



Article Pyrogeography of the Western Great Plains: A 40-Year History of Fire in Semi-Arid Rangelands

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Abstract: This study describes spatial and temporal patterns in fire across the US Western Great Plains over the last 40 years. Although pyrogeographic studies have explored the nexus of fire patterns in relation to the bio-physical environment and socio-ecological trends, most of this research has focused on forested ecosystems and regions long known for conflict between wildfires and human development, especially at the wildland-urban interface. But evidence suggests large wildfire activity is increasing in the US Great Plains, and the Western Great Plains—a Land Resource Region comprised of four ecoregions, Northwestern Plains, High Plains, Nebraska Sandhills, and Southwestern Tablelands-not only contains some of the largest areas of rangeland in the US but also the highest concentration of public land in the Great Plains. As such, the Western Great Plains provides an opportunity to explore fire activity in primarily rural landscapes with a combination of public and private ownership, all dominated by rangeland vegetation. We combined several publicly-available datasets containing fire records between 1992 and 2020 to create two databases, one with georeferenced point data on 60,575 wildfire events in the region, and another with georeferenced perimeter data for 2665 fires. Ignition by humans was the dominant cause of fires. No ecoregion showed a statistically significant trend towards either increasing or decreasing the annual burned area. The Northwestern Plains had the most burned area and the greatest number of incidents—consistently around or above 1000 incidents per year since 1992-with the majority in July. The High Plains showed the greatest increase in annual fire incidence, never reaching more than 200–300 per year 1992-2009, and averaging above 1000 incidents per year since 2010. Few long-term trends in human population, weather, or fuel metrics appear strongly associated with fire patterns in any ecoregion, although the years 2006, 2012, and 2017 stood out for their levels of fire activity, and these years often frequently logged extreme values in wildland fuel metrics. These relationships merit much closer examination in the Western Great Plains, because like other rangeland-dominated landscapes, the fine fuels that comprise these wildland fuelbeds are much more responsive to fine-scale changes in moisture conditions. Rural Western Great Plains landscapes are a mosaic of public and private land ownership, and an increasing impact of wildfires on public grazing lands-which are often situated within other jurisdictions or ownership—will likely have an impact on rural livelihoods.

Keywords: climate-fire; regimes; fire ecology; fire regimes; fire weather; fuels management; rangeland ecology and management

1. Introduction

Pyrogeography is the study of wildland fires at the nexus of ecology, the physical environment, and human cultures and societies [1]. Fire has certainly been a driver of ecological patterns and processes since the evolution and spread of grass-dominated *open ecosystems*, but humans have had greater influence over fire regimes as population density and technology have increased [2,3]. Today, where and when a fire starts, spreads, stops—and resists stopping—in developed countries like the US is strongly affected by humans [4,5].



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). But changing human activity is just one example of global change affecting fire regimes from local to global scales; humans have long driven, responded to, and almost always interacted with other global change factors such as climate and land cover alterations [6–8].

The occurrence, type, frequency, and spatial extent of wildland fires are controlled by several environmental factors that are often modulated by global change and human activity. At the most basic level, fire is a *sustained exothermic reaction* that depends upon oxygen, fuel, and heat [9]. In the wildland fire environment, vegetation serves as fuel and thus the nature of the vegetation—grassland or forest, overall amount of growth, moisture content—strongly determines the nature of the fire [10]. Climate factors determine the amount and type of vegetation in a region, while weather influences how dry, hot, or windy the local environment is in the event of an ignition [11–14]. Ignitions provide the initial heat for combustion, introduced naturally by lightning or, increasingly, sparks and escaped fires from other human activities. Herbivory—from livestock, wildlife, and insects—can interact with climate to determine the overall amount of fuel available at any given time.

Because weather involves several correlated measurements that can interact with fuel properties at different time scales, composite variables often better describe the net impact of weather on potential fire activity than individual parameters [5]. The US National Fire Danger Rating System [15] uses several such variables. Respectively, the *Energy Release Component* and the *Burning Index* reflect the amount of potential energy available for release by combustion, and the relative difficulty of fighting such a fire once ignited; each of these values integrates short-term weather factors by considering weather from the previous seven days [16]. Likewise, *100 h fuel moisture* considers the moisture content of large (2.5–7.6 cm [17]) fuel particles, which are subject to multi-day lags in moisture loss and absorption. Finally, the Hot-Dry-Windy Index [18] combines wind speed—which drives fire spread—with Vapor Pressure Deficit, which correlates well with fuel aridity [19]. Conveniently for pyrogeographers, all the necessary variables have been available across most of the conterminous United States for the last several decades, at daily increments and at 4 km resolution, through products like gridMET [20].

In addition to environmental factors, human activities have a high degree of control over fire regimes. Humans alter fuel availability through land use like farming and grazing management, regulate connectivity through landscape fragmentation and infrastructure development, and can both suppress fire spread and introduce ignition sources through recreation, resource use and management activity, and arson [21]. In the continental USA, humans are the dominant cause of wildfires, accounting for four times as many large wildfires—defined as the top 10% of fires in every ecoregion—as lightning, and increasing the occurrence of fires under fuel and weather conditions that likely would not facilitate lightning ignitions [22]. Other studies have specifically attributed large wildfires and extreme fire behavior to human-caused ignitions [5,23]. These influences of humans on fire patterns are important because the severity of human-caused fires on infrastructure and property is increasing [24].

Persistent literature gaps suggest that the Western Great Plains sub-region of the United States (Figure 1) is overdue for the lens of pyrogeography. A US-scale analysis focused specifically on the ecological effects of large wildfires did not include the Great Plains [25]. After decades of focus on forested ecosystems, wildland fire science is casting a broader look across the conterminous US [26]. But as a semi-arid region dominated by perennial rangeland vegetation (Figure 2 and Table 1), the Western Great Plains are situated between research-heavy areas like the annual grass-invaded deserts to the west [27,28] and mesic grasslands undergoing row-crop conversion and woody plant encroachment to the east [29,30]. While the region is occasionally captured on the eastern and western edges of geographic fire analyses of the western US and Great Plains, respectively (e.g., [31,32]), most research focused on rangelands of the western Great Plains concerns itself with water and grazing management [33–35].



Figure 1. The study region. (**Left**) The four EPA Level III ecoregions within the Western Great Plains Land Resource Region. (**Right**) State codes and select urban areas within the study region. **Inset:** The Western Great Plains Land Resource Region (blue) within the broader Great Plains Level I ecoregion (light grey), within the continental US (dark grey).



Figure 2. Proportion rangeland cover (**Left**) and mean annual precipitation (**Right**) for the Western Great Plains. Dark points indicate urban areas with >2500 residents.

A distinct Land Resource Region in the central US extending east from the base of the Rocky Mountains—and thus subject to the rain shadow—the Western Great Plains are dominated by semi-arid rangeland vegetation (68–92%, Figure 2 and Table 1); although the Nebraska Sand Hills averages above the 500 mm upper range of semi-arid precipitation, the predominantly sandy nature of these soils limits plant-available moisture and sustains semi-arid grassland communities. To account for considerable latitudinal variation in the region, our analyses separately consider four ecoregions within the Western Great Plains

(Figure 1). All four ecoregions are dominated by grasses with woody plants comprising only 10% of the vegetation across all four ecoregions. But shrubs increase and can even become dominant in the absence of fire and grazing.

 Table 1. Mean proportion rangeland cover and mean annual precipitation (1980–2019) for four Level

 III ecoregions within the Western Great Plains Land Resource Region. See Table A1 for data sources.

Ecoregion	Proportion Rangeland (%)	Precipitation (mm)
Northwestern Plains	80	410
Nebraska Sand Hills	92	538
High Plains	68	392
Southwestern Tablelands	90	356

Reconstructions of precolonial fire regimes indicate fairly frequent fires across the western Great Plains. Most of the region had an average fire return interval of 8–12 years with localized areas of 15–22 years in the far north and areas with rough topography and easily eroded soils and landforms in central and western locations [36]. Most lightningcaused fires occurred in the late summer dry season although indigenous burning was concentrated in the spring and fall [37]. Native Americans in the Great Plains burned extensively for bison drive lines, farming, fighting, and many other purposes, to the extent that while the region is considered to have strong weather-driven fuel patterns, precolonial human populations shaped fire regimes that Euro-American settlement substantially altered [37]. Fire interacts with drought and herbivory to drive vegetation dynamics in the region. Historically, fires were patchy with unburned areas within fire perimeters because of extensive wildlife—bison, prairie dog, antelope—and insect—grasshopper, mormon cricket, Great Plains locust-grazing reducing fuel load heterogeneously across the landscape [38,39]. The replacement of bison with cattle and other domestic livestock in the region likely changed fire regimes by altering the nature of fire-grazing interactions as sedentary cattle replaced free-roaming bison [40]. However, the nature of this change is not well understood because of incomplete records of bison and livestock abundance. Fire size was variable but tied to drought, with larger fires occurring in years where high precipitation preceded a year of intense drought [36].

A baseline understanding of the pyrogeography of the region is a necessary first step to understanding how land use and climate might interact to drive fire regime changes in the future and predicting ecosystem responses to those changes. We use publicly available data on historical wildland fire locations, human population trends, weather, and vegetation cover to explore pyrogeographic relationships between fire activity and the biological, physical, and human environments. We seek to describe spatial and temporal patterns in fire frequency and burned area to better understand the impact of fire in these landscapes, and we explore broad relationships between fire activity and environmental, as well as socio-ecological, variables to account for historical variability.

2. Materials and Methods

2.1. Data Employed

This project relies entirely on publicly available, spatially discrete data understood to be correct and current when accessed in November–December 2022. A complete list of data sources, time periods, and references are provided in Table A1. Except where specifically stated otherwise, data wrangling and analyses were conducted in the R statistical environment [41].

2.1.1. Study Region

Our spatial delineation of the Western Great Plains is based on the USDA Natural Resource Conservation Service's Western Great Plains Land Resource Region. Sub-regional delineations are based on the US Environmental Protection Agency's Level III Ecoregions within the Western Great Plains, especially the Northwestern Plains, Nebraska Sandhills, High Plains, and Southwestern Tablelands Figure 1.

We obtained human settlement and population data from the US Census Bureau (Table A1). The location and extent of regional urban areas (>2500 persons in 2020) were obtained with the urban_areas function in the *tigris* package for R [42]. Human population trends were assessed with total population data from 2000, 2010, and 2020 decennial censuses extracted at the tract level with the get_decennial function in the *tidycensus* package for R [43].

2.1.2. Environment and Land Cover

Average annual precipitation for the study period was calculated from monthly weather data obtained for each census block centroid from the TerraClimate dataset, 1980–2020, via the getTerraClim function in the *climateR* package for R ([44], Table A1).

Historical weather data relevant to fire activity were obtained for each census block centroid from the gridMET dataset, 1980–2020, via the *climateR* getGridMET function (Table A1). Daily records for the following variables were retrieved for each centroid: precipitation, wind speed, vapor pressure deficit and three derived variables used in fire risk assessment and suppression effort, including 100 h time lag fuel moisture content (the amount of moisture contained in fuel particles 2.5–7.6 cm diameter), Energy Release Component (potential energy available for release per unit area by flaming front at head of fire), and Burning Index (a measure of the effort required to contain a fire based on fireline intensity) [15]. Vapor pressure deficit and wind speed were multiplied, as their product has utility in summarizing atmospheric contributions to fire behavior at synoptic scales in the Hot-Dry-Windy Index [18]. While our study area is dominated by 1-h fuels, the gridMet dataset provides only 100 h time lag fuel moisture content values; 100 h fuels are not immediately responsive to drought and will only begin to lose moisture after prolonged exposure to drought, thus patterns in 100 h fuel moisture might not precisely represent the fuel moisture of the predominantly fine fuelbed in our study areas. However, fuel moisture is an important variable, and therefore, we included the available 100 h fuel moisture content data as they provide some indication of fine-fuel moisture content and are the only ubiquitous available measure of fuel moisture across the region.

To broadly characterize vegetation within each ecoregion, general land cover data were obtained from the US Forest Service's Extent of US Rangelands raster product (Table A1). This product classifies each 30×30 m pixel in the continental United States as open rangeland, transitional or afforested rangeland, non-rangeland, or other specific classes including water, development and agriculture [45]. The proportion cover was summarized as a non-water area classified as rangeland within each census block using the extract function in the *terra* package for R [46].

More specific vegetation cover data for individual fire events were retrieved from the Rangeland Analysis Platform (https://rangelands.app (accessed on 22 November 2022), version 3 [47]). The Rangeland Analysis Platform applies a machine learning algorithm to remotely sensed data to generate plant cover estimations for 30×30 m pixels across the United States. We used *terra* extract to retrieve the mean cover of Perennial herbaceous vegetation (perennial grasses + forbs), Annual herbaceous vegetation (annual grasses + forbs), Trees, and Shrubs.

2.1.3. Land Management Jurisdiction

Land under the management of state and federal agencies was identified using the US Bureau of Land Management Surface Management Agency dataset, while land under Native American tribal authority was identified in the US Geological Survey's PADUS dataset (Table A1).

We used two primary types of publicly available data on fires. The first was the sixth edition of the *Fire Occurrence Database*, which combines records from wildfire incident reporting systems used by federal, state, and local agencies [48]. While this is by far the most comprehensive list of incidents, with 2.3 million wildfire records, spatial data are limited to the point coordinates and burned area estimations filed in each report. No polygon data of fire perimeters are available in this database, which limits the analysis of vegetation and land tenureship within burned areas.

The second dataset referred to here as the *Federal Fire Polygon Collection*, we compiled by combining four publicly available datasets of fire incidence and extent that include mapped final fire perimeters as geo-referenced features for each incident. Our first source was the Monitoring Trends in Burn Severity (MTBS) dataset, which maps fire perimeters based on changes in pre- and post-fire remotely-sensed vegetation reflectance metrics [49]. This was our primary data source because the burn perimeters are curated by trained specialists and events are classified as wildfires or prescribed burns. However, a limitation of MTBS data in determining fire occurrence is that in the western US, it contains only burned areas greater than 405 ha, which precludes many instances where initial attack prevented the fires from reaching such an extent. Thus, we augmented the MTBS data with three other sources referenced in Table A1: The US Forest Service's final fire perimeter polygon shapefile for the continental US, the US Bureau of Land Management's national fire perimeter polygon shapefile, and the National Interagency Fire Center's (NIFC) national polygon shapefile.

Because many events overlapped in one or more datasets, we eliminated repeat entries by, firstly, creating a list of non-overlapping events unique to each dataset in R; secondly, combining duplicate records among overlapping events that had only subtle name differences within the same year (e.g., "Experiment Station" vs. "Experimental St.") and visually inspecting attributes of remaining overlaps followed by manually identifying remaining fires in QGIS (http://www.qgis.org, (accessed on 22 November 2022) v. 3.22). When repeated records were identified, our preference for the original dataset for inclusion went USFS > BLM > NIFC to take advantage of maximum precision in ignition source information.

2.2. Data Summary and Analysis

overlapped by two or more fires.

2.2.1. Regional Trends in Fire Incidents Incidence and Burned Area

For comparison with potential explanatory variables in fire patterns, we summarized fire activity in the Western Great Plains first within US census tracts and then to EPA Level III ecoregions. Using the Fire Occurrence Database, we summarized the total number of incidents, the incident rate (calculated as total incidents divided by the geographical area), and the total burned area (calculated as the sum of incident-level burned areas in the Fire Occurrence Database). Without spatially explicit polygons for these incidents, it was not possible to account for repeated burns within the study period to determine the actual fire-affected area, a more conservative estimate than repeatedly counting areas potentially

Causes of Fires

Our analysis focuses primarily on *wildfires*—incidents that began with an unsanctioned ignition that did not meet administratively-prescribed conditions and elicited suppression action [9]. The Fire Occurrence Database was developed exclusively for wildfires and presumably includes no records of prescribed burns [48]. Within the Federal Fire Polygon Collection, only the MTBS database explicitly codes records as wildfires or prescribed burns, which in this region are primarily pre-planned, intentional ignitions for management purposes. Given the number of records in the Collection with unknown or unentered causes, we assumed these were wildfire incidents unless the name specifically included

a reference to a prescribed fire. Incidents coded as *Prescribed Fire* in the MTBS dataset and cause code # 9, *Miscellaneous*, in the USFS dataset were specifically removed from the dataset after counts by cause were visualized.

Temporal Trends

The number of wildfire incidents and burned areas in the Fire Occurrence Database were summarized, by ecoregion, both annually over time, 1992–2020, and by month over all years, 1992–2020. Similarly, *human population* and *weather* trends were plotted over time for their respective periods (2000, 2020, 2020; 1980–2020). Because the temporal analysis of fire events indicated the vast majority of fires occurred in July, we simplified the aggregation and presentation of weather data into two categories. Firstly, we summed total cumulative precipitation between January and June of each year, as an indicator of how growing season-specific potential rangeland productivity might affect fine fuel loads in July. Secondly, we summarized mean values for July records of 100 h fuel moisture, Energy Release Component, Burning Index, and Hot-Dry-Windy Index, as indicators of how potentially favorable weather and fuel were to burning each July fire season within each US census tract in each year. To test for general linear trends over the study period, we conducted a nonparametric test on Kendall's tau (τ) using the kendallTrendTest function in the *EnvStats* package for R [50].

2.2.2. Burned Area by Management Jurisdiction and Vegetation Type

Fire-specific vegetation data for each fire event were obtained from the Rangeland Analysis Platform using the coordinates of points provided in the Fire Occurrence Database and polygons in the Federal Fire Polygons Collection. To ensure the remotely-sensed data used in the computation of vegetation cover were not collected after a fire event, we extracted data from the growing season prior to each incident. For each incident, we found both the dominant vegetation cover type (the largest percentage of Perennial herbaceous, Annual herbaceous, Shrub, or Tree cover) as well as the sum of Shrub+Tree cover to assess temporal changes in fuel structure, i.e., shifts in the proportion of herbaceous fine fuel vs. coarse woody fuel.

Although limited to a fewer number of incidents, the spatially explicit perimeter feature data in the Federal Fire Polygon Collection we compiled from USFS, BLM, and NIFC fire records facilitated analysis of fire patterns across burned areas and their various management jurisdictions. Mean vegetation values for the above-mentioned variables were extracted for each jurisdiction separately within each fire perimeter.

3. Results and Discussion

3.1. Regional Fire Patterns

Information in this section refers primarily to the Fire Occurrence Database, 1992–2020 [48]. Data in the main text are mainly limited to the Fire Occurrence Database, with additional information in Appendix B. While the text draws comparisons between patterns in the Fire Occurrence Database and the Federal Fire Polygon Collection, data from this latter dataset appear in Appendix B.

3.1.1. Incidence and Burned Area General Patterns

Across each ecoregion, fires occurred in areas vegetated mostly by perennial grasses and herbaceous plants (40–60% cover, Figure A1A), consistent with the high frequency of rangeland in the region (Figure 3 and Table 2). Woody plants only accounted for 10% of vegetative cover across all ecoregions. Fire activity has been greatest in the Northwestern Plains, with over 2 million ha burned and an incident rate of 0.38 wildfires km⁻² (Figure 3 and Table 2). Most fires, however, were not large: in the Northwest Plains, the median burned area was just 0.2 ha and only 5% of fires exceeded 65 ha.



Figure 3. Regional patterns in fire activity in the Fire Occurrence Database, 1992–2020, mapped by US Census tract. Black dots indicate urban areas. (**Left**): Frequency of fire incidence; (**Right**): Total area burned (includes any repeated or overlapping fires, which cannot be distinguished from the Database).

Table 2. Fire activity statistics for the four EPA L3 ecoregions of the Western Great Plains. Fires, number of fires per km², and Burned area (ha) taken directly from the Fire Occurrence Database, which—because it does not include polygons—does not account for potential re-burns (area affected by two or more fires in the study period), and therefore, these metrics could be slightly underestimated. The t estimated percentage of ecoregion affected by fires mitigates some re-burns by fitting a uniquely-sized buffer (scaled to a radius of a circle matching the area of the final fire perimeter) around each point feature in the Fire Occurrence Database and eliminating overlapping burned area.

Ecoregion	Fires (/km ²)	Burned Area (% of Ecoregion +)
Northwestern Plains	34,069 (0.38)	2,104,345 (21.3%)
Nebraska Sand Hills	1423 (0.03)	251,136 (4.4%)
High Plains	18,807 (0.07)	342,945 (1.2%)
Southwestern Tablelands	6276 (0.1)	394,098 (6%)

Incidence rates for the other three ecoregions were 0.1 or fewer wildfires km⁻², with an average of 330,000 ha burned, and similar quantiles describe these ecoregions (Table A3). In the High Plains, median burned area was <0.1 ha and 5% of fires exceeded 12 ha. However, relatively fewer incidents in the Nebraska Sand Hills and Southwestern Tablelands increased the 95th percentiles of burned area/incident to 325 and 162 ha, respectively.

Fire activity in the Northwestern Plains appears to exceed that of other rangeland ecoregions, including areas that have become known for high fire frequency. For example, 12% of cheatgrass-dominated grassland burned over a ten-year period in the Great Basin, compared to 5% of sagebrush steppe [27]. Unfortunately, such comparisons with published literature are difficult due to a high degree of variability in the way data on fire frequencies are reported, and even which data are used to derive such statistics.

Temporal Trends

These data show no change in the annual burned area across the Western Great Plains (Figure 4A). There were no statistically significant trends in annual burned area for any of the four ecoregions Table A2). This lack of evidence for substantial increases in burned area contrasts with other reports that restricted their analysis to large fires. There is conventional



A. Annual wildfire trends

Figure 4. Temporal trends in fire occurrence and burned area for four Level III ecoregions in the Western Great Plains from the Fire Occurrence Database [48]. (A) Annual records of burned areas and fire incidences. (B) Distribution of wildfire occurrence by month through the 1992–2020 data period.

Conversely, the annual frequency of fires in most of the Western Great Plains has slightly increased since the 1990s (Figure 4A, Table A2). The High Plains showed the greatest increase ($\tau = 0.67$, p < 0.001), especially since 2012. Statistically significant, long-term increases occurred in both the Nebraska Sand Hills ($\tau = 0.47$, p < 0.001) and Southwestern Tablelands ($\tau = 0.36$, p < 0.01). Likely due to considerable annual variability, the linear trend in the Northwestern Plains does not show a statistically significant constant increase through time ($\tau = 0.17$, p > 0.05).

Several years stand out as particularly high in fire activity across the Western Great Plains; the most active years have occurred in the last decade, suggesting fire activity is increasing in the region. In a ranking of the top five years for burned area and number of incidents within each of the four ecoregions—creating a potential total of eight occurrences for any specific year—2012, 2018, and 2020 each appeared five times while 2000 and 2006 appeared four times (Table A4). Such statistics indicate these were the most fire-active years in the Western Great Plains since 1992. The Northwest Plains again stood out in terms of activity, with 389,000 ha burned in 2012 (1963 incidents) and 2148 incidents in 2017 (270,000 ha burned). The High Plains ecoregion had the highest number of incidents

in one year—3091 in 2011, which was also the most fire-active year in the Southwestern Tablelands—but the annual burned area across the region remained an order of magnitude lower outside of the Northwest Plains.

While fires have occurred throughout the year in all four ecoregions, most occur in late summer (Figure 4B). The preponderance of fires in the Northwestern Great Plains have occurred in July and August (>5000 fires/month), while slightly fewer fires have occurred in June and September. Other ecoregions were more even from month to month, with a consistently low number of incidents, although fire activity in the High Plains also peaked in July.

3.1.2. Drivers of Fire Activity

Specific Causes

Humans were the leading cause of wildfires in the Fire Occurrence Database (Figure 5). The dominance of human-caused incidents was consistent across jurisdictions identified at the coordinates in the database, including Federal, Tribal, State, and local or county ownership (Figure A2). These findings are wholly consistent with previous work attributing 80–84% of wildfires in the US to human ignitions [4,22].



Figure 5. Temporal trends in fire occurrence and burned area for four Level III ecoregions in the Western Great Plains from the Fire Occurrence Database [48]. (**Top**) Annual records of burned areas and fire incidences. (**Bottom**) Specific sources of wildfire incidents.

In perhaps the greatest discrepancy between the two datasets compiled here, a much different picture of ignition sources emerges from the Federal Fire Polygon Collection. Despite the limitations on determining causes of fires outside of those incidents recorded in the MTBS database, most of the fires recorded by federal land management agencies

in the Western Great Plains are unintentional and natural (Figure A8). The vast majority of fires in the MTBS database are coded as wildfires (706) rather than prescribed fires and unknown sources (35 each). In the USFS dataset, lightning ignitions accounted for the greatest number of fires (446). "Miscellaneous" described 112 ignitions, while together, known human-attributable causes in the USFS dataset sum to just 123 incidents. The ratio of lightning to human and miscellaneous fires in the USFS dataset, 1.9:1, is the same as the ratio of natural to human ignitions in the BLM dataset (1.9:1). Fires of unknown ignition origin accounted for just 171 fires across the MTBS, BLM, and USFS datasets.

The reasons for this discrepancy are not immediately clear. It is possible that in the rangeland-dominated Western Great Plains, (1) fires able to reach the minimum size threshold for inclusion by the MTBS project (>400 ha) and/or (2) fires to which federal personnel respond—and thus map for inclusion in USFS and BLM datasets—tend to occur in areas with less human settlement and recreational activity than forested areas, and thus fewer potential anthropogenic ignition sources [51]. Likewise, these areas might be less fragmented by roads, which can both increase anthropogenic ignitions and limit fire spread [52,53].

Human Population

We found little evidence that patterns in historical fire activity can be clearly attributed to patterns in the human population over the course of the study period. Across the four ecoregions, the human population remained fairly steady from 2000 to 2020, with only a few peri-urban census tracts in the High Plains, and to a lesser extent the Southwestern Tablelands, recording substantial population increases (Figure 6). Otherwise, across the non-urban census tracts analyzed here, human population densities generally remained below 0.03 persons km⁻². As such, we found little evidence that either burned area or the number of incidents correlate with human population density within any ecoregion (Figure A3).



Figure 6. Human population trends in the four Level III ecoregions in the Western Great Plains from the decennial US census. Bold lines with points and error bars indicate ecoregion means, based on census tract-level trends (lighter broken lines in background). Census tracts explicitly identified as urban have been excluded.

Although increases in human population are often associated with higher incidence of fires and greater burned areas, the largely rural Western Great Plains likely remains well below the settlement densities required to affect fire patterns at broad scales (e.g., census tracts and counties, as used here). Previous research describes non-linear, hump-shaped

relationships between human population and fire activity in which fire incidence first increases with human population density as more human presence increases ignitions, but then declines as the built environment generally reduces vegetative fuel load and continuity [54–56]. Specifically, Syphard et al. [54] reported increasing rates of fire activity as human population density increased to 40 persons km⁻². Human population densities in the Western Great Plains were substantially lower than almost any reported for the WUI regions of California, with only a handful of census tracts reaching or exceeding 0.1 persons km⁻² (Figure 6).

It is possible that the impact of humans on fire activity is spatially discrete and associated more with infrastructure development than general increases in population density. Roads, for example, increase the incidence of fire and have a disproportionate impact on increasing ignition frequency where there is relatively low human impact [52,57], such as rural areas. At the same time, roads can limit fire spread by creating physical barriers to fire and increasing access for suppression [52,53]. This might contribute to the fire activity patterns observed in the High Plains, especially, where fire incidence increased substantially after 2008 without a concurrent increase in burned area (Figure 4A). Since the late 2000s, energy development in Colorado has expanded road networks and fragmented wildland landscapes [58,59]; in addition to creating new roads, energy development dramatically increases traffic in rural areas [60]. The industrialization of rural landscapes creates an interface between wildlands and the built environment not currently encompassed in existing definitions of the wildland–urban interface and ought to be explored further in future studies at smaller scales for rural areas where this dynamic might be at play.

Fire Weather

We found little evidence of long-term changes in the relationship between patterns in historical fire activity and fire weather within the study period. There was no statistically significant trend in 100 h fuel moisture, Hot-Dry-Windy Index, or Energy Release Component in any ecoregion. The High Plains showed a statistically significant increase in Burning Index ($\tau = 0.23$, p = 0.04), but no other ecoregion had a statistically significant trend (Table A2). The Northwestern Plains were the only ecoregion to show a statistically significant trend towards increased growing season precipitation ($\tau = 0.26$, p = 0.02). We observed considerable cyclical interannual variability in composite fire weather and fuel metrics (Hot-Dry-Windy Index, Figure 7A; 100 h Fuel Moisture, Burning Index, and Energy Release Component; Figure 7A, respectively), as well as January–July precipitation (Figure 7B). As such, we found no relationship between July fire activity—incidence rate and relative burned area—and either July fire weather (Figure A5 and Table A5) or cumulative January–June precipitation (Figure A4).

While clearly not a precondition for the occurrence of fire—fire activity, including high incidence rates, spanned the entire range of fuel and weather variables (Figures A5 and A6, Tables A5 and A6—the association between particularly high annual burned area and extreme conditions suggests how fire weather can facilitate disproportionately extensive fire spread during "bad" fire years (Figure A6 and Table A6). This pattern is consistent with previous literature highlighting the role of climate in driving wildfire burned areas [28,61]. Outliers in July fire activity—census tracts with incidence rates > 100 fires 1000 km⁻² Figure A5 and Table A5 and relative burned area > 5000 ha 1000 km⁻² Figure A6 and Table A6—highlight the extreme fire seasons of several years for the region: 2006, 2012, and 2017 (Table A4).

Similarly, there was little evidence of an association between July fire activity and preceding January–June rainfall. There was, however, one interesting trend: years with exceptionally high burned area in July (>2000 ha), in the Northwestern Plains and High Plains, specifically, were all associated with less than 300 mm antecedent rainfall (Figure A4). Otherwise, both burned area and incidence rates occurred across the entire range of variability in antecedent rainfall, which ranged from 50 to 500 mm in the Northwest Plains, Nebraska



Sandhills, and High Plains, and ranged from nearly 0 to 350 mm in the Southwestern Tablelands.

Figure 7. Historical (1980–2020) trends in fuel and fire weather variables from gridMET. Bold lines represent mean for respective Level III ecoregion; lighter background lines represent values for centroids of individual US census tracts within each ecoregion. (**A**) Mean July values for four composite variables relevant to fire risk and behavior. BI = Burning Index, ERC = Energy Release Component, FM = 100 h (coarse) fuel moisture, HDWI = Hot-Dry-Windy Index (product of vapor pressure deficit and wind speed). (**B**) Total January–June (inclusive) precipitation ahead of each fire season, which tends to peak in July (Figure 4).

It is not immediately clear why we did not observe the strong relationships between fire activity and climate reported elsewhere, although most of the published research draws on burned area datasets that satisfy one or more of the following criteria: federally managed land, forest ecosystems, or large wildfires. Throughout this literature, patterns in burned areas across the US have been linked to fire weather [61,62]. Climatic controls on burned areas range from precipitation in the months before the fire season to atmospheric pressure patterns blocking precipitation during the fire season [63]. In forests of the western US, greater vapor pressure deficit has enhanced fuel aridity and increased burned area [64]. Non-forested land has been described as having a fuel-limited climate-fire regime, in which growing season precipitation prior to the fire season determines how much fine fuel is available to burn once the late summer fire season begins [62].

One potential explanation for the weak relationship between fire activity and climate might be related to the dominant land use in the region—livestock grazing. Precolonial patterns of herbivory were driven by interactions between climate and fire, with free roaming bison free to follow productivity or forage quality of recently burned areas [65]. In this type of system grazing likely most often occurred in areas where it was well supported by recent precipitation [66]. Contemporary livestock grazing is intensive and grazer movements are constrained [40], this impacts fuel loads across the landscape, with grazing reducing fuel loads to greater extents during drought as adapting static herd sizes to variable weather is challenging [67]. As a result, the effects of grazing and climate are decoupled under contemporary grazing regimes, and grazing impacts on fuels could overshadow climate effects.

There are some caveats in the composite variables provided by gridMET that might affect the weak patterns between them and fire activity in rangeland. For example, gridMET reports moisture for 100 h fuels, which refers to coarse woody debris 2.5–7.6 cm in diameter; these large fuel particles have long lag times and absorb and release moisture over the course of several days. Only after a prolonged period of drought will coarse woody debris begin to show decreasing 100 h fuel moisture. But rangeland fuelbeds are typically dominated by 1-h fuels—fine vegetation < 0.6 cm, which gains and loses moisture at much faster rates [17]. Grass and herbaceous matter can dry quickly and become available for combustion much faster than larger fuel particles, and thus ignitions on days recording relatively high 100 h fuel moisture can still spread through fuelbeds dominated by fine fuels. This is consistent with conclusions from (Littell et al. [61], p. 1003): *the primary mechanism behind the observed fire–climate relationships is climatic preconditioning of large areas of low fuel moisture via drying of existing fuels or fuel production and drying*.

Likewise, in providing daily National Fire Danger Rating values, gridMET also reports Energy Release Component (ERC) and Burning Index (BI) for a single specific type of vegetation—fuel model G—that was designed for dense, conifer-dominated forests [15]. Given the overall greater fuel load of a coniferous forest versus a grass-dominated rangeland, the potential energy release for the former will likely always exceed that of the latter regardless of variability in moisture content. We suggest that the lack of correlation between fire activity and ERC/BI, except for under very extreme conditions, can be attributed to poor tracking between variability in ERC/BI and actual conditions in fine rangeland fuels. Because of the short lag times in rangeland fuel properties, we suggest researchers and managers focus on fire weather variables like vapor pressure deficit instead of derived variables more appropriate for forests [64,68].

3.2. Wildfire across Jurisdictional Boundaries

Wildfire in the Western Great Plains—and especially in the Northwestern Plains—is agnostic to landownership, burning across private, state, Tribal, and federal land. Heretofore, analysis of wildfire patterns in this paper has considered over 60,500 incidents between 1992 and 2020, but the Fire Occurrence Database requires only a point of origin for each incident [69]; a lack of spatial information on final fire perimeters limits this dataset for pyrogeographic analysis of fire across land ownership types. We turn now to a composite dataset of 2665 fires, which we call the Federal Fire Polygon Collection as it comprises georeferenced final fire perimeter data available from several sources (Table A1).

3.2.1. General Trends

Consistent with the Fire Occurrence Database the Northwestern Plains had by far the greatest burned area among the four Level III ecoregions in the Federal Fire Polygon Collection, with nearly 120,000 ha of Tribal or agency land burned and 60,000 ha of unspecified land ownership (e.g., private, state, etc.; Figure A7). The Bureau of Land Management (BLM) had the greatest total area of fire in the Western Great Plains—690,316 ha burned representing 16% of total BLM land (Figure 8). However, since BLM ownership and large proportions of the burned area are limited primarily to the Northwestern Plains, the only other entity to experience substantial burned area in this database is Tribal authorities in the Northwestern Plains (249,040 ha); less than 2% of US Forest Service land was included in a fire perimeter between 1980 and 2020 (Figure 8). Also consistent with the Fire Occurrence Database, is the dominance of perennial rangeland vegetation across all jurisdictions within fire perimeters (Figure A1B).



Figure 8. Sum of area in wildfire perimeters by surface management authority in the Western Great Plains Land Resource Region, 1980–2020. Italic percentages below bars indicate the proportion of the total area of the region owned by each entity. BLM = Bureau of Land Management, Tribal = Native American reservations, BIA = Bureau of Indian Affairs, USFS = US Forest Service, FWS = Fish & Wildlife Service, NPS = National Park Service, DOD = Department of Defense.

An insight into wildfire activity provided by georeferenced fire perimeters is the diversity of jurisdictions and land ownership individual incidents can include. For example, the largest fire by area in the Western Great Plains—the 2012 Ash Creek Fire in southeastern Montana—covered 102,553 ha across private, state, BLM, USFS, and Tribal reservation land (Figure 9). Other large fires—limited mostly to the Northwestern Plains—also serve as striking examples of the multi-jurisdictional diversity (Figure A10).

Unlike more productive agricultural regions to the east, the Western Great Plains are not only comprised primarily of rangeland but also a matrix of public and private ownership. Furthermore, a "checkerboard" pattern often emerges when ownership differences are limited to one or several *sections*—the 260 ha, 1 mile \times 1 mile blocks that form the basic unit for land surveying in the US. (For examples, see the state-owned sections in Figures 9 and A10).



Figure 9. The 2012 Ash Creek Fire, in southeastern Montana, spread across Tribal land, two federal agencies, state, and private ownership (gray fill). Note, the square tracts assigned to state ownership; these are each 260 ha, square mile *sections* that are often access-limited inholdings within the broad matrix of private or federally-owned land. Both inside (USFS) and outside (BLM) government ownership, most land in the perimeter is included in *grazing allotments* for which specific leases and grazing plans are administered. Agencies vary in how they manage grazing in allotments that have recently burned.

The checkerboard geography of private, state, and federal land ownership invoke all four of the inter-jurisdictional fire management boundaries delineated by Davis et al. [70]: differences in land ownership; risk management functions (e.g., prevention, mitigation, and suppression); organizational differences in missions, incentives, and ability to share resources and conceptual differences in knowledge and responsibilities related to wildfire risk.

One example of interagency boundaries between federal agencies and local fire services include *managed wildfire*, the idea that full suppression is not necessarily the ultimate goal and even unintentional ignitions can advance natural resource management objectives [71,72]. Federal managers might adopt a less aggressive "let burn" approach to reduce firefighter risk when potential resource threats are minimal, such as in wilderness or rural areas [73]. Although managed wildfires have been creeping into federal policy, on-the-ground adoption has been slow and is often at odds with suppression-focused county-level personnel and their tax base of private landowners [74]. As wildfires increasingly affects publicly-owned land surrounded by private ownership, especially in the Northwestern Plains, goals between large land management agencies and local communities will need to be reconciled. Evidence suggests that beyond managed wildfire, cooperative prescribed fire operations or mechanical treatments combined with post-treatment burning to reduce wildland fuel loads and maintain grass-dominated, open ecosystem states provide opportunities for collaboration between federal and local entities [74,75].

3.2.2. Wildfire and Public grazing lands

While much of the Western Great Plains landscape consists of a mosaic of public and private land ownership, at the same time, these areas are characterized by a relative degree of homogeneity in their principal land use: commercial livestock production. The rugged topography and shallow soils have left much of the native prairie communities intact, and grazing is the primary means to convert millions of hectares of generally low-quality herbaceous biomass into marketable agricultural products. Thus, while many citizens associate public land ownership with conservation land use to the exclusion of commercial enterprise, the vast majority of public land in the Western Great Plains—excluding the limited National Park Service properties—is divided into *grazing allotments* and leased for commercial livestock.

Wildfires have occurred on a substantial proportion of public grazing lands, and in some jurisdictions, wildfires are increasing. The number of grazing allotments that burned in wildfires in the Western Great Plains has increased since 2000, especially on rangeland owned by the BLM (Figure 10 and Table 3). Between 1980 and 2020, 31% of BLM allotments and 51% of USFS allotments in the Northwestern Plains had at least one wildfire (Figure 10 and Table 3).



Figure 10. The number of US Forest Service (USFS) and Bureau of Land Management (BLM) grazing allotments affected each year by wildfires across the Western Great Plains.

Table 3. The proportion of federal grazing allotments in the Western Great Plains affected by a wildfire since 1980. The Values are conservative as they are derived from the Federal Fire Polygon Collection (2665 wildfire events), and not the Fire Occurrence Database (60,575 incidents).

Ecoregion	Agency	Fire-Affected Allotments
Northwestern Plains	BLM	1032 (31%)
	USFS	365 (51%)
High Plains	BLM	40 (16%)
-	USFS	83 (24%)
Nebraska Sand Hills	BLM	1 (8%)
	USFS	39 (80%)
Southwestern Tablelands	BLM	8 (3%)
	USFS	23 (21%)

While this area is well-adapted to fire and grazing disturbance, under current management guidelines, wildfires on public grazing land create an issue for commercial livestock producers and potentially puts greater stocking pressure on neighboring unburned pastures. Whether through policy or suggested practice, federal agencies have generally recommended livestock be excluded from burned areas for as many as two seasons after fires [76,77]. This means that in the Northwestern Great Plains alone, at least 1397 grazing allotments and their respective lease agreements had to be evaluated following fires, and livestock use was likely restricted for at least 1–2 seasons on these grazing lands. But grazing exclusion might be unnecessary. Surveys of remotely-sensed vegetation data from across the Great Plains and western rangelands suggest that prairie communities are resilient to wildfire [78,79], and field data from the Northern Plains, specifically, call into question the necessity of grazing exclusion [80–82]. In fact, research on prescribed fire suggests recently-burned vegetation provides higher-quality forage, supports better livestock weight gains, and enhances pollinator resources without negative impacts on soil carbon and microbes, generally increasing ecosystem service delivery and buffering against drought [83–88]. However, it remains to be determined whether these same positive outcomes for livestock production can be realized from wildfires. Such information would be of great benefit to livestock producers in the Western Great Plains, who might find fire to create opportunities for better grazing resources rather than complications to their management.

3.3. On Differences among Pyrogeographic Data and Reporting

Ultimately, our analysis of spatial and temporal patterns in wildfires across the US Western Great Plains over the last 40 years did not support two patterns frequently reported in previous publications: an increasing trend in wildfire activity, and strong correlations between wildfire activity and patterns in climate and weather. Variability among data sources on fire activity likely underlies variability in conclusions. As mentioned above there are common themes in the underlying data used in most pyrogeographic analyses and reports on climate-fire regimes, such as bias towards land under agency management (e.g., [61,89]); dominance of forested land (e.g., [63,64]) and/or a focus on large fires (e.g., [5,6,22,28]). For example, one analysis focused on large wildfires from the MTBS database showed an increase in burned area for the High Plains and either declines or no data for change in the annual occurrence of large wildfires throughout the Western Great Plains [32]. Conversely, the Fire Occurrence Database used here—which has no minimum size threshold for wildfire incidents—indicates the High Plains showed the greatest increase in reported incident frequency and no change in the total burned area (Figure 4).

There is also considerable variability in how data are collected and recorded. Despite the large number of records and diversity of sources in the Fire Occurrence Database, the lack of geospatial final fire perimeters severely limits its utility for studying fire with respect to spatially discrete questions such as land cover, topography, and land ownership. Remotely sensed products generally fall into categories that include active fire detection and burned area estimation [90]. In addition to the point data in the Fire Occurrence Database, and polygon data in the datasets, we include in the Federal Fire Polygon Database—both of which are compiled mostly from agency reports—pyrogeographers have also used radiometry data (e.g., [27]).

Our analysis places greater emphasis on the total burned area as defined by small as well as large fires. Fire size by area is a common means of characterizing *extreme wildfire events*, which garners considerable media and research attention because they incur substantial control costs, devastate the built environment (homes, infrastructure, etc.), and/or provide evidence for the "new normal" suggested by global change predictions [91]. However, large wildfires do not necessarily affect negative ecological outcomes [25], and overall burned area is rarely the only relevant consideration—actual burn severity is highly variable and is often driven by vegetation type and topography [92]. For example, within 3 yrs of a 254,000 ha "megafire" in the Southern Great Plains, structural vegetation properties had returned to pre-fire conditions, and post-fire vegetation patterns were attributed to pre-fire composition and not burn severity [93], which had generally been low throughout the area within the final fire perimeter. Likewise, evidence from the Northern Great Plains suggests wildfires in rangeland have a minimal negative impact on ecosystem service delivery [80,81].

By focusing on the total burned area and incidence frequency that includes fires of all sources and sizes, we highlight the impact of fire activity on local resources. While "local" often refers to county and municipal fire services, in this context it ought to also consider federal resources based in the focal jurisdiction (Figure 11). Both federal and nonfederal resources are frequently made available for assignment to large incidents outside of their locality [94], which reduces actual local capacity among county, state, and federal entities. These local resources are most likely the first to respond to wildfire incidents and provide the initial action, especially for ignitions on non-federal land, and many smaller incidents will be handled wholly by local resources—recall that median fire size is just 0.04–1.2 ha across the Western Great Plains (Table A3). But outside of the specific context of the wildland–urban Interface (e.g., [95]), there is little published literature on local fire resources in the rural Western Great Plains evaluating their preparedness for wildland fire responses, especially in the High Plains, where the number of incidents has been increasing (Figure 4).



Figure 11. An example of multi-jurisdictional wildfire management. Members of the Custer County (MT) Volunteer Fire Department pause to anticipate a C-130 tanker while performing mutual aid duties for a wildfire on US Forest Service land. The Incident Commander, an employee of the Bureau of Land Management, ordered the retardant drop to ensure secure control lines where the fire burned along a boundary between National Forest and private land.

4. Conclusions

Although few long-term trends emerged to support changes in fire weather and fuel conditions as a driver of increasing fire activity in the Western Great Plains, associations between years of highly burned areas and extreme weather conditions underscore the supporting role of weather in facilitating fire spread under adequate fuel conditions and necessary ignitions.

There is, however, clear evidence that wildfires are increasingly impacting public grazing lands, especially in the Northwestern Plains. Conventional practice is to defer or entirely curtail livestock grazing on burned federal land. Because commercial livestock grazing is the primary mode of economic activity in communities of the region, wildfires on grazing lands present a direct concern for rural livelihoods until more nuanced grazing management practices can be developed for wildfire-affected rangeland.

Pyrogeography provides a unique lens to view the relationships between fire and humans in the Earth system, but the utility of the discipline is currently limited by variability in data used and standards in reporting. The variability is understandable, as most of the data employed by researchers were initially collected by managers for use in monitoring fire management efforts both on the ground and from budget and resource allocation perspectives. Management agencies have put considerable effort into standardizing data collection, as evidenced by Web-based, national-scale incident reporting systems [69] and centralization of fire perimeter data at the National Interagency Fire Center, although inclusion criteria remain variable at the agency level [96].

All members of the wildland fire community have a vested interest in reducing the risks and costs of unplanned wildfires. To reduce potential conflicts between land man-

agement agencies and local communities who might not have the same attitude towards let-burn policies instead of full suppression, stakeholders ought to be made aware of programs that work proactively to reduce fuel loads and maintain open rangeland ecosystems.

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Appendix A. Additional Information on Methodology

Table A1. Data sources employed in this analysis, with links to online resources and references to formal descriptions of data. (All accessed on 22 November 2022).

Data Type	Name	Description	Available From	Ref.
Biogeographical	Land Resource Regions	Broad landscape divisions based on bio-geo- physical attributes	USDA NRCS ¹	[97]
	Level III ecoregions	Areas with similar ecosystems and type, qual- ity, and quantity of environmental resources	US EPA ²	[98]
Environmental	Extent of US rangelands	Land cover from LANDFIRE & FIA	USFS ³	[45]
	Rangeland Analysis Platform	Plant cover to functional group 1986-present	https://rangelands.app	[47]
	TerraClimate	Monthly historical weather, 1958–2019	Public Domain ⁴	[99]
	gridMET	Daily gridded (4 km) surface weather, 1979–yesterday	Public Domain ⁵	[20]
Demographic	Urban areas of the US	Populated areas > 2500 in 2020	Census Bureau ⁶	[100]
	US decennial census	Total population in 2000, 2010, 2020	Census Bureau ⁷	
Management	Surface Management Agency	Surface land management under state and federal jurisdiction	US BLM ⁸	[101]
	PADUS 2.1	Protected Areas Database: Fee, declaration, easement, and proclamation	US Geological Survey ⁹	[102]
Fires	Fire Occurrence Database	Wildfire records acquired from reporting systems of federal, state, and local fire organizations, 1992–2020.	USFS ¹⁰	[48]
	MTBS	Fire perimeters > 405 ha, 1984–2021	USFS ¹¹	[49]
	Inter Agency Fire Perimeters	Final fire perimeters for various state and fed- eral agencies, early 1900s–2021	NIFC ¹²	
	National Fire Perimeters	Fire perimeter data to 2019	US BLM ¹³	
	S_USA.FinalFirePerimeter	Final fire perimeters for the continental USFS, early 1900s–2021	USFS ¹⁴	

¹ https://www.nrcs.usda.gov/sites/default/files/2022-10/MLRA_52_2022.zip, ² https://www.epa.gov/ecoresearch/level-iii-and-iv-ecoregions-continental-united-states, ³ https://apps.fs.usda.gov/arcx/rest/services/ RDW_LandscapeAndWildlife/Extent_of_US_Rangelands/MapServer, ⁴ https://www.climatologylab.org/ terraclimate.html, ⁵ https://www.climatologylab.org/gridmet.html, ⁶ https://www.census.gov/programssurveys/geography/guidance/geo-areas/urban-rural.html, ⁷ https://www.census.gov/programs-surveys/ decennial-census/data/datasets.html, ⁸ https://www.arcgis.com/sharing/rest/content/items/6bf2e737c59d4 111be92420ee5ab0b46/data, ⁹ https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-datadownload, ¹⁰ https://www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.6, ¹¹ https://www.mtbs.gov/ direct-download, ¹² https://data-nifc.opendata.arcgis.com/datasets/nifc::interagencyfireperimeterhistory-allyears-view/about, ¹³ https://services1.arcgis.com/KbxwQRRfWyEYLgp4/ArcGIS/rest/services/BLM_Natl_ Fire_Perimeters_Polygon/FeatureServer, ¹⁴ https://data.fs.usda.gov/geodata/edw/datasets.php?xmlKeyword= S_USA.FinalFirePerimeter.

A. Land cover by point of fire origin High Plains Nebraska Sand Hills 60 40 20 Vegetation cover MeanCover 0 Annual herbaceous Perennial Northwestern Plains Southwestern Tablelands herbaceous Trees + 60 Shrubs 40 20 0 1990 2000 2010 2020 1990 2000 2010 2020 Year B. Land cover with fire polygons by agency BLM USFS State Tribal 80 60 40 20 MeanCover 1990 2000 2010 2020 FWS Other Fed Other/Unknown 80 Vegetation cover 60 Annual herbaceous 40 Perennial herbaceous Trees -20 Shrubs 0 1990 2000 2010 2020 1990 2000 2010 2020 1990 2000 2010 2020 Year

Appendix B. Additional Data



Figure A1. Dominant vegetation in the season before fires as retrieved from the Rangeland Analysis Platform. (A) Vegetation cover at the point of origin given for 60,575 incidents in the Fire Occurrence Database. (B) Vegetation cover within 1027 fire perimeters in the Federal Fire Polygon Collection. Vegetation cover is reported by ownership class of land within perimeters as determined by the BLM Surface Management Agency spatial layer [101].

Table A2. Results of long-term trend analysis calculating Kendall's τ for fire activity and weather data from each of four Level III ecoregions of the Western Great Plains, 1992-2020. Fire incidence and area data plotted in Figure 4. July fire weather data plotted in Figure 7A, and growing season precipitation data plotted in Figure 7B.

Variable	Ecoregion	τ	р	Slope (95% CI)
Fire activity				
Burned Area	Northwestern Plains	0.15	> 0.05	0.77 (-0.86, 3.5)
	Nebraska Sand Hills	0.15	> 0.05	0.06 (-0.04, 0.22)
	High Plains	0.24	>0.05	0.21 (-0.02, 0.53)

Variable	Ecoregion	τ	р	Slope (95% CI)
	Southwestern Tablelands	-0.03	>0.05	-0.026 (-0.33, 0.64)
Incidents	Northwestern Plains	0.17	>0.05	12 (-6.1, 40)
	Nebraska Sand Hills	0.47	< 0.001	1.8 (1, 2.9)
	High Plains	0.67	< 0.001	42 (24, 56)
	Southwestern Tablelands	0.36	< 0.01	11 (2, 21)
July fire weather				
100 h FM	Northwestern Plains	-0.08	>0.05	-0.023(-0.07, 0.03)
	Nebraska Sand Hills	-0.04	> 0.05	-0.01(-0.07, 0.04)
	High Plains	-0.16	> 0.05	-0.029(-0.07, 0.01)
	Southwestern Tablelands	-0.17	> 0.05	-0.025(-0.08, 0.01)
BI	Northwestern Plains	0.13	> 0.05	0.14(-0.08, 0.4)
	Nebraska Sand Hills	0.13	> 0.05	0.13 (-0.09, 0.39)
	High Plains	0.23	0.04	0.19 (0.02, 0.38)
	Southwestern Tablelands	0.19	> 0.05	0.18 (-0.02, 0.36)
ERC	Northwestern Plains	0.05	>0.05	0.087(-0.2, 0.34)
	Nebraska Sand Hills	0.01	>0.05	0.006 (-0.19, 0.3)
	High Plains	0.18	> 0.05	0.15(-0.04, 0.41)
	Southwestern Tablelands	0.22	0.05	0.21 (0.002, 0.43)
HDWI	Northwestern Plains	0.04	>0.05	0.01 (-0.04, 0.05)
	Nebraska Sand Hills	0.01	>0.05	0.003 (-0.04, 0.05)
	High Plains	0.13	>0.05	0.02 (-0.01, 0.04)
	Southwestern Tablelands	0.09	>0.05	0.01 (-0.02, 0.04)
Growing season precipitation				
<i>. . .</i>	Northwestern Plains	0.26	0.02	1.9 (0.34, 3.4)
	Nebraska Sand Hills	0.21	> 0.05	2.1 (-0.18, 4)
	High Plains	0.12	> 0.05	1 (-0.87, 2.3)
	Southwestern Tablelands	-0.12	>0.05	-0.96 (-2.7, 0.7)

Table A2. Cont.



Figure A2. Number of incidents by identified ownership at ignition site and broad attributed cause of fire for four Level III ecoregions in the Western Great Plains, 1992–2020.



Figure A3. Mean annual burned area (**top**) and mean annual number of incidents (**bottom**) plotted against human population density for 3, 10-yr US Census periods in the four EPA L3 ecoregions of the Western Great Plains.

Table A3. Quantiles of individual fire sizes as burned area (ha) for each of four Level III ecoregions of the Western Great Plains, 1992–2020.

Ecoregion	25%	50%	95%
Northwestern Plains	0.04	0.2	65.0
Nebraska Sand Hills	0.4	1.2	324.0
High Plains	0.04	0.04	12.2
Southwestern Tablelands	0.04	0.04	162.0

Table A4. Five highest years of fire activity by ecoregion, in terms of both total annual burned area and total number of incidents.

Ecoregion	Year (Burned Area $ imes$ 1000 ha)	Year (Incidents)
Northwestern Plains	2012 (389)	2017 (2148)
	2017 (270)	2006 (2043)
	2006 (257)	2012 (1963)
	2000 (136)	2020 (1872)
	2020 (135)	2016 (1865)
Nebraska Sand Hills	2012 (75)	2012 (221)
	1999 (45)	2017 (125)
	2000 (41)	2020 (122)
	1995 (23)	2018 (71)
	2015 (11)	2000 (66)
High Plains	2012 (84)	2011 (3091)
-	2006 (53)	2017 (1963)
	2018 (31)	2018 (1713)
	2000 (24)	2020 (1654)
	2002 (18)	2010 (1156)
Southwestern Tablelands	2011 (60)	2011 (625)
	2006 (55)	2017 (594)
	2018 (47)	2016 (588)
	2020 (30)	2018 (516)
	2008 (29)	2013 (454)



Figure A4. Total burned area (**top row**) and total number of reported incidents (**bottom row**), both limited to July in each year, plotted against calendar year-to-date precipitation (previous January–June) for four EPA L3 ecoregions of the Western Great Plains.



Figure A5. Wildfire incidence rate (total number of incidents/total area, by U.S. Census tract) plotted against mean July values for four composite fuel and fire weather variables for four Level III ecoregions of the Western Great Plains, 1992–2020.

Table A5. Three particularly high July fire incidence rates (number of fire incidents per 1000 sq km). In all three cases 100 h fuel moisture was <10%, but other indices were only just above median.

County, State	Year	Incident Rate
Todd County, SD	2006	123
Todd County, SD	2017	112
Oglala Lakota County, SD	2012	119







Figure A7. Total area included in fire perimeters in four EPA LIII ecoregions of the Western Great Plains across land either designated as under tribal or federal or state agency management by the Bureau of Land Management's Surface Management Agency shapefile, or land unassigned to an agency by the BLM, which includes, but is not necessarily limited to, privately-owned land.



Figure A8. Identified causes of fires in three federal agency fire polygon databases for the four Level III ecoregions in the Western Great Plains, 1980–2020. See Table A1 for data sources; note the NIFC database does not include cause.



Figure A9. Temporal trends in fire occurrence and burned area in four federal agency fire polygon databases for the four Level III ecoregions in the Western Great Plains, 1980–2020. (**Top**) Annual records of fire incidences. (**Bottom**) Counts of fire incidences by month. See Table A1 for data sources.



Internal white lines indicate BLM grazing allotments

Figure A10. Three large fires from the Northwestern Plains highlighting the variability of land ownership within fire perimeters. Gray areas are private or county owned. Note the 260 ha, square mile *sections* and *grazing allotments*.

Table A6. Highlighted details on instances of exceptional relative burned area in the figure and associated derived variables from gridMET. RBA = Relative Burned Area (sum of July ha burned per U.S. census tract divided by total area of tract), BI = Burning Index, ERC = Energy Release Component, FM = 100 h (coarse) fuel moisture, HDWI = Hot-Dry-Windy Index (product of vapor pressure deficit and wind speed).

Ecoregion	County, State	Year	RBA	BI	ERC	FM	HDWI
Northwestern Plains	Big Horn, MT	2006	22,359	45.6	68.5	7.4	6.8
Northwestern Plains	Todd, SD	2012	19,215	47.4	69.3	6.5	11.8
High Plains	Scotts Bluff, NE	2000	12,082	23.2	42.0	12.5	5.9
Northwestern Plains	Yellowstone, MT	2006	11,592	40.8	68.9	6.7	8.0
Northwestern Plains	Garfield, MT	2017	9646	59.8	76.8	6.2	10.0
Nebraska Sand Hills	Brown, NE	2012	9415	54.2	71.0	6.6	14.5
High Plains	Dawes, NE	2006	5624	33.4	50.8	9.4	9.0

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