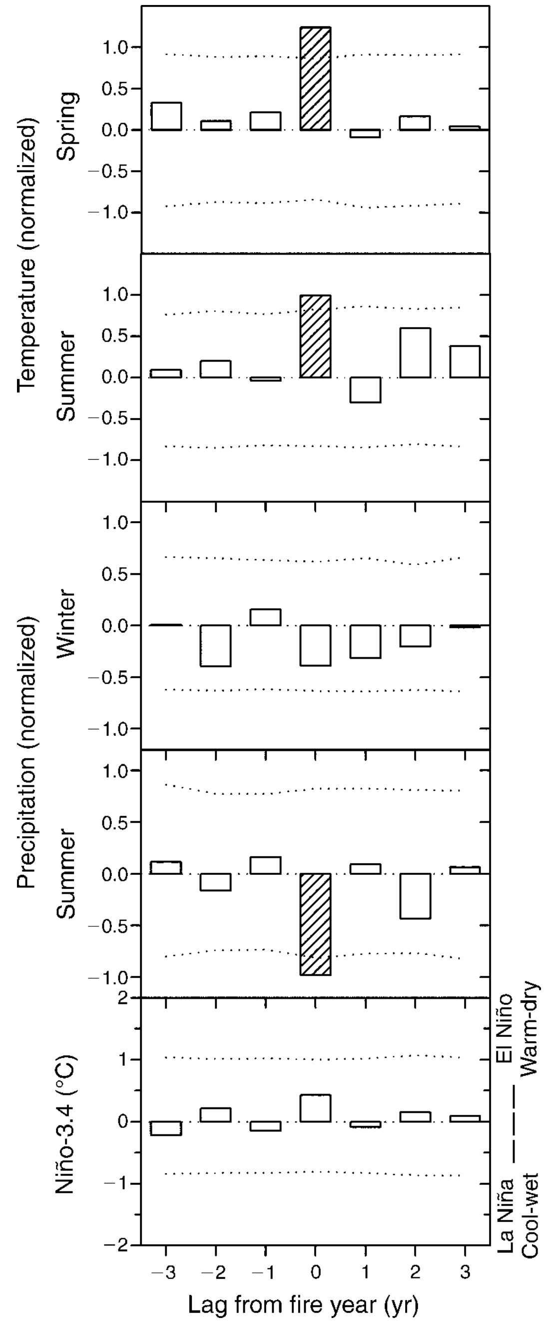

FIG. 4. Lagged annual relationship of fire and climate (spring [March–May] and summer [June–August] temperature, prior winter [December–February] and summer precipitation) or large-scale climate patterns (Niño-3.4 [December–February] as an index of ENSO), showing average departures during the 11 years exceeding the 90th percentile in annual fire extent across the northern Rockies from 1900 to 2003, and the years preceding and following such years. Hatched bars indicate departures that exceed 99% confidence intervals (dotted lines). Precipitation and temperature are averages for the five climate divisions covered by the fire atlas recording area, normalized over the analysis period (1900–2003).

While the distribution of total fire extent among vegetation types was not disproportionate to their occurrence on the landscape ($P = 0.9486$), fire extent within each vegetation type was much less than the area of that vegetation type (Fig. 6 top). Total fire extent in cold forest was 39% of the area of cold forests, 59% for mesic forests, 41% for dry forests, 53% for woodland, 44% for mesic shrub, 43% for dry shrub, 61% for

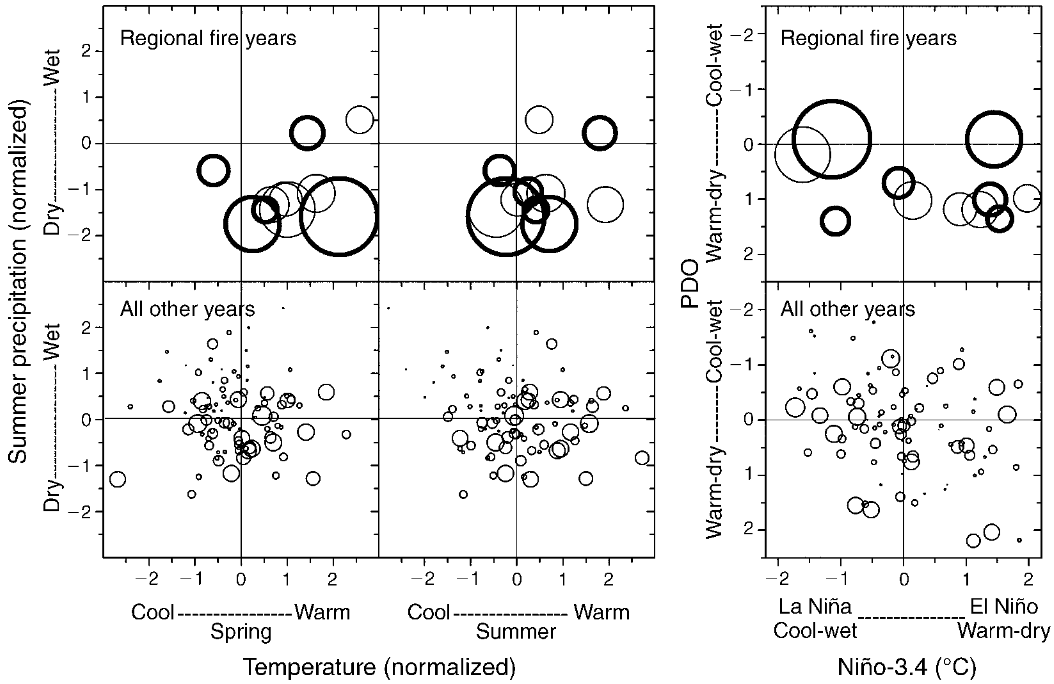

FIG. 5. Combined influence of spring (March–May) and summer (June–August) climate (left) and large-scale climate patterns (right) on regional-fire years (top) and all other years (1900–2003; bottom). Area of the circles is proportional to annual fire extent in the northern Rockies (minimum nonzero fire extent was 81 ha; maximum was 1 167 458 ha). Regional-fire years that occurred early in the 20th century (i.e., 1910–1934) are indicated with heavy circles. Precipitation and temperature are averages for the five climate divisions covered by the fire atlas, normalized over the analysis period (1900–2003). ENSO and PDO primarily affect spring climate in this region.

grassland, and 27% for the other ESP group. During regional-fire years, proportionately more mesic forest burned in the early 20th century than in the late 20th century ($P < 0.0238$, mean 19% early and 2% late), but there was no difference in the proportion of other forest types burning early versus late in the century ($P > 0.05$, Bonferroni correction applied). If we had identified years exceeding the 90th percentile in annual fire extent within cold, mesic, and dry forest types individually, most of the years would agree with the 11 identified from all forest types combined (10 of 11 for mesic and dry forests and seven of 11 for cold forest).

The pattern we saw from the entire fire atlas of relatively more mesic forest burned early versus late in the 20th century was also evident when we examined the fire-atlas record only from the four forests with the longest records (results not shown).

DISCUSSION

Climate synchronized widespread fires for nearly four centuries

Despite fire suppression, logging, road building, grazing, and other land uses during the 20th century, fires burned synchronously across diverse geographic areas and vegetation types when climatic conditions were conducive. In regional-fire years, fires were widespread and burned large areas of dry, cold and mesic forests of Idaho and western Montana. They also burned extensive areas in shrublands and grasslands (Collins et al. 2006) not well represented in the fire atlas.

Our findings that fires were more extensive during warm, dry summers following warm springs in the northern Rockies support previous findings in this region for the late 20th century (Westerling et al. 2006) and extend them to the early 20th century. Fire occurrence in the Pacific Northwest varied with PDSI in the late 20th (Westerling et al. 2003, Gedalof et al. 2005, Collins et al. 2006) and earlier centuries (Hessl et al. 2004). When ignited during extended warm, dry and windy conditions, fires spread readily through dry fuels on the surface and in tree crowns (Agee 1993, Hessl et al. 2004). The moisture and abundance of fine fuels, and therefore the effect of moisture in years antecedent to fires, is important to fire spread in grasslands, many shrublands, and some dry forests, but less so in cold forests where the occurrence of large fires is more limited by same-year drought (Westerling et al. 2003, Schoennagel et al. 2005, Collins et al. 2006, Sibold and Veblen 2006). The lack of an effect of climate during antecedent years on regional-fire years in either the past (Heyerdahl et al. 2008) or the 20th century in the forests of the northern Rockies suggests that when warm, dry summers follow warm springs, fuels dry sufficiently in spring and summer to carry extensive mid- to late-summer forest fires if ignitions occur and weather is

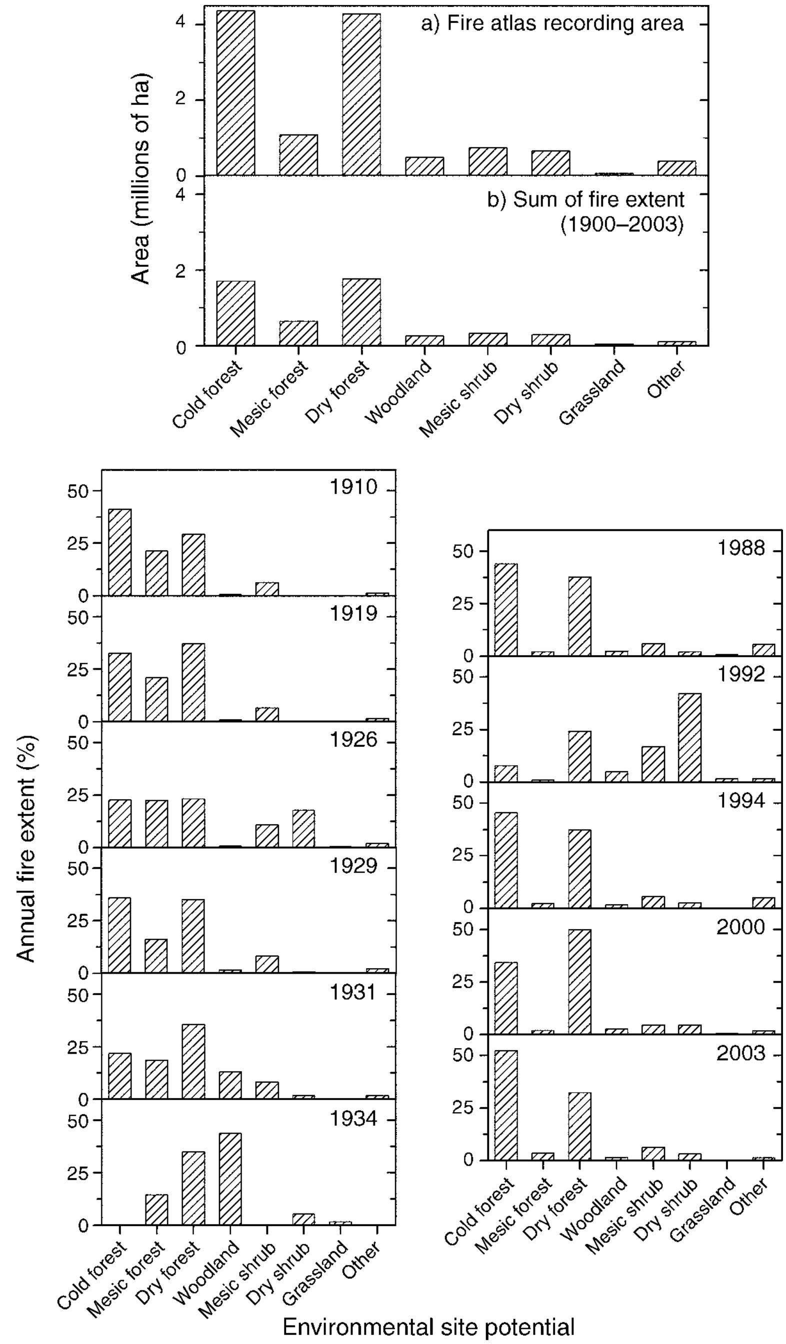

FIG. 6. The upper panel shows the area in each vegetation type (ESP, environmental site potential) (a) within the fire atlas recording area and (b) for total fire extent from 1900 to 2003 by vegetation type. Lower panels show the distribution of fire extent by potential vegetation during each of the 11 regional-fire years (from 1900 to 2003). Regional-fire years in the left column occurred early in the 20th century, while those in the right column occurred late in the 20th century. No regional-fire years occurred between 1935 and 1987.

favorable. The role of prior winter precipitation in driving the occurrence of regional-fire years through snowpack accumulation appears to be secondary to the role of spring temperature in melting that snowpack. The lack of a statistically significant ENSO signal is consistent with ENSO's relatively weak influence on spring climate here and variable influence on historical fire elsewhere in the northern United States (Heyerdahl et al. 2002, Hessl et al. 2004, Schoennagel et al. 2005). Our finding of a significant effect of PDO on 20th-century regional-fire years despite a lack of such effect on pre-20th-century regional-fire years in the northern Rockies may be due to changes in the PDO or to differences in the fire records used in these two time periods (Heyerdahl et al. 2008).

The 20th-century climate drivers of fire that we identified are similar to those that operated in dry forests of the region in prior centuries. Past regional-fire years (32 years that exceeded the 90th percentile of sites with fire scars from 1650 to 1900 [Heyerdahl et al. 2008]) also occurred when warm-spring summers were followed by warm-dry summers. The past and present climate drivers of fire that we reconstructed from the fire atlas and the fire scar record are similar despite differences in geographic and biophysical coverage of the fire data. The fire-scar data are primarily from dry forests, include more sites in Montana than in Idaho, and record fire occurrence at points. The fire atlas includes all forest types, covers more of Idaho than Montana and records fire extent.

The fire atlas provides information critical for understanding climate and non-climate drivers of 20th-century variation in fire in the northern Rockies. Although the fire atlas contains some inaccuracies in fire locations and gaps in recording, it is (1) the only spatially explicit record of fire for the entire 20th century; (2) consistent with short fire records (e.g., National Interagency Fire Management Integrated Database and satellite imagery [Gibson 2006, Shapiro-Miller et al. 2007]) and with long fire records (e.g., tree rings [Shapiro-Miller et al. 2007]); and (3) contains records that are sufficiently accurate to reveal modern climate drivers of fire that are consistent with historical ones (Heyerdahl et al. 2008). The collection and preservation of fire atlas records should be a priority in other regions of North America.

Ecological and fire management implications

Even in the face of very effective modern detection, initial attack, and aggressive, well-funded, and well-equipped fire suppression during the late 20th century, widespread fires burned synchronously across 1–10% of the recording area (from 117 167 ha to 1 167 458 ha; Fig. 2) during some years (Gibson 2006). In some of these years, large fires burned in more than eight national forests in two states with attendant challenges for fire suppression and threats to people and property. If, as projected, snowpack melts earlier under human-induced climatic change (McCabe and Wolock 1999, Kittel et al. 2002, Mote et al. 2005), then we are likely to experience regional-fire years more often in the future.

Despite the importance of relatively warm springs in driving the occurrence of regional-fire years in the northern Rockies, our analysis of the fire atlas record did not detect strong evidence for an effect of the late 20th-century climatic change that resulted in warm springs and reduced snowpack in this region. However, we did not consider absolute fire extent, number of fires per year, or possible changes in fire seasonality or severity.

Westerling et al. (2006) found that, since 1970 in the northern Rockies, strong trends toward longer fire seasons and more large fires were concentrated at elevations from 1680 to 2290 m. These elevations encompass 74% (8 978 376 ha) of our fire atlas recording area and include vegetation types in rough proportion to their occurrence across our study area (cold forest [32%], dry forest [22%], and dry shrub [26%] with less mesic forest [2%], woodland [9%], mesic shrub [9%], and other vegetation types [2%]), consistent with Running's (2006) conclusion that all forest types are potentially vulnerable to the effects of climate change on fires in the northern Rockies.

Fire managers are only just beginning to understand and plan for the synergy between fire and climatic change. In the face of a warming climate and increased fuels in some forest types, fire suppression will likely become even more challenging. The late 20th-century increase in large forest fires was greater in the northern Rockies than other regions of the western United States (Westerling et al. 2006). As climate changes, the number of large fires may increase in this region despite increased investment in fire suppression and fuels management (Fried et al. 2004), though such investments may reduce fire severity or help protect people and their property or other resources.

Variation in fire extent among forest types

Not only did the climate drivers of 20th-century regional-fire years not vary through time, they did not vary among forest types. This is not surprising given that the three forest types occur in relatively small, often juxtaposed patches (Fig. 1) so that when one forest type burned, others burned too. However, the distribution of fire extent among forest types did vary through time, with relatively more mesic forest burning during regional-fire years early vs. late in the 20th century (Fig. 6). This change in mesic forest burned may have been due to several factors. Fire extent may have been over-reported in mesic forest early in the century because it occurs close to towns that depended on their timber resources and also because of the heightened fear of fire after the extensive 1910 fires. In addition, fire extent may have been underreported in cold forests because they were distant from towns and often relatively inaccessible. The change in mesic forest burned is not likely due to variation in the length of fire-atlas records among National Forests. The fire records for some of the national forests in the study area do not include the entire 20th century, but the change in mesic forest burned is evident in records from the four National Forests that have the longest fire atlas records. During warm springs, earlier melting of persistent snowpack lengthens the fire season (Larsen and Delavan 1922, Gedalof et al. 2005, Westerling et al. 2006), so we expected the warmer spring temperatures and earlier melting of snowpack that occurred in the late 20th century (Hamlet et al. 2005, Mote et al. 2005) to affect fire extent more in the high-elevation cold forests than in either mesic or dry forests. However, the change we saw was in the relative amount of mesic forest only. Finally, our sample size is small (only six regional-fire years in the early 20th century and five in the late).

The fire-climate relationships we analyzed probably do not accurately reflect those in non-forested areas in the northern Rockies as less than 19% of the fire atlas recording area is non-forested. Modern climate drivers of fire in forests differ from those in non-forested areas where increased moisture in antecedent years is necessary to grow the continuous fine grass and herbaceous fuel that carry fire (Westerling et al. 2003, Collins et al. 2006).

Was the late 20th-century increase in regional-fire years due to climate, fire exclusion, or both?

The late 20th-century increase in fire extent (Fig. 3) has been attributed to the cumulative effects of fire exclusion due to fire suppression, logging, grazing and other land uses (Covington 2000), but could also be driven, at least in part, by climate (Westerling et al. 2006). Although our data confirm the conclusions of Westerling et al. (2006) that warm springs led to regionally synchronous fires in the late 20th century, we found that the same was also true in the early 20th century. We suggest that these variations throughout the 20th century resulted from complex interactions of climatic variation and fire exclusion.

The long mid-century period (1935–1987) with relatively low fire extent (<68 000 ha/yr) in the northern Rockies (Fig. 3) could be due to recording or other inaccuracies, but more probably resulted from interaction between climate and fire exclusion. Climate-driven gaps in fire occurrence associated with below-average temperature have occurred in the past, e.g., 1696–1703, but this mid-20th-century gap in regional-fire years is much longer than any in the prior 250 years in the northern Rockies (Heyerdahl et al. 2008). The relatively high fuel moistures that likely resulted from cool springs, lack of extremely dry summers, and perhaps few fire ignitions during the gap may have limited fire spread, thus increasing the likelihood of successful fire suppression. Fire fighters were well funded, well trained, and well equipped, and fire policy supported very aggressive fire suppression. Even in those summers during this period that were drier than some of the regional-fire years, fires were of very limited extent, probably due to this fire suppression. The increase in fire extent in recent decades occurred despite continued technological advancements, funding and efforts in fire fighting.

The sharp increase in fire extent in the late 20th century was not likely due to fire suppression, logging and land uses alone: climate was also important. With relatively little area burned from 1935 to 1987, accumulated biomass would likely have increased fire size and severity (e.g., Covington 2000) rather than decreased it, especially in dry forests. Furthermore, intensive land use and fire suppression were more effective at reducing fire occurrence and extent in dry than cold forests (Hessburg et al. 2000). Consequently, if fire exclusion was the sole cause of the mid-century gap in fire, we would have expected extensive fires in cold forests during at least some of the years in the mid-century gap.

It is also unlikely that the late 20th-century increase in fire extent is merely an artifact of better reporting. Although mapping technology has improved in recent years with more people available to map and report fires, these improvements are not sufficient to account for the large fire extents recorded in recent years. At 1 446 114 ha, fire extent during the five late-20th century regional-fire years is 2.3 times the extent recorded during the mid-century gap (639 423 ha during the 53 years from 1935 to 1987).

We think that climatic variation is partly responsible for both the mid-20th century gap in regional-fire years and the increase in fire extent since the 1980s. Warm springs and warm, dry summers have been driving the occurrence of regional-fire years throughout the 20th century in the northern Rockies (Fig. 3), and the relatively cool springs, cool-phase PDO and a lack of extremely dry summers likely decreased the probability of large fires because fuel conditions were not conducive to fire spread and thus made fire suppression more effective during the mid-century gap in large, widespread fires. Since about 1980, spring temperature has been higher, summer precipitation more extremely dry and PDO above average for the 20th century, and five of 24 years had large and widespread fires (Fig. 3). Although intensive land use has likely decoupled fire-climate relationships at some local spatial scales (e.g., Heyerdahl et al. 2002), the congruence of modern and past regional fire-climate relationships suggests that climate continues to be a major driver of widespread, synchronous fires despite intensive fire suppression efforts, logging and other land uses. Although we cannot identify their relative contributions with our data, climatic variability, fire suppression and land use likely all played a role in regional fire activity in the past and will continue to do so in the future.

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SUPPLEMENT

Time series of annual fire extent in the U.S. northern Rockies (*Ecological Archives* E089-039-S1).