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Changing fire regimes in the Great Basin USA

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Abstract

Wildfire is a natural disturbance in landscapes of the Western United States, but the effects and extents of fire are changing. Differences between historical and contemporary fire regimes can help identify reasons for observed changes in landscape composition. People living and working in the Great Basin, USA, are observing altered fire conditions, but spatial information about the degree and direction of change and departure from historical fire regimes is lacking. This study estimates how fire regimes have changed in the major Great Basin vegetation types over the past 60 years with comparisons to historical (pre-1900) fire regimes. We explore potential drivers of fire regime changes using existing spatial data and analysis. Across vegetation types, wildfires were larger and more frequent in the contemporary period (1991–2020) than in the recent past (1961–1990). Contemporary fires were more frequent than historical in two of three ecoregions for the most widespread vegetation type, basin and Wyoming big sagebrush. Increases in fire frequency also occurred in saltbush, greasewood, and blackbrush shrublands, although current fire return intervals remain on the order of centuries. Persistent juniper and pinyon pine woodlands burned more frequently in contemporary times than in historical times. Fire frequency was relatively unchanged in mixed dwarf sagebrush shrublands, suggesting they remain fuel-limited. Results suggest that quaking aspen woodlands may be burning less frequently now than historically, but more frequently in the contemporary period than in the recent past. We found that increased fire occurrence in the Great Basin is associated with increased abundance and extent of nonnative annual grasses and areas with high concentrations of anthropogenic ignitions. Findings support the need for continuing efforts to reduce fire occurrences in Great Basin plant communities experiencing excess fire and to implement treatments in communities experiencing fire deficits. Results underscore the importance of anthropogenic ignitions and discuss more targeted education and prevention efforts. Knowledge about signals of fire regime changes across the region can support effective deployment of resources to protect or restore plant communities and human values.

KEYWORDS
aspen woodland, biophysical setting, ecoregion, fire frequency, fire history, ignition, nonnative annual grasses, pinyon-juniper, reburn, sagebrush, salt desert shrub, Snake River Plain

INTRODUCTION

Natural disturbances are important to our understanding of ecosystems, their composition, recovery, and function. Fire is one of the more common and imposing natural disturbances in the Great Basin, USA. In this study, general references to the Great Basin region include the Central Basin and Range (CBR), Northern Basin and Range (NBR), and the Snake River Plain (SRP) Environmental Protection Agency (EPA) Level III ecoregions (Omernik & Griffith, 2014). Fire plays a critical role in the structure and function of the various Great Basin plant communities and their ecosystem services. By understanding the historical fire regimes associated with these plant communities, we gain insight into the evolutionary pressures and plant adaptations that have guided ecosystem recovery and stability. By comparing historical with contemporary fire regimes, we can gain an understanding of the underlying reasons for observed changes associated with additional ecosystem pressures such as land use, nonnative species proliferation, climate change, human population growth, and sources of fire ignition. People living and working in the West and in the Great Basin are aware that fire regimes are changing but need information about the degree and direction of change.

Fire regime concept

Fire regimes describe spatial and temporal patterns and ecosystem impacts of wildfire (Morgan et al., 1999). Fire regimes describe a combination of fire frequency, fire intensity, burn severity (impacts on ecosystem components), seasonality, and spatial distribution and variability (Morgan et al., 1999). Fire regimes are often described as cycles, rotations, or intervals because some parts of the histories usually get repeated, and the repetitions can be counted and measured (FEIS, n.d.). A common fire-occurrence metric (and the one used throughout this paper) is the fire return interval (FRI) is the number of years between two successive fires in a specified area. It is often used to designate an average of intervals (mean FRI or mFRI) (FEIS, n.d.). Fire regimes are affected by climate, fuels, and ignition sources (Morgan et al., 1999).

Understanding historical fire regimes and comparing them to contemporary fire regimes can aid in understanding successional vegetation dynamics and observed changes in landscape composition within ecosystems (Morgan et al., 1999). LANDFIRE (landfire.gov) has documented fire frequency and severity patterns across the United States for the past two decades (Blankenship et al., 2011; Rollins, 2009).

Historical fire regimes in the Great Basin

The Great Basin in the western United States is a region of semiarid and arid climates, dominated by sagebrush shrublands and semiarid woodlands. Describing past fire regimes in the Great Basin has been notoriously difficult because of the absence of fire-scarring trees. Because fires are typically stand-replacing in Great Basin vegetation types, historical fire occurrence has largely been inferred from postfire recovery rates of dominant species and fire-scarring trees in surrounding forests and woodlands (e.g., Miller & Heyerdahl, 2008). Estimates of past fire occurrence in the Great Basin vary widely by vegetation type (Baker, 2006; Kitchen & Weisberg, 2013; Miller & Heyerdahl, 2008).

Studies in the Great Basin have linked fire occurrence to the availability of fuels, which change with soil and climate conditions. Miller and Heyerdahl (2008) found fires to be more frequent in areas with deep, productive soils capable of supporting abundant and continuous herbaceous vegetation, resulting in higher amounts of burnable biomass. They also found fires were less frequent in areas with shallow, coarse soils where fine fuels were likely limited in both amount and continuity.

Through the evaluation of fire-scar studies and shrub species recovery rates throughout the sagebrush biome, Baker (2006) suggested minimum fire rotation estimates of 325–450 years in low sagebrush (e.g., *Artemisia arbuscula* and *Artemisia nova*), 100–240 years in Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*), and 35–100 years in more mesic mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana*). FRI equivalents would approximate 163–225 years for low sagebrush, 50–120 years for Wyoming big sagebrush, and 17–50 years for mountain big sagebrush based on calculations presented by Baker (2006). Research suggests that fire frequency can also vary geographically. On the western margin of the Great Basin in Lava Beds National

Monument, California, Miller and Heyerdahl (2008) estimated that historical FRIs in some sagebrush habitats lasted many decades. Kitchen and Weisberg (2013) estimated a historical fire frequency of 24.9 years in mountain big sagebrush stands in the eastern Great Basin using fire-scarred trees in adjacent vegetation. Findings from macroscopic charcoal analysis in the central Great Basin supported a mean FRI of up to 100 years in Wyoming big sagebrush vegetation (Mensing et al., 2006).

FRIs were variable in the fire history studies of persistent pinyon and juniper woodlands. Bauer and Weisberg (2009) found historical fires in single-leaf pinyon (*Pinus monophylla*)-Utah juniper (*Juniperus osteosperma*) woodlands to be infrequent, small, and stand-replacing in the Barrett Canyon watershed in central Nevada. They found no evidence of stand-replacing fires in post-settlement time. Kitchen (2012) calculated point mFRIs as low as 50–73 years and indicated other stands were largely unaffected by fire for more than 800 years in single-leaf pinyon-juniper (*Juniperus* spp.) woodland stands in east-central Nevada and west-central Utah. In single-leaf pinyon-juniper and ponderosa pine stands in the Mount Irish Range in southeastern Nevada, fire-scarred ponderosa pine trees indicated that small fires occurred frequently (1–19 year FRIs) but that larger fires were less common (40–123 year FRIs) between 1550 and 1860 (Biondi et al., 2011). From fire-scar chronologies available for pinyon and juniper woodlands, a decline in fires began in the late 1800s (Miller et al., 2019). Decreased fire frequency in pinyon-juniper stands after about 1860, or Euro-American settlement, was also reported by Kitchen (2012) who attributed it to the removal of fine fuels by grazing animals and loss of Indigenous burning.

Shinneman et al. (2013) characterized fire regimes for quaking aspen (*Populus tremuloides*) in the Mountain West in a thorough literature review that included aspen stands that naturally succeed to conifer trees and aspen stands that remain stable due to site conditions and lack of competition from conifer species. The review noted evidence of frequent low-severity fires (Baker, 1925); however, contemporary studies rarely found fire scars on aspen stems, suggesting a rarity of low-severity fires. In a stand age reconstruction study beginning in 1880 in the San Juan National Forest on the Colorado Plateau, Romme et al. (2001) estimated stand ages from 10 years to over 120 years, with half of the stands estimated to be younger than 70 years. LANDFIRE Biophysical Settings (BpS) models emphasize the importance of understanding that aspen is considered a fireproof vegetation type that historically did not burn during the normal lightning season (LANDFIRE, 2020b). However, other lines of evidence and fire scars on aspen and from adjacent conifer stands suggest that Indigenous burning was a common practice in spring and fall (e.g., Baker, 1925; Kay, 2000). An earlier literature review of fire history studies for quaking aspen reported general agreement among the available studies that fires were more frequent before and during the mid-nineteenth century than any time since (Howard, 1996). LANDFIRE BpS models for the Great Basin therefore suggest mFRIs of about 70 years for stand-replacing fire in aspen stands, but more frequent mFRI (27–30 years) when historical low to moderate severity fires are accounted for.

Fire history studies are generally lacking for other Great Basin vegetation types. Most of what is reported about past fire occurrence in mixed dwarf sagebrush, greasewood, saltbush, and blackbrush communities has been extrapolated from fuel characteristics (arrangement and biomass production), which suggests that fires were limited by widely spaced shrubs and low fine fuel abundance (Paysen et al., 2000; West, 1994). The rarity of fire was also expected because dominant species were killed by fire (e.g., low sagebrush [*A. arbuscula*], saltbush [*Atriplex* spp.], blackbrush [*Coleogyne ramosissima*]; Anderson, 2001; Howard, 2003; Steinberg, 2002).

Recent changes in fire occurrence

Many studies report that fire frequency and fire size have increased in the western United States (e.g., Crist, 2023; Dennison et al., 2014; Littell et al., 2009; Westerling et al., 2006) especially since about 1970. Increased fire activity has been associated with warmer climates and an abundance of flammable fuels (nonnative annual grass in our study area) (Crist, 2023; Littell et al., 2009). Littell et al. (2009) found relationships between climate and area burned between 1916 and 2003 in the Great Basin, where year-prior precipitation was especially important in large fire years and warm, wet conditions in the winter and spring led to larger areas burned a year or more into the future. Parks et al. (2016) quantified departures from expected area burned across the West. They found a surplus of fire across large expanses of non-forested regions, including the northern Great Basin and southern Columbia Plateau. Dennison et al. (2014) found that the number of large fires trended higher for most Western US ecoregions from 1984 to 2011. This included the SRP and NBR ecoregions but not the CBR; and although trends were increasing, the increases were not statistically significant for SRP or NBR. In an evaluation of fire trends (1984–2020) across the contiguous United States, contemporary FRI varied by location and were 180 years for an ecoregion that included the southern portion of our study area (mainly the CBR) and 73 years in the northern portion of our study area (NBR and SRP) (Vanderhoof et al., 2022). Total area burned was 14% for the southern and 32% for the northern portion of our study area, and areas that did burn tended to burn repeatedly (Vanderhoof et al., 2022). When fire history metrics were merged with cheatgrass (*Bromus tectorum*) cover, portions of the Great Basin with greater than 15% cheatgrass cover showed a greater proportion of area burned (38% compared with 14%) (Vanderhoof et al., 2022). It is worth noting that most of the above studies are describing changes in fire frequency and size since 1984 (Dennison et al., 2014; Parks et al., 2016; Vanderhoof et al., 2022).

Causes of changing fire regimes

Spread of nonnative flammable grasses and expanding human populations have been identified as factors associated with changing fire regimes in the study area (Crist, 2023; Crist et al., 2023; Pilliod et al., 2017). Climate warming has been associated with increased fire activity in forested systems (Westerling et al., 2014), but changes in the amount and timing of precipitation and its association with fine fuels drove increases in fire likelihood in the Great Basin (Pilliod et al., 2017).

Increases in the abundance of nonnative annual grasses in the Great Basin have co-occurred with climate changes. Pilliod et al. (2017) evaluated herbaceous vegetation cover and litter accumulations, temperatures, and precipitation from 1980 to 2014 in the CBR, NBR, and SRP ecoregions. Cheatgrass cover and litter accumulations were associated with years of high precipitation. The number of fires was highest when the preceding two winters and springs were particularly wet and when the summer of the fire year was dry. When dry summers were not preceded by wet years, fires were less common, and the area burned was less. Smith et al. (2021) found that climatic water deficit and annual minimum temperature increased from 1958 to 2020 in the CBR, NBR, and SRP, especially between 1990 and 2020. Growing season precipitation did not change much, but summer precipitation steadily declined over the last 60 years. These changes in climate co-occurred with a more than 8-fold increase from 1990 to 2020 in annual grass dominance (Smith et al., 2021).

The annual rate of increase in annual grass dominance in the Great Basin since 1990 averaged 2373 km^2/year (a geometric mean increase of 7.5%) (Smith et al., 2021). By 2020, annual grass dominance clusters occupied 17% of rangeland vegetation in CBR, 18% of rangelands in NBR, and 43% of rangelands in SRP. Several studies have linked increases in nonnative grasses to increases in fire size and frequency in the Great Basin. Knapp (1998) evaluated fire records for the Intermountain West from 1980 to 1995 and found that large fires (>2800 ha) were associated with areas of flatter terrain and high annual grass cover. Large fire years were also associated with the previous summer's moisture, with 80% of large fires occurring when previous summer precipitation was normal or above. Greater cheatgrass cover was associated with more area burned and increased the chance of repeated fires for the Great Basin (Bradley et al., 2018). Almost 11% of the region with high cheatgrass cover (≥15%) burned between 2000 and 2014, while just 5% of the region with low cheatgrass cover (<15%) burned over the same period.

Balch et al. (2013) found a trend of increasing total burned area and number of fire events in the Great Basin, and a portion of the adjacent Mojave Desert, from 1980 to 2007. From 1980 to 1989, a total of 16,294 km^2 burned in 2139 unique events; from 1990 to 1999, a total of 28,484 km^2 burned in 3232 unique events; and from 2000 to 2007, a total of 41,326 km^2 burned in 3250 unique events. The cheatgrass-dominated vegetation type had the largest total proportional area burned relative to other cover types (montane [mountain big sagebrush], sagebrush [basin and Wyoming big sagebrush], pinyon-juniper, shrub [saltbush, creosote bush]). This burned portion of cheatgrass cover corresponded to an FRI of 78 years, while the FRI for native land cover ranged from 169 to 1946 years (Balch et al., 2013).

Across the contiguous United States, increasing human ignitions interact with climate and land cover change to increase fire frequencies and fire season length (Cattau et al., 2020, 2022). The Great Basin is seeing rapid human population growth, as Utah, Idaho, and Nevada were the nation's first-, second-, and fifth-fastest growing states, respectively, between the 2010 and 2020 censuses (Mackun et al., 2021). Accompanying that growth is increased use of the public lands where most of the region's wildfires occur. For example, the USDI Bureau of Land Management (BLM) estimates recreation visitor-days rose by 35% in Idaho and 59% in Utah between 2020 and 2021 (BLM, 2021, 2022a). Analysis of the relationship between population growth and rangeland condition in the three counties in the region with the highest human population growth rates (Ada County, ID; Tooele County, UT; and Lyon County, NV) found that climate and wildfire were the strongest drivers of rangeland degradation (Requena-Mullor et al., 2023). Bradley et al. (2018) found that in the Great Basin, human ignitions started 75% of the 19,492 fires in areas with ≥15% cheatgrass cover but just 27% of the 24,584 fires in areas with <15% cheatgrass cover. Human-ignited fires in areas with ≥15% cheatgrass cover burned significantly earlier in the season (mean burn date July 19) than human ignited fires in other land-cover types (mean burn date July 29). Human-caused fires in areas with ≥15% cheatgrass were more likely in the summer, especially on July 4 (Bradley et al., 2018).

While others have documented dramatic changes in fire regimes for portions of the Great Basin over the last 40 years (Menakis et al., 2003; Pilliod et al., 2017), we offer an analysis of fire regime changes within a broad historical context of over 100 years for the various vegetation types occurring in the Great Basin. Having this context can aid the interpretation of the changes and help to identify potential sources of how, where, and why fire regimes change.

Our overarching objectives were to determine how fire regimes have changed in the Great Basin by examining fire regime characteristics over the past 60 years (availability of recorded measurements) and historical fire frequency, and to explore potential drivers of change. Specifically, we (1) quantify fire regime characteristics (area burned, number of fires, average fire size and max fire size) from 1961 to 2020 for the study area; (2) compare fire frequency in contemporary (1991–2020), recent past (1961–1990), and historical (prior to Euro-American settlement) time periods for important and widespread Great Basin plant communities over time; and (3) examine invasive annual grasses, climate characteristics, and human-caused ignitions as potential drivers for observed changes in fire regimes.

We hypothesized wildfire to be more frequent and larger in the contemporary time (1991–2020) than in the recent past (1961–1990) across vegetation types because of increases in flammable nonnative annual grasses, a changing climate, and human populations in the Great Basin. We also expected more frequent fire in the contemporary time than in the historical time period, especially in lower elevation (warmer and drier) vegetation types. We anticipated to find a fire deficit in the contemporary time periods in higher elevation vegetation types when compared with historical fire regimes because higher elevation sites have less cheatgrass and are likely still experiencing reduced fire occurrence that was associated with heavy grazing and the removal of Indigenous burning that accompanied Euro-American settlement (Baker, 1925; Farella et al., 2016; Kitchen, 2012). We expected fuel-limited vegetation types, those occupying the most arid, shallow soil, and/or saline soil sites (blackbrush, dwarf sagebrush, greasewood, saltbush) to have similar fire frequencies in the historic, recent past, and contemporary time periods because this vegetation often supports less cheatgrass cover and thus remains fuel-limited.

METHODS

Study area

The study area encompasses a total area of approximately 503,000 km^2 in the Great Basin of the United States and includes three EPA Level III ecoregions (Omernik & Griffith, 2014): SRP (54,000 km^2), NBR (140,000 km^2), and CBR (309,000 km^2). Topography in the Great Basin is characterized by mountain ranges interspersed with valleys and basins ranging in elevation from 630 m in the basins to 4340 m on the mountain tops. Most of the Great Basin is in a semiarid to arid climate with warm summers, wet springs, and cold winters. Low to mid elevations receive 152–305 mm, while mid to upper elevations receive 305–406 mm of annual precipitation (Miller et al., 2019). Higher elevation areas are cooler and receive more precipitation, and the highest elevations experience alpine climate. The proportion of precipitation falling in summer increases on a gradient moving from the northwest toward the southeastern part of the basin. Given the varied topography, the varying moisture gradient from west to east, and the influences of geology and soil characteristics, the flora is highly variable across the region (Miller et al., 2019).

Data sources and analysis

Several publicly available data sources were used for the analysis. We used the LANDFIRE (http://landfire.gov) BpS spatial layer (LANDFIRE, 2020a) and models (LANDFIRE, 2020b), which represent the vegetation and fire regimes that were likely dominant on the landscape prior to Euro-American settlement (Rollins, 2009). LANDFIRE's BpS is derived from both the current biophysical environment and an approximation of the historical disturbance regime (Blankenship et al., 2021) and can therefore be interpreted to be similar to the reference condition concept in ecological site descriptions (Caudle et al., 2013). Each mapped BpS has an associated BpS model that is used to estimate its pre-colonization mFRI based on the best available data and expert judgment (Blankenship et al., 2021). These estimates of fire frequency include the influence of Indigenous burning if known. The data used to build these models, including information about Indigenous burning, varied by BpS type and is reported in the BpS description document that accompanies each model (Blankenship et al., 2021). We used BpS because they represent the potential vegetation which we assume has remained essentially constant over the time period of study from pre-Euro-American colonization to the contemporary time period. To reduce the number of vegetation types in this study, we combined BpS types into BpS groups composed of similar vegetation and with similar pre-Euro-American fire regimes as determined and used by the Fire Effects Information System (FEIS, 2022). For BpS types not included in FEIS groupings, we lumped the very few remaining BpS types using dominant vegetation and similarity of FRIs reported in LANDFIRE BpS models (see data deposition at https://doi.org/10.6084/m9.figshare.26832169.v2). All spatial analyses were performed using ArcGIS software by ESRI (ESRI, 2015).

Fire perimeter data from 1961 to 2020 were obtained and combined from three sources: the comprehensive western American/Canadian fire dataset 1880–2018 (Welch, 2021), BLM fire perimeter dataset 1878–2020 (BLM, 2022b), and Monitoring Trends in Burn Severity burned area perimeter dataset 1984–2020 (MTBS, 2022). We used the dataset compiled by Welch (2021) for fire perimeters 1961–2018 and complemented it with fire perimeters from the BLM (2022b) and MTBS (2022) for the 2019–2020 period. We acknowledge that these fire perimeter data do not capture all small fires nor some low-severity fires, and we further acknowledge that there are unburned areas within the mapped fire perimeters.

Annual herbaceous cover averaged from 2016 to 2018 was obtained from the Rangeland Analysis Platform (RAP) (Allred et al., 2021) and is described by Maestas et al. (2020). RAP was developed per request from the Western Governors Association-appointed Western Invasive Species Council to serve as a toolkit for nonnative annual grass management across the Western United States (Maestas et al., 2020). We used the Fire Program Analysis fire-occurrence database (FPA FOD, Short, 2022) from 1992 to 2020 to examine current fire ignition patterns by cause (human vs. lightning). FPA FOD provides a point location for each fire and was used instead of the combined fire perimeter dataset because it included the cause of each fire.

To verify that climate change is likely to influence changes in Great Basin fire regimes, we obtained measurements of vapor pressure deficit (VPD), a climate variable used as an indicator of wildfire risk (Hegewisch & Abatzoglou, 2024; Jain et al., 2022), mean temperature, and mean precipitation. Climate data was obtained from the Climate Toolbox (Hegewisch & Abatzoglou, 2024) specifically for the Great Basin study area during May–September, the season when fires occur in the region. Trends in VPD, temperature, and precipitation over time were statistically evaluated with regression analysis.

We analyzed fire regimes for 11 BpS groups that occupied at least 1% of the area within the CBR, NBR, or SRP ecoregions (Table 1, Figure 1). These BpS groups cover 95% of the burnable area within SRP, NBR, and CBR ecoregions. Areas currently classified as agriculture, water, rock, and barren were excluded from the analysis encompassing 8% of the CBR, 16% of the NBR, and 39% of the area within the SRP ecoregion. The most common BpS groups were the Basin and Wyoming big sagebrush shrubland (29%), mixed dwarf sagebrush shrubland (22%), Saltbush shrubland (17%), Mountain big sagebrush shrubland (10%), Greasewood shrubland (5%), Great

TABLE 1 The Biophysical Settings (BpS) groups investigated in this study and the proportion of the burnable area they occupy in the Central Basin and Range (CBR), Northern Basin and Range (NBR), and the Snake River Plain (SRP) ecoregions.

	CBR		NBR		SRP		Total	
Vegetation types	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Basin and Wyoming big sagebrush	3,937,961	16	5,256,151	43	2,295,099	72	11,489,211	29
Mixed dwarf sagebrush	5,441,101	22	3,470,395	28	103,548	3	9,015,044	22
Saltbush	6,568,086	27	212,364	2	121,106	4	6,901,556	17
Mountain big sagebrush	1,602,210	7	1,916,945	16	432,755	14	3,951,910	10
Greasewood	1,901,400	8	365,948	3	15,031	0	2,282,379	6
Great Basin pinyon-juniper	2,010,307	8	132,098	1	3425	0	2,145,830	5
Big sagebrush semidesert	1,546,434	6	102,692	1	945	0	1,650,071	4
Blackbrush	918,318	4	1	0	0	0	918,319	2
Low-elevation riparian	466,274	2	238,290	2	198,069	6	902,633	2
Quaking aspen	196,473	1	508,956	4	19,703	1	725,132	2
Western juniper	181	0	92,844	1	423	0	93,448	0
Total burnable area	24,588,745		12,296,684		3,190,104		40,075,533	

Note: Each of these BpS groups occupied at least 1% of the area within at least one ecoregion.

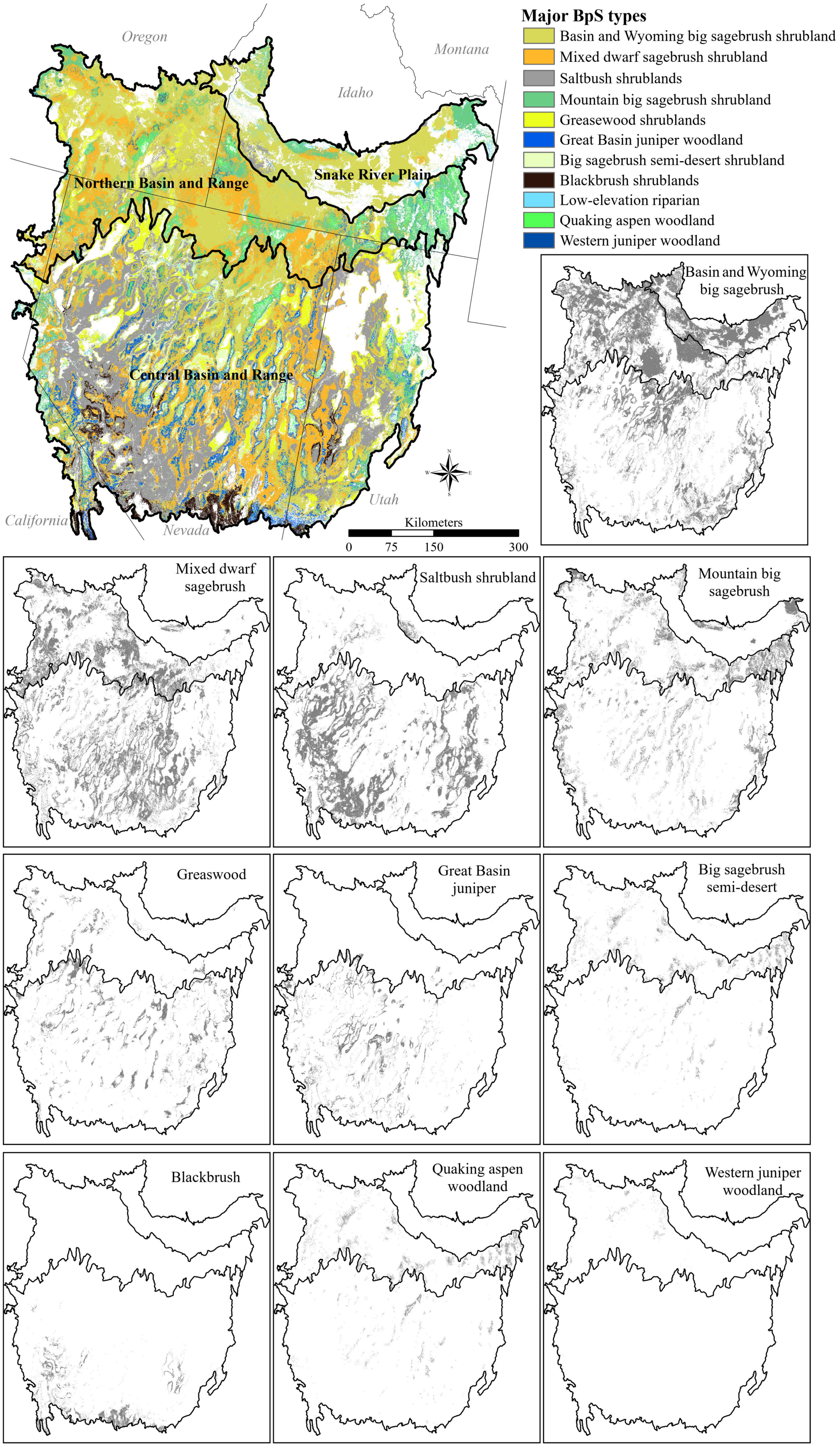

FIGURE 1 Major Biophysical Settings (BpS) groups in the study area as mapped from LANDFIRE BpS layer. Lands currently classified as agriculture, water, rock, and barren are excluded from analysis. The extent of each BpS group included in our analysis is illustrated separately.

Basin pinyon-juniper woodland (5%), Big sage semidesert shrubland (4%), Blackbrush shrublands (2%), Low-elevation riparian (2%), and Quaking aspen woodland (2%). We also included Western juniper woodland because it is an important BpS group in the NBR ecoregion (Table 1, Figure 1). For a list of all BpS groups occurring in the study area and the proportion of the area they occupy in the CBR, NBR, and SRP, see data deposition at https://doi.org/10.6084/m9.figshare.26832169.v2.

Vegetation (BpS groups)

Basin and Wyoming big sagebrush shrublands occur on shallow to deep well-drained loam to sandy soils at low- to mid-elevation (900–2100 m) sites where average annual precipitation ranges from 180 to 360 mm or more. Mixed dwarf sagebrush shrublands, dominated by low-growing shrubs like *A. arbuscula* and *A. nova*, grow in shallow soils. The stony loam to clay soil depths are often restricted by claypan or bedrock layers. This type occupies a large elevation range of 230–3000 m where sites receive 150–760 mm of annual precipitation. Saltbush shrublands dominated by *Atriplex confertifolia* and other drought- and salt-tolerant shrubs grow in fine-textured alkaline and saline soils often with low infiltration rates. Saltbush shrublands occupy hot, dry, low-elevation sites (1160–1980 m) where annual precipitation can be as low as 130 mm. Mountain big sagebrush shrublands grow in moderately deep to deep loam soils at elevations above 1000 m where the climate is cool and average annual precipitation ranges from 300 to 890 mm. Greasewood shrublands occupy saline soils with shallow water tables that experience intermittent flooding even though they grow in arid (100–200-mm annual precipitation) locations at elevations of 1160–1770 m. Great Basin pinyon-juniper woodlands support several juniper (*Juniperus* spp.) and pinyon (*Pinus* spp.) species, but in our study area *J. osteosperma* is the most common juniper species. This woodland type occupies rocky or gravelly sandy loam to clay soils within a 1000–2700 m elevation range in warm, dry habitats where average annual precipitation ranges from 300 to 460 mm. These woodlands occupy areas where ecological site characteristics and historical disturbance regimes allow woodlands to develop into a late successional stage; sometimes these areas are referred to as persistent woodlands. Persistent woodlands are ecologically different from wooded shrublands that developed after Euro-American settlement (Romme et al., 2009). Big sagebrush semidesert shrublands are dominated by Wyoming big sagebrush and occupy moderately deep to deep (>460 mm), well-drained loam soils at the 900–2100 m elevation range where annual precipitation is less than 250 mm. These shrublands are distinct from the other big sagebrush vegetation types because they generally lack the precipitation to support trees. Blackbrush shrublands (*C. ramosissima*) occupy soils with a shallow restrictive layer within an elevation range of 670–1980 m where annual precipitation averages 120–300 mm. Blackbrush shrublands are restricted to the CBR. Low-elevation riparian vegetation is tree-dominated (*Alnus*, *Betula*, *Populus*, *Salix* spp.) with a diverse shrub component. This type occurs on alluvial deposits with seasonal flooding at elevations of about 600 m and higher. The quaking aspen woodlands (*P. tremuloides*) occur on various soil types from about 910–3050 m in elevation. Western juniper woodlands (*Juniperus occidentalis*) commonly occur in shallow and often rocky soils from 610 to 1800 m in elevation where mean annual precipitation ranges from 250 to more than 380 mm. The western juniper woodland BpS group refers to persistent woodlands and does not include areas encroached by juniper following Euro-American settlement. Western juniper woodlands were largely restricted to the NBR and thus only analyzed for that ecoregion. The authors note that the LANDFIRE estimated area of the western juniper woodland BpS group is likely an underestimation for the Owyhee mountains and part of eastern Oregon (E. Strand & R. Miller, personal communication, August 2023). The data deposition at Data Figshare Repository (2024) https://doi.org/10.6084/m9.figshare.26832169.v2 provides climate, soil, and elevation characteristics associated with each BpS group as reported by LANDFIRE and FEIS.

Fire regime characteristics and time periods

We compared fire regime characteristics (fire size, mFRI, repeat burn area) between three time periods. We used LANDFIRE's definition of the pre-Euro-American colonization period, which is generally defined as prior to 1900 (Blankenship et al., 2021), and the historical period hereafter. The period 1961–1990 is referred to as the recent past. This time frame began with the first availability of reliable fire perimeter data from the BLM and the USDA Forest Service (USFS) and ended with the last time the global average temperature was within ±0.25°C of the mid-20th century average (The Learning Network, 2023). We call 1991–2020 the contemporary period, a time period characterized by consistent global warming (IPCC, 2023; The Learning Network, 2023).

Changes in area burned, number of fires, average fire size and max fire size were compared between the recent past and the contemporary time period using the combined fire perimeter dataset described in "Data sources and analysis" above. Significance of change between the two time periods was determined using a *t* test (SYSTAT, 2009) between the recent past and the contemporary time period. Fire size is the area included in the mapped fire perimeter. Fire perimeter data for the historical period was not available for the analysis of area burned, number of fires, or fire size.

mFRI for the historical period was obtained from the LANDFIRE BpS models (LANDFIRE, 2020a). For BpS types that were grouped, we applied the mFRI of the most widespread BpS type in the ecoregion to the group. The mFRI for the recent past and the contemporary time periods was determined from spatial overlay analysis between annual fire perimeters and the BpS group layer according to guidelines in the FRCC Guidebook (2010). The area burned for each BpS group within each of these two periods was summarized and divided by the length of the time period (30 years for each of these two time periods) to obtain the average area burned per year over the recent past and contemporary time periods. The mFRI was calculated by dividing the total area of the BpS group by the average area burned within the period (FRCC Guidebook, 2010). The calculation was done separately for each of the three ecoregions.

Repeatedly burned area by BpS group and by ecoregion was estimated from the combined fire perimeter dataset using ArcGIS (ESRI, 2015). The fire perimeters for all years (1961–2020) were spatially combined using the *union* command and then split using the *multipart to singlepart* command. The number of times an area occurred within a burn perimeter was determined using the *join* command. Repeatedly burned area for each BpS group was determined by ecoregion to evaluate if some types are more prone than others to repeated burning within the evaluated period. We identified the proportion of each BpS group supporting high (>15%) cover of annual herbaceous cover. The mean and SD of annual herbaceous cover were summarized by the number of times areas burned within the period 1960–2020 using the *zonal statistics* tool in ArcGIS (ESRI, 2015). The area with more than 15% annual herbaceous vegetation by BpS group was estimated using the *tabulate areas* tool.

Ignitions by cause

We spatially overlaid the FPA FOD points from 1992 to 2020 with our ecoregions to calculate the number of ignitions and area burned by ignition cause. We assumed that all area burned within the ecoregion that each point intersected. We used Theil-Sen's slope to determine if there were trends in lightning-and human-caused ignitions over time by ecoregion and tested for significance with the Mann–Kendall test using the Kendall function in the R spatialEco package (Evans & Murphy, 2021). Following the methods of Balch et al. (2017), we defined fire season length as the interquartile range of the burn day of year and used the ratio of human to lightning-caused fires to measure the percent season expansion. We buffered developed areas (LANDFIRE, 2020c) and major roads (ESRI, 2021) by 400 m and overlaid the FPA FOD to calculate the number of ignitions by cause within and outside of the 400 m development buffer. We used a χ^2 test to test the null hypothesis that there is no difference in fire cause near development or major roads for each ecoregion.

RESULTS

Change in area burned, number of fires, average fire size, and maximum fire size

Annual area burned, number of fires, average size of fires, and maximum fire size increased throughout the three ecoregions between the recent past and contemporary time periods (Figure 2). A statistical comparison of the annual area burned (Figure 2a), number of fires (Figure 2b), and average (Figure 2c) and maximum (Figure 2d) fire size suggests larger ($t = 4.45$, $p < 0.001$) and more numerous fires ($t = 2.81$, $p = 0.007$) are contributing to an increased annual area burned ($t = 4.32$, $p < 0.001$) and increased average fire size ($t = 5.80$, $p < 0.001$) when comparing the contemporary and recent past time periods (Figure 2a–d). The change in maximum fire size between the two time periods is particularly noteworthy. In the recent past, maximum fire size was generally 5000–25,000 ha with an occasional fire size larger than 50,000 ha, while fires of 100,000 ha or larger occurred in 11 of 30 years in contemporary time.

Changes in fire frequency

Identifying changes in current fire frequency is best accomplished with a record of current fires at least as long as the historical mFRI and ideally longer (Figure 3a–c). The 60-year record of recent and contemporary fires allows us to detect when fires are becoming more frequent relative to historical, but it makes it difficult to detect when fires are becoming less frequent given that most BpS groups in the Great Basin have historical mFRIs greater than the period of record. Acknowledging this limitation, we present results for all BpS groups, regardless of the historical mFRI, to allow for the detection of more frequent fire in

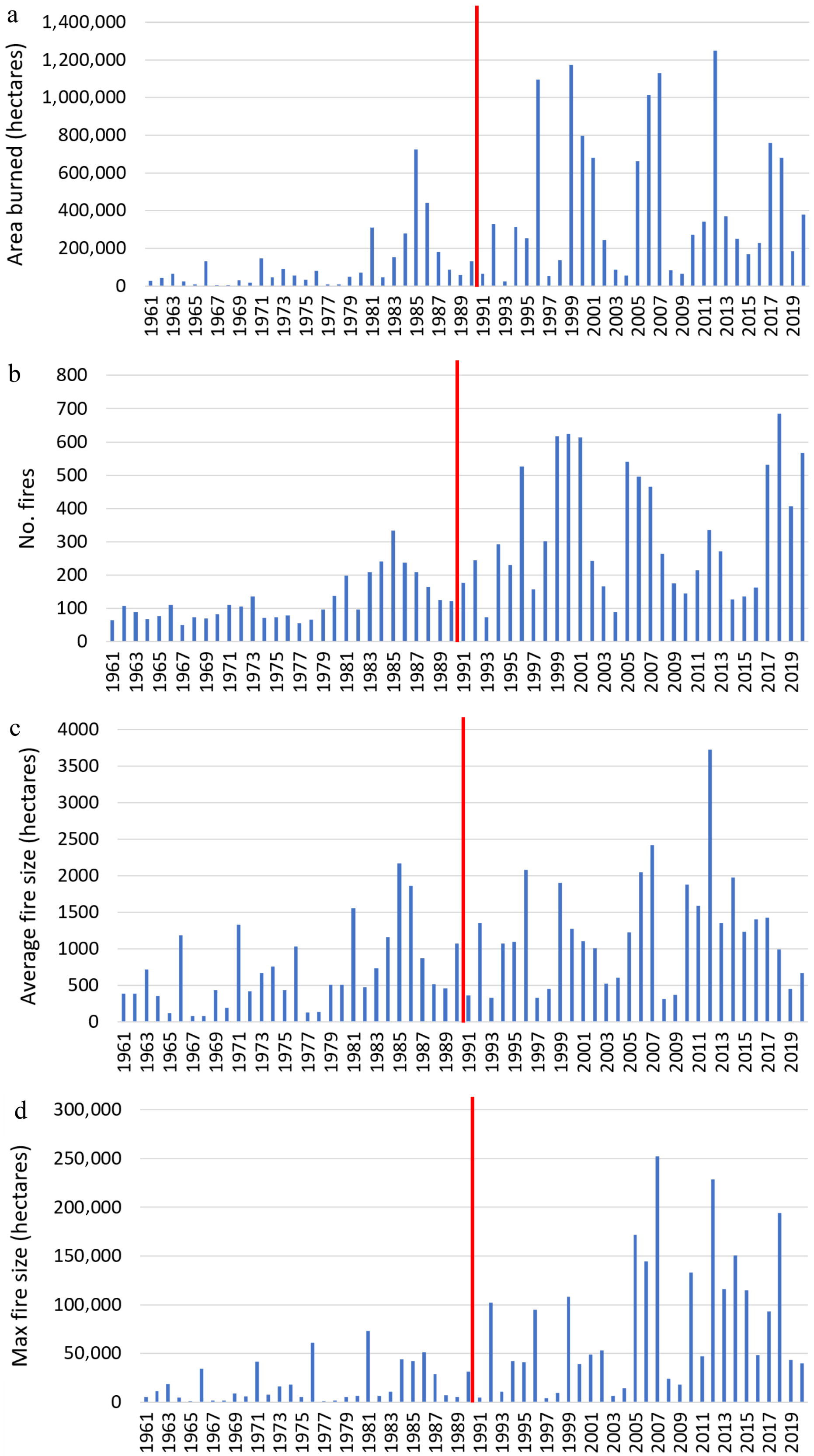

FIGURE 2 (a) Area burned, (b) number of fires, (c) average fire size, and (d) maximum fire size by year has increased when comparing annual values between the recent past and the contemporary time periods. Red vertical lines indicate the division between the recent past (1961–1990) and the contemporary period (1991–2020).

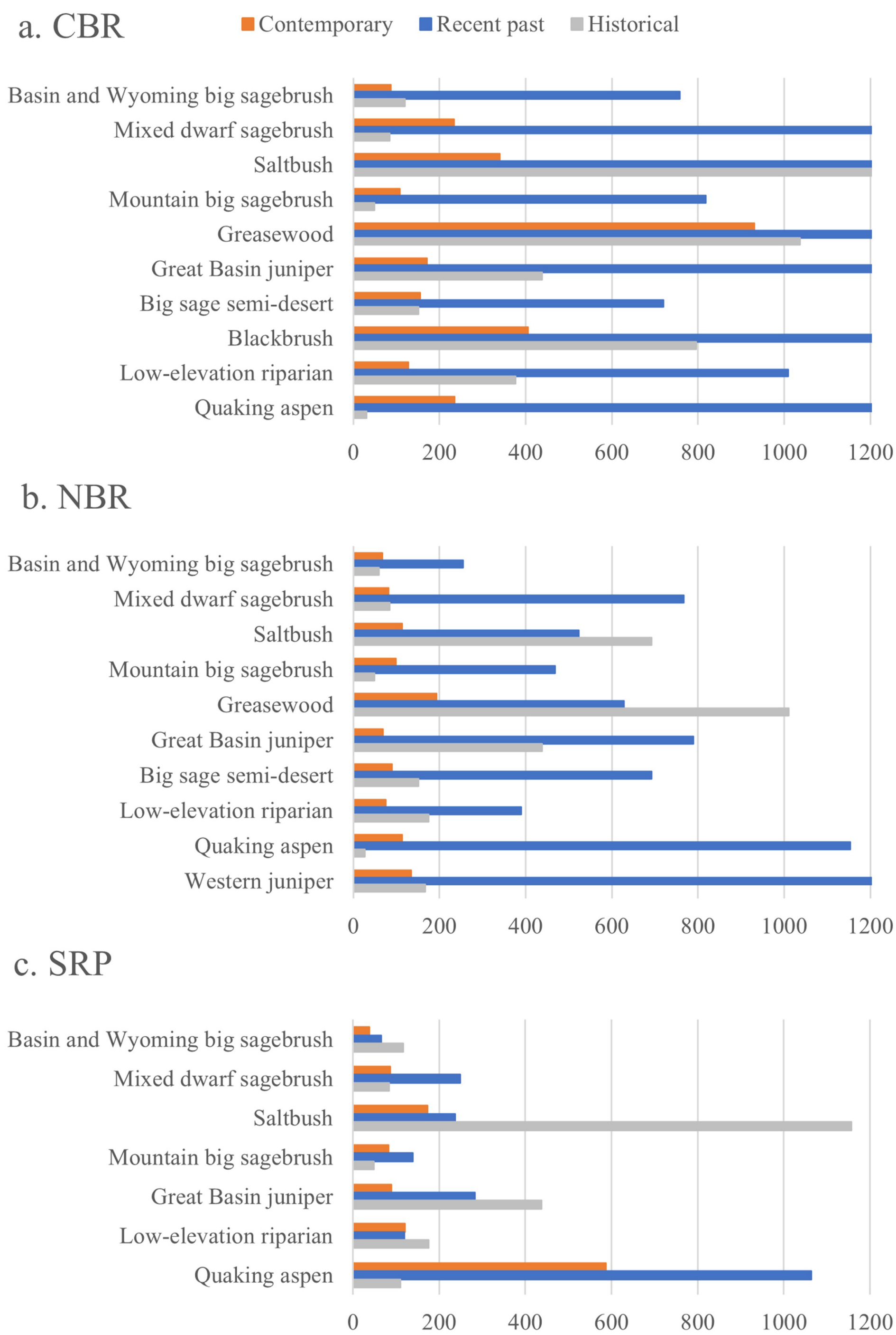

FIGURE 3 Mean fire return interval (in years) for major Biophysical Settings (BpS) groups in the (a) Central Basin and Range (CBR), (b) Northern Basin and Range (NBR), and (c) Snake River Plain (SRP) ecoregions by historical (before 1900), recent past (1961–1990), and contemporary time (1991–2020) periods. Longer bars mean less fire comparatively, and shorter bars mean more fire comparatively. Note that the historical fire return interval for quaking aspen includes historical low and moderate severity fires.

the recent past and contemporary periods compared with historical, and to show trends in mFRI between the recent and the contemporary period. While we are cautious when inferring results of lengthening mFRIs relative to historical, without the comparisons made here, we risk missing signals of change.

For most BpS groups throughout the study area, fire was a relatively rare occurrence in the recent past. Frequency increased from the recent past to the contemporary for all BpS groups except Low-elevation riparian in the SRP, where frequency was relatively constant between the two periods. In the CBR, fire was more frequent for 6 of 10 BpS groups when comparing contemporary to historical. In NBR, the two most widespread BpS groups (i.e., Basin and Wyoming big sagebrush and mixed dwarf sagebrush) had contemporary mFRIs similar to those of historical, and 6 of 10 BpS groups showed a two- to six-fold increase in fire frequency in contemporary time from historical. In the SRP, fire frequency increased for most BpS groups in both the recent and contemporary periods relative to historical.

BpS types with higher contemporary fire frequency compared with historical estimates

In the SRP, fires were approximately two times more frequent in the recent past and three times more frequent in the contemporary period compared with the historical period for basin and Wyoming big sagebrush (Figure 3c). In the NBR, fire frequency was similar between the historical and contemporary periods (Figure 3b), and in the CBR, fires in the contemporary period were more frequent than in the historical period for basin and Wyoming big sagebrush (Figure 3a). However, in the NBR and CBR, there was less fire (mFRI three and six times longer) in the recent past compared with historical estimates for basin and Wyoming big sagebrush (Figure 3a,b).

Contemporary fires were nearly two times more frequent in NBR compared with historical fires for big sage semidesert shrublands (Figure 3b). In the CBR, where this type is concentrated, fire frequencies were similar for the contemporary and historical times (Figure 3a). In both NBR and CBR, there was less fire (mFRI about six times longer) for big sage semidesert shrublands in the recent past than historically (Figure 3a,b).

In all ecoregions, fire was six to seven times more frequent in contemporary time than historically in saltbush shrublands (Figure 3). In greasewood shrublands in the NBR, fires were five times more frequent in contemporary than historical times (Figure 3b). In greasewood shrublands in the CBR, there was a slight increase in fire frequency between contemporary and historical times (Figure 3a); this may represent a trend toward more fire, given that the increase was registered over the 30-year contemporary assessment period.

Historically, fires in Great Basin pinyon-juniper woodlands had an estimated mFRI of ~400 years. The contemporary mFRI estimate for Great Basin pinyon-juniper woodlands is 100–150 years in NBR and CBR (Figure 3a,b) However, in the recent past, there was less fire in these woodlands compared with historical, with recent past mFRIs estimated at ~800 years in NBR and over 1000 years in CBR (Figure 3a,b).

BpS types with lower or similar contemporary fire frequency compared with historical estimates

Fires were less frequent in mountain big sagebrush when contemporary (~100 year mFRI) and historical (<50 year mFRI) times were compared (Figure 3). Fire frequency for mountain big sagebrush shows much longer mFRIs (several centuries for CBR and NBR) compared with historical mFRI estimates. Contemporary fire frequency estimates for mixed dwarf sagebrush in the SRP and NBR were similar to historical, ~100 years (Figure 3b,c). In CBR, the contemporary mFRI for mixed dwarf sagebrush was about double that of historical estimates (Figure 3a). In the recent past, fire frequency of mixed dwarf sagebrush showed a much longer mFRI (several centuries for CBR and NBR; Figure 3a,b).

The mFRI for quaking aspen woodlands was estimated at about 250 years in CBR and about 100 years in NBR for the contemporary period, which is longer than the historical estimates of about 30 years. In the SRP, fire also appears to be less frequent in quaking aspen woodlands when contemporary and historical estimates are compared (Figure 3). We acknowledge the difficulty in assessing historical mFRI in aspen woodlands because of the relatively short-lived aspen ramets, 100–150 years according to Shepperd et al. (2001), and the rarity of fire scars in aspen woodlands. Note that the estimated ~30--year mFRI suggested in the LANDFIRE BpS models for aspen woodlands in CBR and NBR includes all fires (e.g., low to moderate severity fires), while the replacement fire mFRI for aspen in CBR and NBR is estimated at ~70 years. Similar to mountain big sagebrush shrublands, fire frequency in aspen woodlands showed a much longer mFRI (several centuries) when the recent past was compared with historical.

Repeat fires

Our findings show that repeat fires are occurring in all three ecoregions, but areas that burned three or more times from 1961 to 2020 are concentrated in the north-central portion of the study area (Figure 4, Table 2). Areas that burned six or more times are concentrated in the SRP.

Repeatedly burned area was evaluated for each of the main BpS groups by ecoregion (Figure 5). Fire occurrence and repeated burning were less common in the CBR compared with the SRP and NBR (Figure 5). BpS groups experiencing the most reburning in the CBR were basin and Wyoming big sagebrush and mountain big sagebrush (Figure 5a). Similarly, in the NBR (Figure 5b), repeated

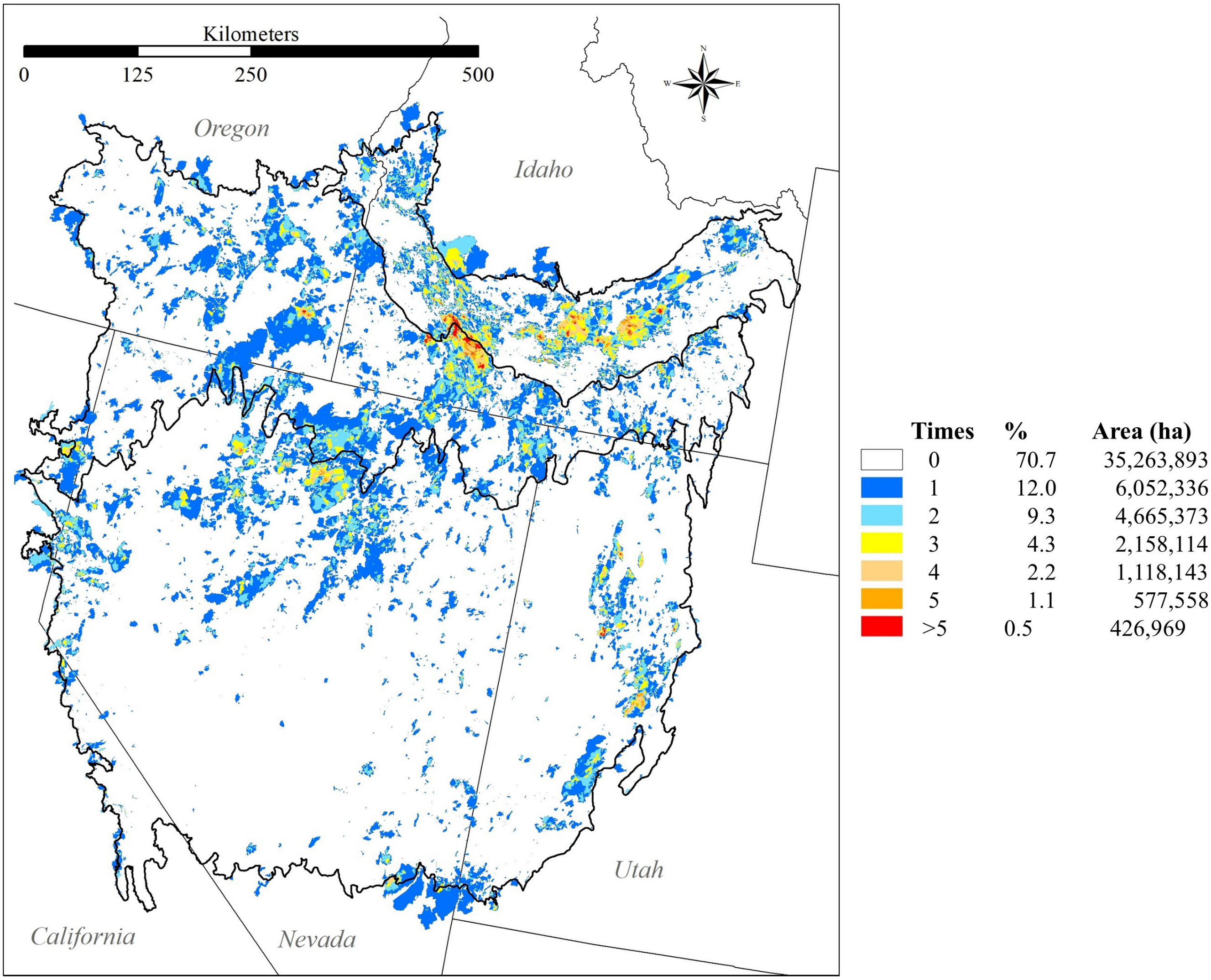

FIGURE 4 The number of times burned, area burned, and percent area burned from 1961 to –2020 in the study area. Only areas within the study ecoregions were included in calculations, but fire perimeters intersecting the ecoregion boundary are shown for display purposes.

TABLE 2 Area and percent of area repeatedly burned in the Central Basin and Range (CBR), Northern Basin and Range (NBR) and the Snake River Plain (SRP) ecoregions.

	CBR		NBR		SRP	
No. times burned	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**
0	87.1	26,889,747	69.9	9,797,028	64.5	3,457,807
1	9.2	2,836,570	21.9	3,070,172	18.1	968,778
2	2.7	842,205	5.9	831,011	8.9	477,356
3	0.7	222,375	1.5	205,739	4.9	265,169
4	0.2	68,505	0.5	66,447	2.5	132,747
5	0.1	16,591	0.2	30,138	0.8	44,884
>5	0	3032	0.1	19,273	0.3	15,913

burning was occurring in the basin and Wyoming big sagebrush BpS group and in the low-elevation riparian type. In the SRP (Figure 5c), repeated burning was observed in all BpS groups over the 60-year time period; however, most notably in the basin and Wyoming big sagebrush. Repeated burning was also occurring in the

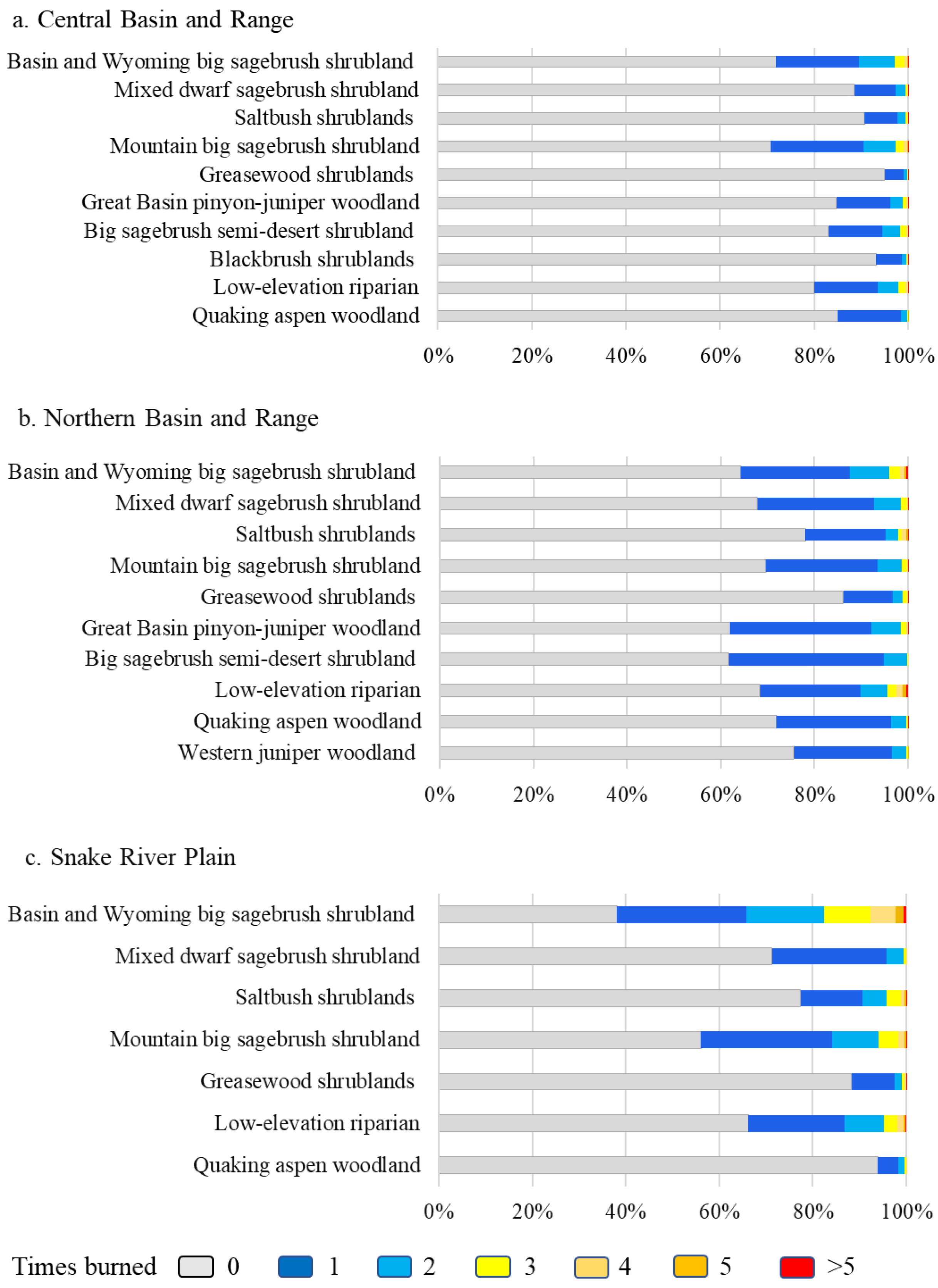

FIGURE 5 Proportion of area within Biophysical Settings groups that burned different numbers of times during the recent past and the contemporary time period (1961–2020) for (a) Central Basin and Range, (b) Northern Basin and Range, and (c) Snake River Plain.

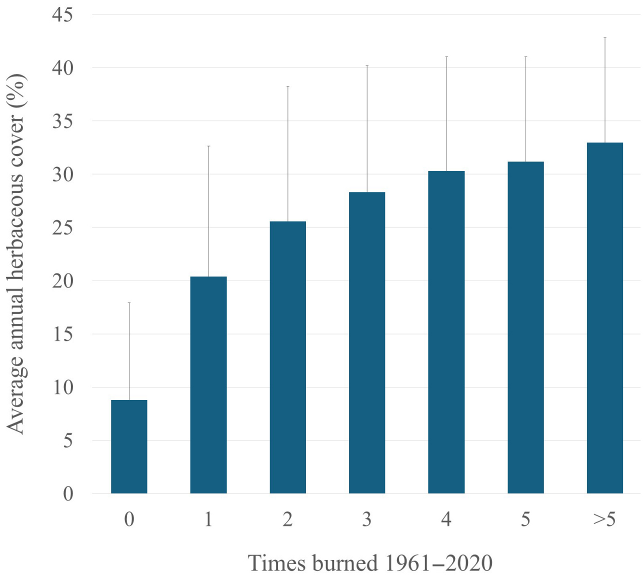

FIGURE 6 Cover of annual herbaceous vegetation 2016–2018 (Maestas et al., 2020) by the number of fires from 1961 to 2020 for the study area (mean + SD).

mountain big sagebrush and low-elevation riparian types. Quaking aspen, mixed dwarf sagebrush shrublands, and greasewood shrublands have not burned repeatedly in the SRP (Figure 5c).

Average annual herbaceous cover was higher in areas that had experienced multiple fires compared with areas that had not burned since 1960. According to the GIS overlay analysis between annual herbaceous cover and the number of times an area burned 1961–2020, areas not burned since 1960 averaged 8.8 ± 9.1% (mean ± SD) annual herbaceous cover, while areas burned one time averaged 20.4 ± 12.2% annual herbaceous cover, with increasing annual herbaceous cover the more times an area burned (Figure 6).

Drivers of change

We explored potential drivers of observed changes in fire regime characteristics, including changes in annual grass cover, climate, and ignition patterns. The amount of area with high annual herbaceous cover was greatest for those BpS groups occurring in the SRP, then the NBR, and finally the CBR (Table 3; Figure 7). The BpS groups with the greatest amount of area supporting high annual herbaceous cover included the basin and Wyoming big sagebrush shrublands, saltbush shrublands, and greasewood shrublands, which burned more frequently in contemporary times than historically (Figure 3a,b).

Analysis of the trend in VPD (Figure 8a) during the typical fire season in the Great Basin (May–September) showed an increase over time ($R^2 = 0.239$, $p < 0.001$) for data that were available starting in 1979. VPD had been higher than the 1979–2020 average in 15 of the last 21 years (Figure 8a). Mean temperature showed an upward trend ($R^2 = 0.244$, $p < 0.001$; Figure 8b), and mean precipitation showed a downward trend ($R^2 = 0.087$, $p = 0.058$; Figure 8c).

Lightning ignitions were more common than human ignitions in the CBR and NBR, but in the SRP, human ignitions were most common (Figure 9a). In all ecoregions, lightning ignitions accounted for the most area burned (Figure 9b). The number of human ignitions increased significantly over time ($p < 0.05$) in the CBR and the SRP (Figure 10a), and in all ecoregions, the number of lightning ignitions decreased significantly over time ($p < 0.05$; Figure 10b). Regardless of cause, ignitions showed a seasonal pulse in the summer months, but human ignitions started fires throughout the year (Figure 11), expanding the fire season by 164%–192% (Table 4). When the cause of human ignitions was known, equipment use, debris burning, and firearms accounted for the most ignitions (Figure 12). An overlay of developed areas and major roads with ignitions illustrates that human ignitions are more common near major roads and development. A χ^2 test of the null hypothesis that there was no difference in fire cause near development or major roads for each ecoregion was significant ($p < 0.05$) (Figure 13).

DISCUSSION

Using data from various public sources, we characterized fire regime changes in the CBR, NBR, and SRP ecoregions of the Great Basin. As we hypothesized, wildfires were generally larger and more frequent in the contemporary period (1991–2020) than in the recent past (1961–1990) across the region. Similar findings have been reported by others (Balch et al., 2013; Brooks et al., 2015). However, this pattern did not hold for all ecoregions or all BpS groups when factoring in the historical (pre-1900) time period. For nearly all BpS groups in the CBR and NBR, fires were less frequent (longest mFRIs) in the recent past than historical, but in the SRP, fires were more frequent in the recent past and contemporary periods than historical.

Fire frequency

A trend of increasing fire occurrence was found in many BpS groups in the study area when mFRIs for historical times were compared with contemporary times. In the

TABLE 3 Annual herbaceous cover by ecoregion and Biophysical Settings (BpS) groups including: (1) percentage of BpS with more than 15% annual herbaceous cover and (2) mean and SD of percent annual herbaceous cover (2016–2018, Maestas et al., 2020).

BpS group	Central Basin and Range		Northern Basin and Range		Snake River Plain	
	Percentage of area with >15% annual herb	Percent cover of annual herb	Percentage of area with >15% annual herb	Percent cover of annual herb	Percentage of area with >15% annual herb	Percent cover of annual herb
Basin and Wyoming big sagebrush shrublands	39.2	14.5 ± 12.2	48.7	16.9 ± 10.9	77.2	28.0 ± 13.7
Mixed dwarf sagebrush shrublands	14.9	7.7 ± 8.6	25.9	11.8 ± 8.6	46.3	17.7 ± 9.9
Saltbush shrublands	26.8	11.0 ± 11.5	59.2	18.7 ± 9.2	89.0	27.3 ± 9.9
Mountain big sagebrush shrublands[a]	38.9	14.1 ± 10.6	22.7	11.0 ± 7.5	33.4	13.0 ± 11.3
Greasewood shrublands	17.2	7.8 ± 6.6	38.3	14.7 ± 9.9	86.4	28.3 ± 10.6
Big sagebrush semidesert shrublands	28.9	12.1 ± 14.7	58.4	21.9 ± 15.4	NA	NA
Blackbrush shrublands	2.9	5.6 ± 4.2	NA	NA	NA	NA
Low-elevation riparian[a]	46.9	17.6 ± 13.9	47.7	18.8 ± 13.2	88.5	33.6 ± 12.7

Note: BpS groups that do not occur within an ecoregion are marked with NA.

[a]Only the treeless BpS groups and treeless portions of any BpS group were included in the annual herbaceous source map (Maestas et al., 2020), the Great Basin pinyon-juniper woodlands, quaking aspen woodlands, and western juniper woodlands were excluded from analysis.

SRP, the basin and Wyoming big sagebrush BpS group exhibited fire frequencies that were two times as frequent in the recent past and three times more frequent in contemporary times compared with historical times (Figure 3). While changes in fire frequency occurred in basin and Wyoming big sagebrush shrublands in the NBR and CBR, increases and decreases in fire occurrence over all time periods do not seem to exceed a recovery threshold for the dominant vegetation based on the recovery time for Wyoming big sagebrush (50 year lower limit) reported by Baker (2006) and are in line with mFRIs of up to 100 years reported by Mensing et al. (2006) and 50–100 years reported by Miller and Tausch (2001). Conditions in the SRP (Table 3), likely due to an abundance of cheatgrass, roadways, and human populations, are contributing to rates of fire recurrence that will likely limit recovery and persistence of big sagebrush without broadscale rehabilitation efforts (Crist, 2023; Crist et al., 2019).

Increases in fire frequency were also found in the saltbush, greasewood, and blackbrush shrublands, although the mFRI for the contemporary time periods is still on the order of centuries. We acknowledge that long mFRIs were estimated using a short temporal interval in the contemporary analysis. If increases in fire frequency continue the trajectory reported for the contemporary time period, these BpS groups and the large proportion of our study area they occupy could see future fire recurrence that potentially leads to replacement by nonnative, fire-adapted communities or monocultures, as has been observed in Mojave Desert ecosystems immediately to the south (Brooks & Matchett, 2006). The blackbrush BpS group is not fire-adapted. *C. ramosissima* is killed by fire, and reestablishment on burned sites is slow (Wright, 1972).

Both juniper woodland BpS groups burned more frequently in the contemporary period than historically. Note that areas mapped as juniper woodland BpS are the persistent woodlands where juniper or pinyon-juniper is the reference plant community. These woodlands are different from the expansion woodlands or wooded shrublands (Romme et al., 2009) where juniper has expanded into adjacent plant communities, for example, mountain big sagebrush shrublands or quaking aspen woodlands (Strand, Vierling, & Bunting, 2009; Strand, Vierling, Bunting, & Gessler, 2009; Wall et al., 2001). Increased fire frequency (shorter mFRI) in contemporary times suggests that persistent Great Basin pinyon-juniper and western juniper woodlands may experience fire frequencies that threaten their future persistence in areas where they have existed for centuries and provide critical habitat for many woodland-dependent species (Tack et al., 2023). Persistent juniper and pinyon pine woodlands have experienced contraction in recent decades due to climate change stresses and extreme wildfire behavior, causing concern about their ecological resilience (Redmond et al., 2023). Similarly, while old-growth pinyon and juniper are most likely to occur on sites with

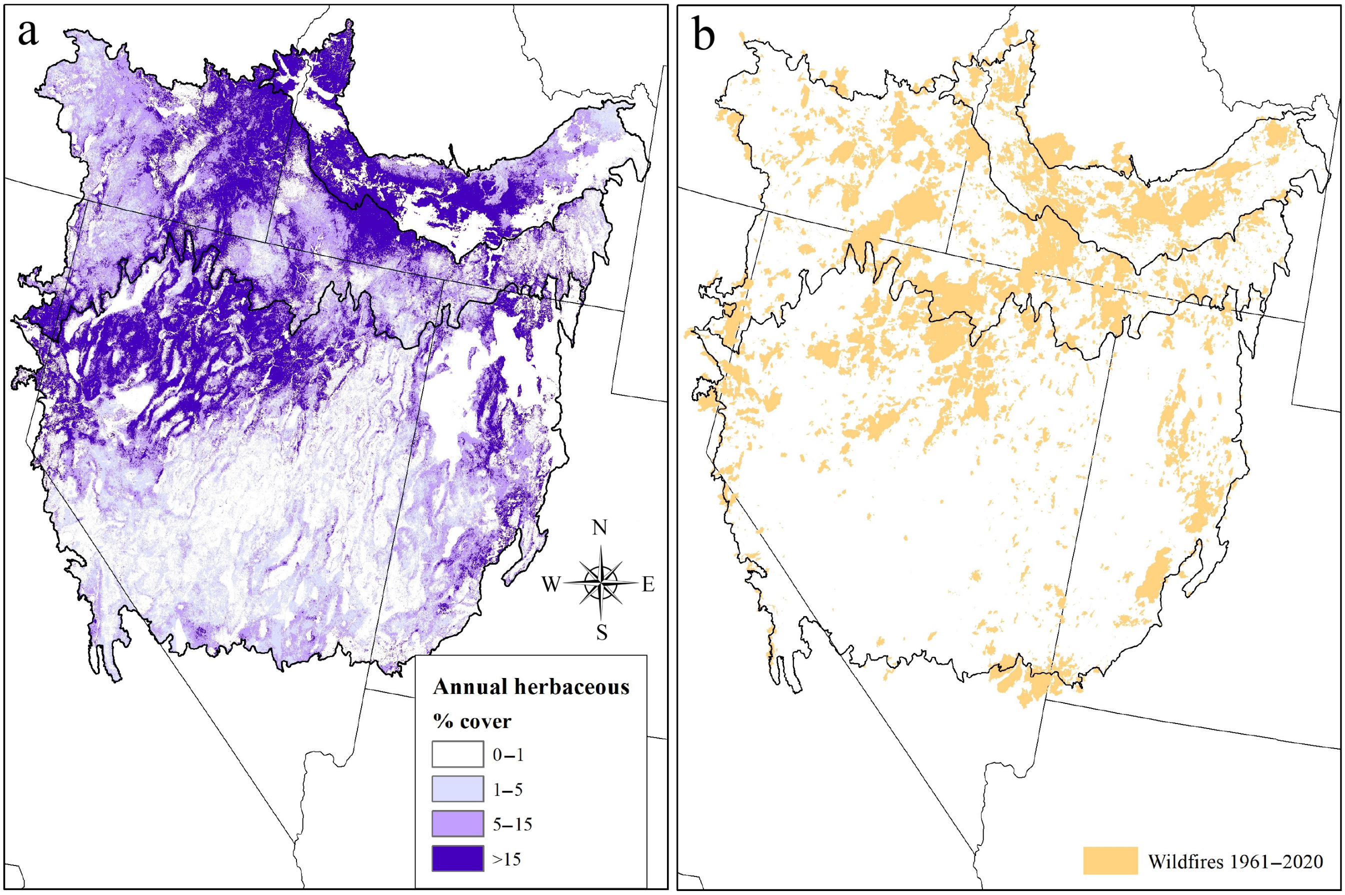

FIGURE 7 (a) Annual herbaceous plant cover (Maestas et al., 2020) for the study area from 2016 to 2018 (Maestas et al., 2020). (b) Areas that burned in wildfire 1961–2020.

low fire risk (Weisberg et al., 2008), the change in mFRI, exacerbated by drought and heat stress in a changing climate, may signal increased risk to these old-growth stands as well; see, for example, Strand and Bunting (2023). The Sagebrush Conservation Design (SCD) that provides a spatial framework for identifying and protecting sagebrush core areas from threats of fire, nonnative annual grasses, and woody encroachment (Doherty et al., 2022) provides a method that could be adapted to identify and protect vulnerable woodlands.

Fire frequency has increased in low-elevation riparian vegetation, likely because surrounding vegetation is experiencing higher fire frequencies. Low-elevation riparian vegetation that is not highly degraded or lacks an abundance of nonnative species recovers quickly following fire (Reeves et al., 2005). For this reason, increased fire occurrence in this BpS group may be a lower management priority.

Our results indicate that the two BpS groups that burned the most historically, mountain big sagebrush and quaking aspen woodlands, may be burning similarly to or less frequently today. In the mountain big sagebrush BpS group, interpretation is limited by the time period of our analysis, but a decrease in fire in this BpS group could explain at least some of the juniper expansion documented in the study area (Burkhardt & Tisdale, 1976; Miller et al., 2005, 2019). Additional research that follows the future fire frequency in mountain big sagebrush is needed to determine if this type is burning less than historically. Our analysis did reveal a clear fire deficit for quaking aspen woodlands occurring throughout the study area, especially in the CBR and NBR. Historically, the mFRI for aspen woodlands varied from a few decades to a century (Baker, 1925; Romme et al., 2001; Wall et al., 2001), with the mFRI estimate being shorter when historical Indigenous low-to moderate-severity burning is included. In the recent past, the mFRI for aspen woodlands was over 1000 years in all ecoregions. Effective fire suppression and loss of fine fuels from livestock and elk grazing pressure may explain reduced fire occurrence as well as poor recovery after wildfire (Romme et al., 1995; Smith et al., 2016) leading to a loss of aspen woodlands and successional conversion to

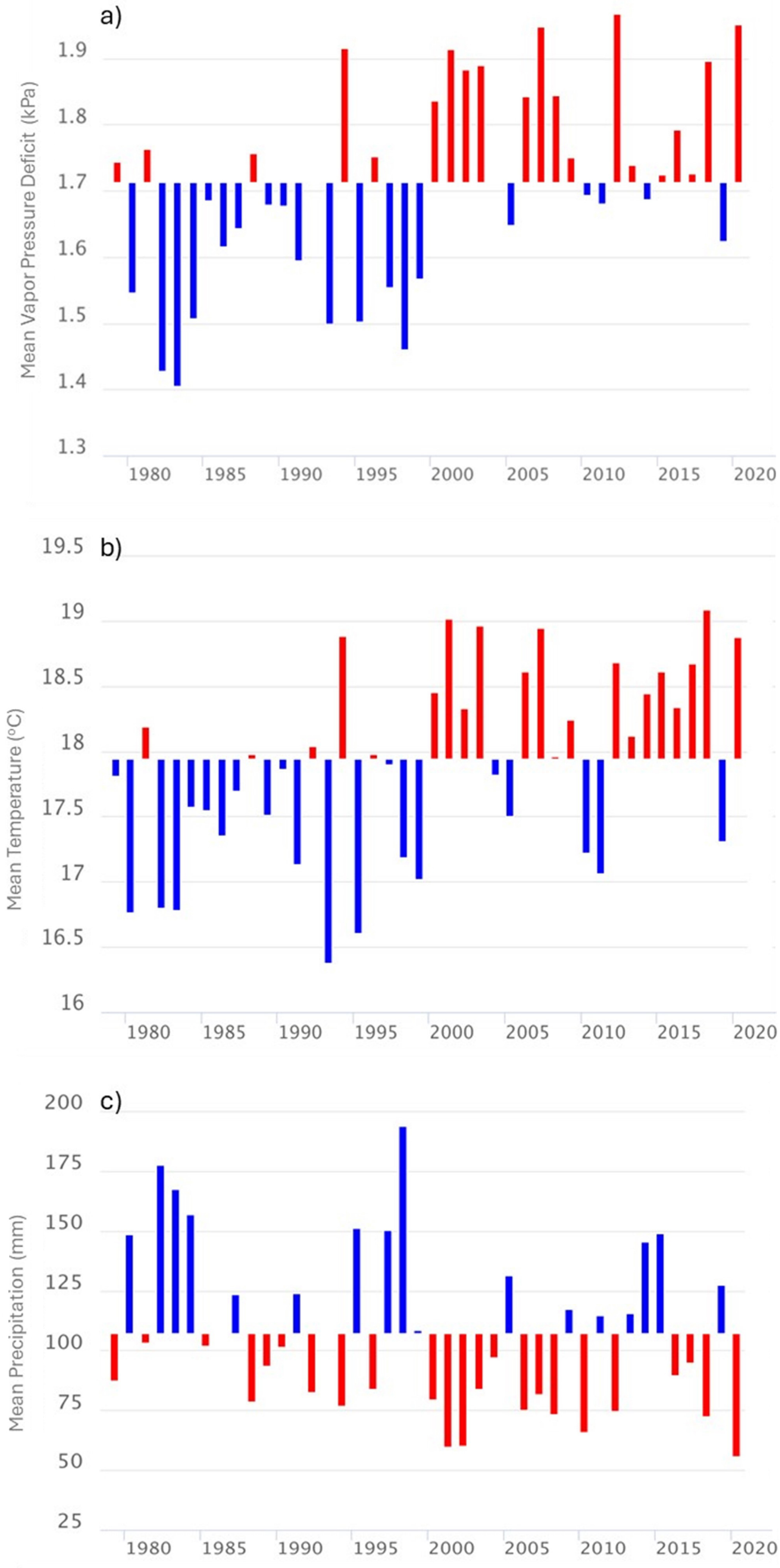

FIGURE 8 (a) Mean vapor pressure deficit, (b) temperature, and (c) precipitation during May–September for the Great Basin (coordinates 36.2684–43.6119 N, 110.9688–119.1211 W) from 1979 to 2020. Vapor pressure deficit is an indicator of fire danger (Hegewisch & Abatzoglou, 2024).

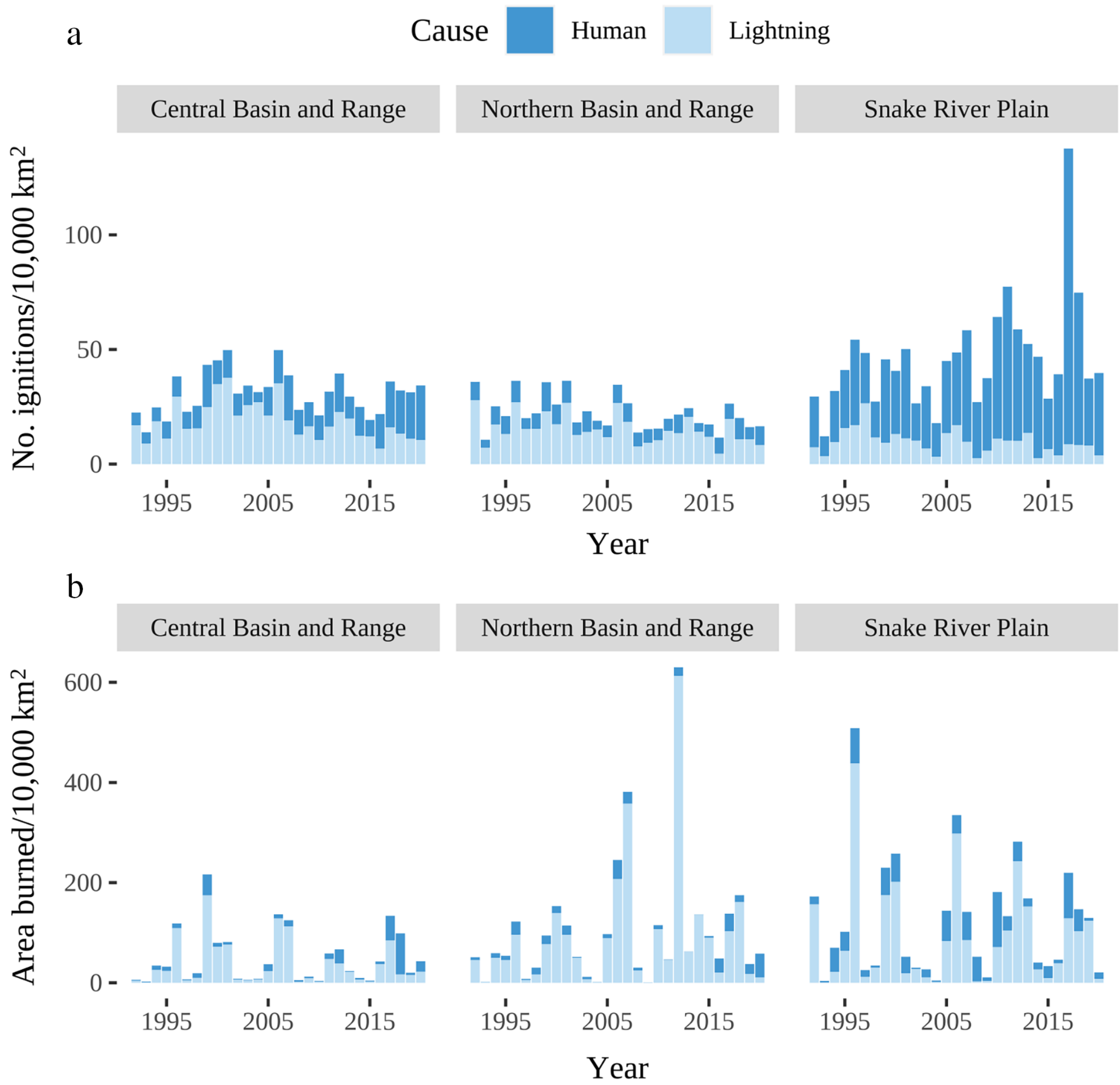

FIGURE 9 (a) Number of ignitions and (b) area burned by human- and lightning-caused fires by ecoregion from 1992 to 2020.

conifer-dominated ecosystems across the study area, as reported by others (Refsland & Cushman, 2021; Strand, Vierling, & Bunting, 2009; Strand, Vierling, Bunting, & Gessler, 2009). The 1000-year mFRI derived from reliable fire atlas data for the recent past is an extrapolation based on fire occurrence for just a 30-year time period (1961–1990). While still in fire deficit, increased mFRI in aspen woodlands in contemporary time compared with the recent past will likely result in more area in early to mid-successional stages and reduce the amount of aspen that is overtopped by conifers (Strand, Vierling, & Bunting, 2009; Strand, Vierling, Bunting, & Gessler, 2009). Differences in aspen woodland response to fire may vary by elevation and source of moisture for local aspen clones (Shinneman et al., 2013; Strand, Vierling, Bunting, & Gessler, 2009).

Repeat fires

Large expanses of the study region had burned more than once during the 60-year period of analysis for the recent past and contemporary time periods, with the area covered by repeat fires ranging from 3.7% in the CBR to 17.4% in the SRP (Table 2). It is important to recognize that the repeat occurrence of fires alone does not signal altered fire regimes. For the mountain big sagebrush BpS group, the occurrence of one to three fires between 1961 and 2020 is within the historical mFRI estimate (Figure 3). For the other BpS groups, which occupy most of the study area, the occurrence of two or more fires in 60 years exceeds what occurred historically. The basin and Wyoming big sagebrush BpS groups that are most susceptible to invasion by annual grasses experienced the

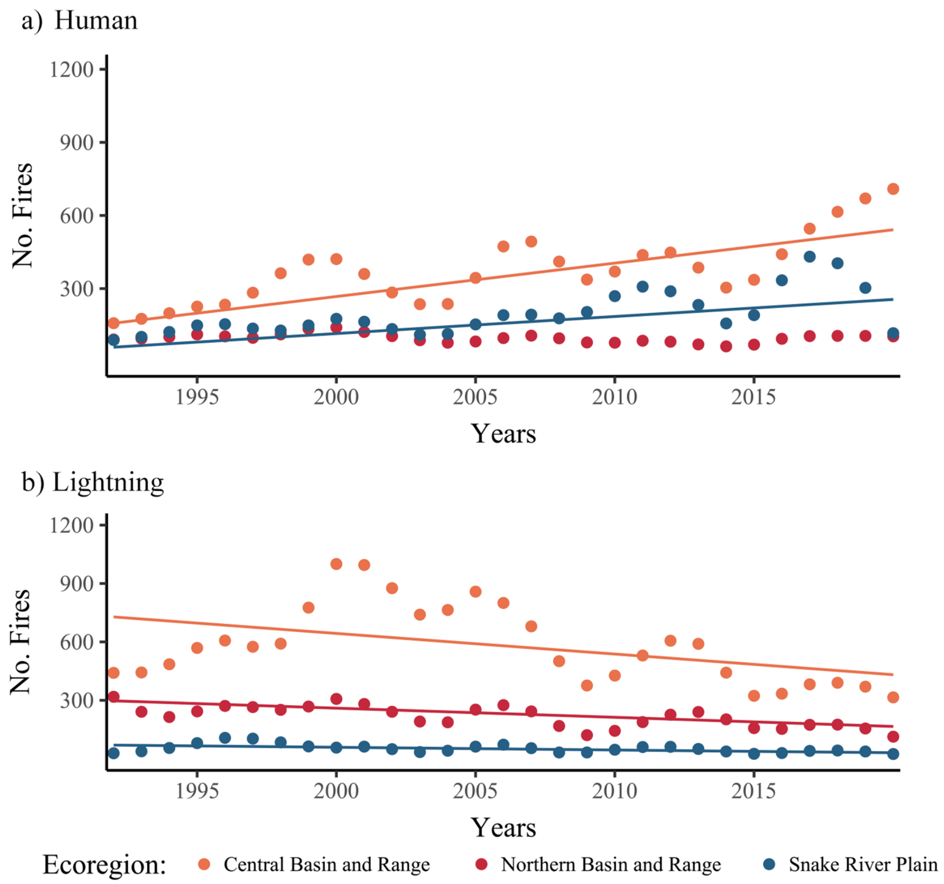

FIGURE 10 Number of (a) human- and (b) lightning-caused fires by ecoregion from 1992 to 2020. Lines show where trends are significant ($p < 0.05$).

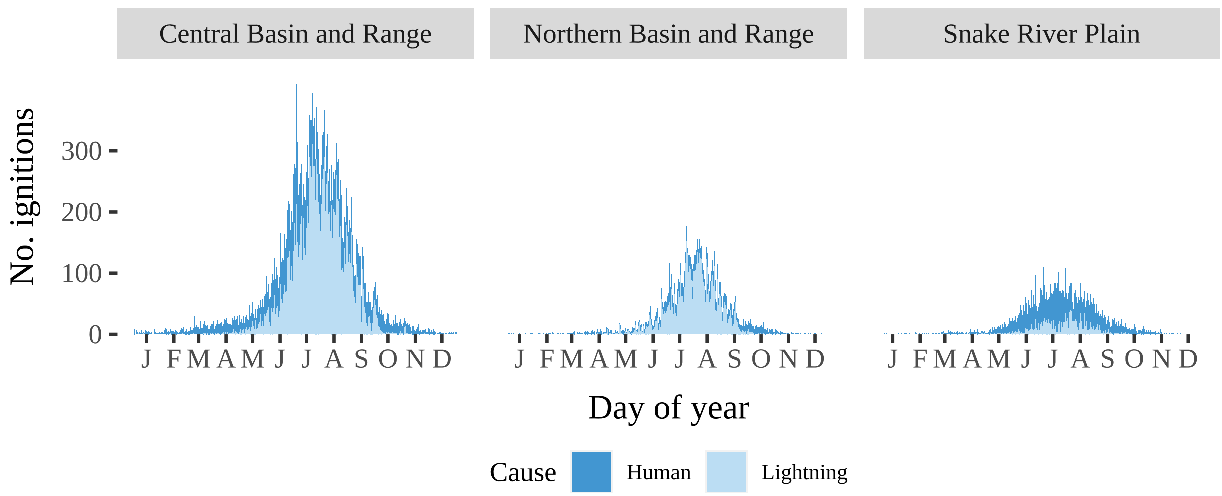

FIGURE 11 Number of ignitions caused by humans and lightning per day by ecoregion from 1992 to 2020.

most repeated burning. Repeat fires were most common in the SRP and the northern portion of the NBR (Figure 4), the same region with the highest annual herbaceous cover (Figure 7). We acknowledge that a recent (2016–2018) snapshot of annual herbaceous cover data (Maestas et al., 2020) does not allow for a direct correlation between contemporary area burned and annual herbaceous cover. It does, though, provide supporting evidence that high annual herbaceous cover is contributing to and resulting from repeat burning, since high

TABLE 4 Number of fires, area burned, and fire season length (in number of days) by ignition cause for the Great Basin and its three ecoregions from 1992 to 2020.

	No. fires		Area burned (ha)		Fire season length (no. days)		
Ecoregion	**Human**	**Lightning**	**Human**	**Lightning**	**Human**	**Lightning**	**Human expansion (%)**
Central Basin and Range	10,899	16,739	1,092,917	3,349,632	179	109	165
Northern Basin and Range	2792	6225	528,232	3,746,750	142	85	167
Snake River Plain	5647	1498	517,338	1,413,968	139	73	192
Great Basin	19,338	24,462	2,138,487	8,510,350	154	89	173

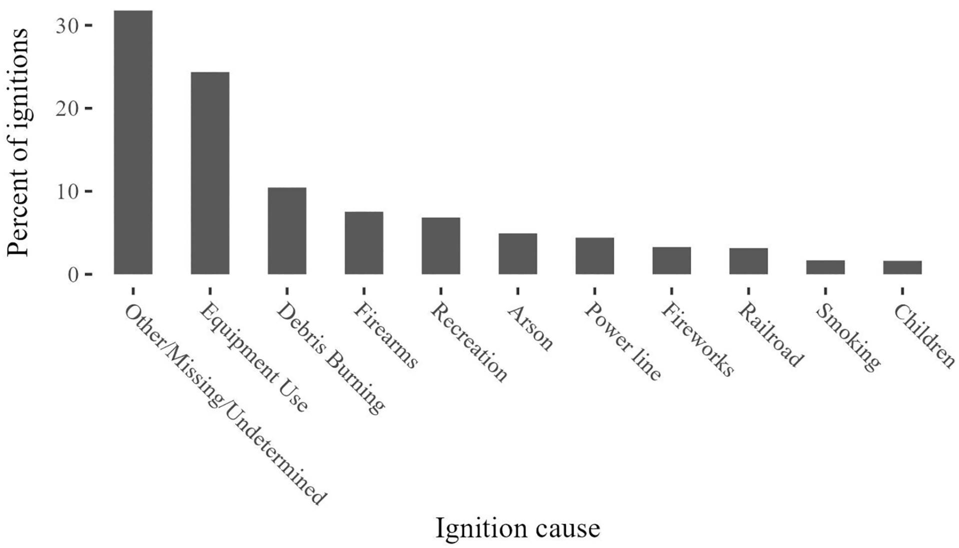

FIGURE 12 Percent of human ignitions by cause for all ecoregions from 1992 to 2020.

annual cover is concentrated in the BpS groups with increased fire frequency (basin and Wyoming big sagebrush shrublands, saltbush shrublands, and greasewood shrublands).

Another factor likely contributing to increased fire occurrence is the observed changes in climate over the study period. VPD and average temperature during fire season (May–September) have increased significantly over the study period. VPD is calculated from temperature and relative humidity and is the difference between the actual amount of water vapor in the air and the amount of water vapor the air can hold when saturated. VPD increases with higher temperature and lower relative humidity, conditions linked to drought and increased flammability of vegetation (e.g., Burton et al., 2023; Seager et al., 2015).

Ignition sources

As hypothesized, fire regime changes in the study region were associated with nonnative annual grasses and anthropogenic ignitions. Until relatively recently (Balch et al., 2013, 2017), sources of ignition have not been investigated to any large degree for rangeland wildfires. Fuels and the proliferation of nonnative herbaceous vegetation, associated with moisture availability and disturbance, have been the focus of most fire regime studies in western rangeland ecosystems because they are the side of the fire triangle that we can most easily control (Maestas, Smith, et al., 2022; Scasta et al., 2016). This focus has neglected the other side of the fire triangle that is at least partially within human control: ignitions. A paleoecological study has shown that throughout history, ecosystem transitions globally are most rapid and persistent where landscape flammability is increased by human activities (McWethy et al., 2013). Rapidly increasing (Requena-Mullor et al., 2023) human populations contribute to both fire ignitions and the spread of annual grasses, which will likely expand the area impacted by the self-perpetuating cycle of nonnative grasses fueling frequent fires. Increasing VPD and a warming climate likely contribute to increased flammability and area burned. This grass-fire cycle associated with extreme

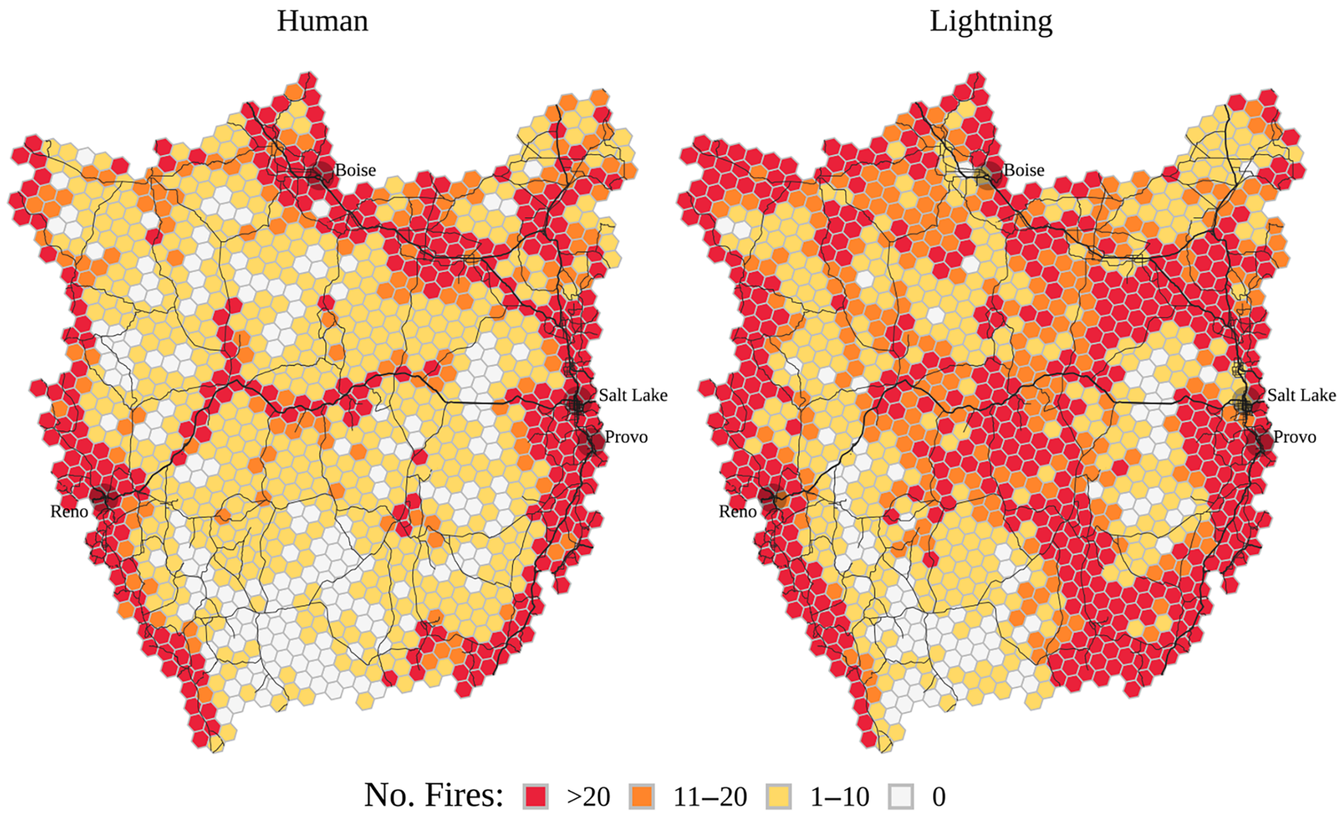

FIGURE 13 Number of (a) human- and (b) lightning-caused fires for all ecoregions from 1992 to 2020 (hex cells are 500 km^2). Human ignitions were more common within 400 m of development and major roads.

degradation of native ecosystems is a critical concern in human-dominated areas within the Great Basin (Shinneman et al., 2023).

In this research, we addressed several fire regime characteristics, including fire size, fire frequency, and ignition risk; however, other characteristics of fire, such as the season of burn, burn patchiness, and burn severity, also determine fire effects and postfire recovery and needs for rehabilitation. Fire pattern research addressing additional fire regime characteristics is warranted to fully understand how fire contributes to changing the Great Basin landscape.

MANAGEMENT IMPLICATIONS

The Great Basin region covered by this research consists primarily of public lands managed by the BLM, USFS, and other federal and state agencies that conduct extensive efforts to address factors leading to a surplus or deficit of wildfire. Many of these activities focus on the fuels side of the fire triangle, including vegetation removal projects, especially in forests and areas of recent woodland expansion, invasive species treatments, and the creation of a large network of fuel breaks (Crist et al., 2019; Shinneman et al., 2023). To reduce human ignitions, state highway departments conduct mowing and prescribed burning projects along roadways, and federal and state fire and lands agencies invest millions in public awareness campaigns (Prestemon et al., 2010; Storey et al., 2020). By documenting changes in fire frequency and size in all major vegetation types across the study region, our research affirms the rationale for these intensified efforts.

Yet even with such a high level of current attention to the region's wildfire challenge, the scale of the problem exceeds our current capacity to address it. Wildfires pose threats to lives, property, and livelihoods in a region where nature-dependent industries such as ranching, forest products, and outdoor recreation/tourism remain economically vital (Brunson & Tanaka, 2011). These risks occur across vegetation types, but fuels reduction and fire suppression efforts have been directed more toward forest than non-forest types (Crist, 2023). Our results suggest that greater attention should be paid to vegetation communities where the reduction in FRI is greatest, that is, sagebrush, and juniper and pinyon pine woodlands, especially in places where the risk of human ignition may be greatest.

The SCD (Doherty et al., 2022) that builds on the "Defend the Core" approach (Maestas, Porter, et al., 2022) provides a solid basis for choosing where to target fuel-reduction activities but does not offer a landscape-scale approach to prioritization of fuel-reduction treatments. By characterizing changes in fire regimes for different ecoregions and BpS groups, our research offers guidance for prioritizing those protective efforts for effective use of scarce resources, allowing managers to make informed decisions about how best to apply the Resist-Accept-Direct framework (Schuurman et al., 2021; Shinneman et al., 2023) that is increasingly used in federal agency planning (NPS, 2024).

While fire occurrence is increasing in most BpS groups from 1961–1990 to the 1991–2020 time period, the aspen woodland BpS group's contemporary mFRI estimates are approaching those of the historical time period. In aspen stands, a return to a fire regime with more frequent fires as well as improved postfire recovery is possible where elk numbers are relatively low and cattle grazing can be closely managed (Durham & Marlow, 2010; Smith et al., 2016). For the mountain big sagebrush BpS group, we need more time to assess if this group is experiencing less fire than historically. Nevertheless, aspen woodlands and mountain big sagebrush communities may be low priorities for investment in fuel-reduction efforts except when the goal is to protect human settlements or when the plant community is altered to a degree that fire resilience is lost or reduced.

Fuels management efforts already prioritize the basin and Wyoming big sagebrush BpS group (Shinneman et al., 2023), and this research underscores the continued need to do so. We also found reduced mFRI in greasewood, saltbush, blackbrush shrublands, and persistent juniper woodlands that have not received as much management attention and are likely less resilient to wildfire. While fuels reduction is already a high priority for juniper encroaching into sagebrush as a method for conserving sagebrush communities, our research suggests that particular attention also be given to protecting persistent and old-growth woodlands.

Our findings also underscore the importance of anthropogenic ignitions coupled with flammable invasives like cheatgrass in changing Great Basin fire regimes. While government agencies invest heavily in public education, these campaigns may benefit from specific targeting of this outreach to focus on non-recreational sources such as equipment use and debris burning that are the most frequent types of human-caused ignition. Agencies also try to regulate behavior by imposing restrictions on human activities when wildfire risk is high; this research can help land managers target the places where restrictions are needed most.

CONCLUSIONS

As reported by previous researchers, this research affirms that more frequent and repeated fires are occurring where nonnative annual grass cover is high and human population effects (e.g., increased road density) are greatest. In our analysis of fire occurrence, repeated fires, nonnative species, and ignition sources, we add to the existing body of work by comparing current trends to historical reference conditions under which native ecosystems evolved and by examining changes by vegetation type. In some areas, increased fire occurrence is a concern, but this is not true everywhere; in fact, aspen woodlands may benefit from more fire based on our estimates of their historical fire regimes. Changes in fire regimes are greatest in the northern part of the study region, where not only is there a higher cover of nonnative annual grasses, but also larger human populations to provide an ignition source. Knowledge about the variation in fire regime changes across the region can help rangeland and forest managers better deploy resources to protect ecosystems and human values.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sets utilized for this research are as follows: LANDFIRE (http://landfire.gov) Biophysical Settings spatial layer (LANDFIRE, 2020a) and models (LANDFIRE, 2020b). Fire perimeter data: Welch (2021) (https://cedar.wwu.edu/wwuet/1031), BLM fire perimeters (https://catalog.data.gov/dataset/blm-natl-fire-perimeters-polygon), and Monitoring Trends in Burn Severity (https://www.mtbs.gov/direct-download). Annual herbaceous cover as described by Maestas et al. (2020). Fire Program Analysis fire-occurrence database: https://doi.org/10.2737/RDS-2013-0009.6. Climate data from the Climate Toolbox: https://climatetoolbox.org/. Data describing the biophysical setting group classification (Gucker et al., 2024) are available from Figshare: https://doi.org/10.6084/m9.figshare.26832169.v2.

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