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Research article

Recreation and firearms use as an emerging wildfire risk on western United States National Conservation Lands

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ABSTRACT

Public lands are sources of valuable ecological, social, cultural, economic, scientific, and recreational resources in the United States. Wildfires may threaten the continued provision of some of these benefits. Fire management on public lands is increasingly challenging due to the growing array of human activities responsible for fires, including recreational target shooting. We used detailed information in agency fire reports from 1992 to 2020 to advance our understanding of contemporary wildfire ignition sources and patterns on a subset of public lands managed by the Bureau of Land Management (BLM): the National Conservation Lands (NCL) system. We used a multi-scale approach, first exploring patterns of wildfire causes across 17 NCLs. Natural ignitions were dominant within 71 % of NCLs and accounted for 73 % of all ignitions. Although less frequent, human-caused ignitions have increased since 1992 across all NCLs, indicative of a potential departure from regional patterns. Second, we focused on a case study site, the Morley Nelson Snake River Birds of Prey (MONE) National Conservation Area. MONE represents an exception among and potential future state for other NCLs. We found that 25 % of all BLM NCL ignitions from 1992 through 2020 were within MONE and furthermore, 68 % of ignitions at MONE were attributed to human activities, predominantly firearms and explosives use (34 %). Previous work exploring national patterns in ignitions has shown that the non-coastal western US has more natural ignitions, but we found that MONE, with its high rate of human-caused ignitions, serves as an example of ignition patterns in a conservation area with intense recreational use and diverse human impacts. Ultimately, we emphasize the need for targeted outreach and regulatory approaches to reduce recreational shooting ignitions and advocate for increased use of improved reporting standards for fire cause data.

1. Introduction

Wildfire is a ubiquitous natural disturbance that is integral to many biomes and ecosystems (Chapin et al., 2008; Jones et al., 2022; Schoennagel et al., 2017; Stavi, 2019; Westerling, 2016). In recent years, fire regimes across the western United States (US) have shifted, typified by shorter fire return intervals, increased fire size and severity, and extended fire season lengths (Balch et al., 2017; Crist et al., 2023; Dennison et al., 2014; Schoennagel et al., 2017). Shifting fire regimes have been documented widely, from shrublands and grasslands (Radeloff et al., 2023; Stavi, 2019), to California's chaparral and coniferous forests (Stevens et al., 2017; Underwood et al., 2022), and the boreal forests of Alberta, Canada (Whitman et al., 2022). Wildfires can be started naturally by lightning, intentionally (e.g., cultural and prescribed burning, arson), or unintentionally (e.g., accidental human-caused ignition) (Shuman et al., 2022). Human-caused ignitions drive current fire regimes, accounting for 84 % of all wildfires documented in the US from 1992 to 2012 (Balch et al., 2017). Human-caused ignitions have increased large wildfire frequency (Nagy et al., 2018), accounting for 44 % of burned areas and tripling the fire season length (Balch et al., 2017). Climate change is also altering fire patterns by rising temperatures, variable precipitation, and drought which enhance fuel aridity and exacerbate wildfire risk (Brice et al., 2020; Dennison et al., 2014; Holdrege et al., 2024; Pilliod et al., 2017; Westerling, 2006, 2016).

Public lands, covering nearly 40 % of the US, are valuable resources

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managed primarily by four federal agencies: the Bureau of Land Management (BLM), US Forest Service, US Fish and Wildlife Service, and the National Park Service (Hoover et al., 2021). The BLM, the largest agency, manages over one million km^2 of public land, 15 % of which is protected as National Conservation Land (NCL) under the National Land Conservation System (Kleinhesselink et al., 2023). Much of this land is semi-arid shrubland (Kleinhesselink et al., 2023). Historically expansive across the western US, semi-arid sagebrush (*Artemisia* spp.) steppe systems have contracted and fragmented in recent decades, with the spread of invasive grasses like cheatgrass (*Bromus tectorum*) becoming the most prominent threat to these landscapes (Boyd et al., 2024; Crist et al., 2023; Holdrege et al., 2024; Mozelewski et al., 2024). Invasive grasses influence wildfire frequency and behavior by altering fuel density and continuity, accelerating the grass-fire cycle, and placing arid public lands under threat (Pilliod et al., 2017, 2021).

Increasingly, federal land managers face growing challenges from multiple-use objectives, climate change, and disturbance (e.g., wildfire) regimes. Too, the socio-environmental context of public lands is changing rapidly due to rising residential development and urban sprawl fueled by population growth and migration (Mockrin et al., 2018; Requena-Mullor et al., 2023). These pressures increase recreational demands and the risk of human-caused fires, which can arise from sources such as vehicles, fireworks, firearms use, and campfires. Understanding the patterns and sources of such fires is critical for managing public lands to support biodiversity, conservation, and recreation.

Compared to lightning ignitions, human-caused ignitions can produce more carbon emissions (Liu and Yang, 2021). Human-caused ignitions are more common near higher population and housing density areas, road networks, specific land cover types, and certain socioeconomic factors such as income, employment, and age demographics (Balch et al., 2017; Enterkine et al., 2024; McGranahan and Wonkka, 2024; Reilley et al., 2023). Research in the US Pacific Northwest found that most human-caused fires are linked to recreational activities or debris burning (Reilley et al., 2023). Targeted education and regulation may reduce these incidents. Wildfire-cause data are integral to well-informed and effective prevention programs. As such, it is important they reflect emerging human ignition sources. In 2020, the National Wildfire Coordinating Group (NWCG) revised the national wildfire cause data standard to include *Firearms and explosives use* (NWCG, 2020a), due to growing recognition that civilian firearms use is a nontrivial source of wildfires across the western US, including BLM lands (Short and Finney, 2022).

Human-caused ignitions in the US have been studied at national (Balch et al., 2017; Liu and Yang, 2021), regional (Reilley et al., 2023), ecoregion (Nagy et al., 2018), and state (Grala et al., 2017; Jiménez-Ruano et al., 2022) levels. However, finer-scale analysis is needed to understand, as predictors and drivers of wildfires can vary at the sub-ecoregional level (Chen and Jin, 2022). Public lands, as social-ecological systems, represent an ideal setting for such studies, particularly regarding human-caused ignitions linked to recreational activities. Fire use (e.g., for warming, cooking) is a common component of outdoor recreation in the US, and over 99 % of BLM public lands are open to recreational shooting, hunting, and fishing opportunities. Previous studies have noted increasing levels of recreational shooting on public lands, but have not linked this activity to wildfires (Aberg, 2023; Thomason et al., 2024). Recreation-related ignitions have also been studied in national forests of Washington, Oregon, and California, but without examining specific fire causes or links to recreational shooting (Jenkins et al., 2023).

To better understand wildfire causes on public lands, we analyzed wildfire data from agency reports spanning 1992 to 2020 using a multi-scale approach. First, we assessed ignitions across 17 NCL units and asked: What are the patterns of human versus natural ignitions across BLM-managed NCLs? Our findings revealed that most NCLs were dominated by natural ignitions, with the stark exception of the Morley Nelson Snake River Birds of Prey NCA (MONE), that was inordinately dominated by human-caused ignitions. Given the increasing trend of human-caused wildfires nationally (Balch et al., 2017), coupled with the expansion of recreational activities, MONE serves as a prime case study of a site with high recreational use and diverse human impacts, offering valuable insights into potential future NCL conditions. We secondarily focused on the MONE and asked: In an NCA where numerous and diverse human activities are allowed, which specific activities are the primary drivers of human-caused wildfires? Our objective was to improve the understanding of human-caused fires on multiple-use public lands in ways that can refine existing and inform new educational and outreach content targeted to alter human behavior and minimize undesirable wildfire impacts. This research provides valuable insights into the impacts of recreational pressures on public lands, presenting a case study that deepens our understanding of how human activity influences fire ignition patterns within a defined spatial context.

2. Materials and methods

2.1. Study area

2.1.1. National Conservation Lands (NCLs)

Located primarily in the western states, these conservation lands are diverse, protecting ecosystem processes, biodiversity, and cultural heritage; and providing social and recreational opportunities. The NCL system encompasses over 149,733 km^2 of National Conservation Areas (NCA), National Monuments, Wilderness Areas, Wilderness Study Areas, Wild and Scenic Rivers, and National Scenic and Historic Trails. Each unit is managed according to the agency's multiple-use and sustained yield mandates under the 1976 Federal Land Policy and Management Act, which directs the BLM to maximize opportunities for uses including recreation, livestock grazing, energy development, and timber harvesting. Under the 2024 Conservation and Landscape Health Rule (Public Lands Rule), the BLM must now also support public land health, ecosystem resilience, and conservation by protecting intact landscapes, restoring habitats, and making data-driven, science-informed management decisions that include Indigenous Knowledge (Federal Register, 2024).

To delineate our study area, we used vector polygons from the BLM National NLCS National Monuments, National Conservation Areas and Similar Designations Polygons, available on the BLM geospatial platform (Bureau of Land Management BLM, 2022). NCL units vary in their establishment date and size. For example, Idaho's Craters of the Moon, designated in 1924, is the oldest and one of the largest units, covering 3,040 km^2, while the California Coastal National Monument, established in 2000, spans just 4 km^2. To reduce the potential influence of NCL establishment date and size on our analysis, we omitted units with (1) establishment dates later than our fire data time span (i.e., after 2020, see Sect. 2.2) and (2) a total area less than 1,000 km^2. This left 17 NCL units for analysis, accounting for 52,848 km^2. This group of units consisted of 12 National Monuments, four NCAs, and one Cooperative Management and Protection Area (Fig. 1).

2.1.2. Morley Nelson Snake River Birds of Prey (MONE)

Located in southwestern Idaho, the MONE was designated an NCA in 1993 in recognition that the area contained the largest and densest population of nesting raptors in North America, and valuable habitat to support their prey sources (Thomason et al., 2024). It features semi-arid sagebrush steppe comprising Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and native bunchgrasses (*Poa secunda*, *Pseudoroegneria spicata*, and *Agropyron cristatum*) (Enterkine et al., 2024). The MONE has experienced extensive yet heterogeneous degradation from livestock grazing, military training, recreation, and the establishment and spread of invasive annual grasses such as cheatgrass, Russian thistle (*Kali tragus*) and annual mustards (*Descurainia* ssp., *Sisymbirum* ssp.) (Enterkine et al., 2024). Unique among the NCLs, the MONE includes an enclosed area managed by the Idaho Army National Guard

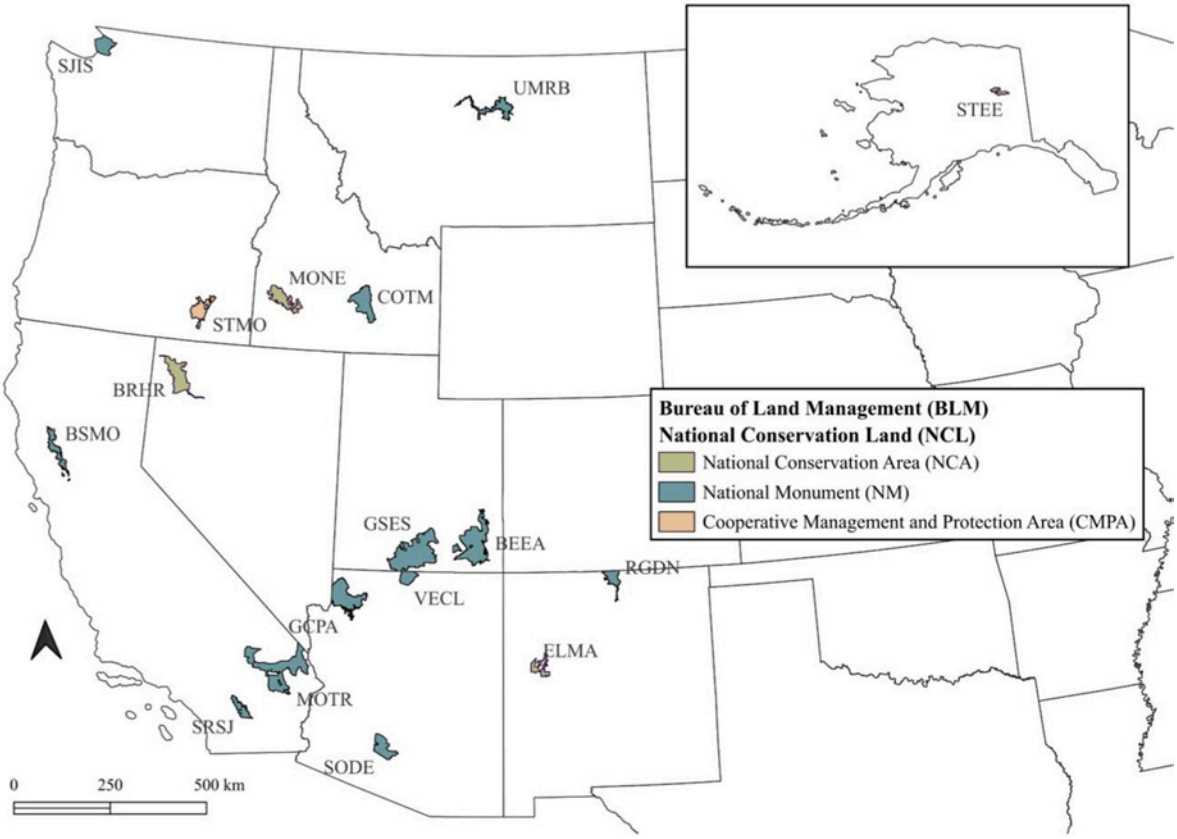

Fig. 1. Bureau of Land Management (BLM) National Conservation Lands (NCL): National Monuments (NM) and National Conservation Areas (NCA), and Cooperative Management and Protection Area (CMPA). The following NCL abbreviations are used, listed in alphabetical order: Bears Ears (BEEA), Berryessa Snow Mountain (BSMO), Black Rock Desert/High Rock Canyon (BRHR), Craters of the Moon (COTM), El Malpaís (ELMA), Grand Canyon-Parashant (GCPA), Grand Staircase-Escalante (GSES), Mojave Trails (MOTR), Morley Nelson (MONE), Río Grande del Norte (RGDN), San Juan Islands (SJIS), Santa Rosa-San Jacinto Mountains (SRSJ), Sonoran Desert (SODE), Steens Mountain (STMO), Steese (STEE), Upper Missouri River Breaks (UMRB), and Vermilion Cliffs (VECL).

(the Orchard Combat Training Center), as well as the Mountain Home Air Force Base and Small Arms Range. The Training Center, established in 1953, permits year-round live-fire training. Public recreation is permitted across the MONE (e.g., hunting, fishing, camping, target practice and bird watching) (Mutz et al., 2004), except in areas used for military training or where shooting is restricted. To explore the impact of recreation on human-caused ignitions, we excluded military-related ignitions from our analysis. The MONE was the only unit with an active military training area, and reporting of military-related ignitions within these areas may be higher compared to other human-caused ignitions outside military boundaries. Removing military ignitions from MONE left 788 ignitions for analysis.

2.2. Data

We used two sources of agency fire reports to understand ignition causes both across the NCL system scale and at the individual NCL level.

Fire Program Analysis Fire-Occurrence Database (FPA FOD): We obtained agency fire reporting data from the 6th edition of the publicly available FPA FOD (Short, 2023). This national database includes the spatial (ignition point) locations of ~2.3 million wildfire records from 1992 to 2020, derived from US federal, state, and local reporting systems. FPA FOD data elements include discovery date, ignition location, final fire size, and *Cause Classification* (natural or human), and each human-caused fire is further attributed to one of 11 known *General Causes* (Fig. 2). The cause attributions used in the FPA FOD conform to the NWCG data standard approved in 2020 (NWCG, 2020a; NWCG, 2020b), but do not extend beyond general cause. These data only include the top two tiers of fire cause information hierarchy: *Cause Classification* and *General Cause*. Of the 7522 FPA FOD ignition points that fell within the 17 NCL unit boundaries, 4978 fires met our selection criteria, i.e., being recorded within the NCL boundaries after the establishment date of each area.

Wildland Fire Management Information (WFMI): The BLM has historically stored its final agency (bureau) fire reports in the US Department of Interior's WFMI system. These are also the source of the relevant subset of FPA FOD records, but include additional details about fire causes, including narrative text, not part of the FPA FOD. The FPA FOD retains a unique WFMI database identifier for each record from that source, which can be used to connect the two datasets (Short, 2014). We used this connection to (1) leverage the standardized high-level cause information in the FPA FOD, and (2) extract additional details about each cause that we mapped over to the *Specific Cause* and *Specific Cause Detail* levels of the NWCG standard (Table S1).

Once the datasets were connected, we further filtered the 4978 ignitions that met our study area criteria to exclude those with *Cause Classification* and *General Cause* both unknown (i.e., recorded as *Missing data/not specified/undetermined* in the FPA FOD) and where WFMI cause information was also absent. We also removed any ignitions attributed to military ordnance and operations. This left a total of 3108 incidents with sufficient high-level cause information for our analyses, meaning that approximately 62 % of NCL unit ignitions met the criteria for inclusion. Of those 3108 records, 50 % had additional fire-cause information available in WFMI under *Specific Cause*, and 40 % also had *Specific Cause Detail*. Once we had our final set of ignitions for analyses, we extracted additional details about each cause, where possible, from the WFMI narrative text to map over to the *Specific Cause* and *Specific Cause Detail* levels of the NWCG standard. For example, causes listed as

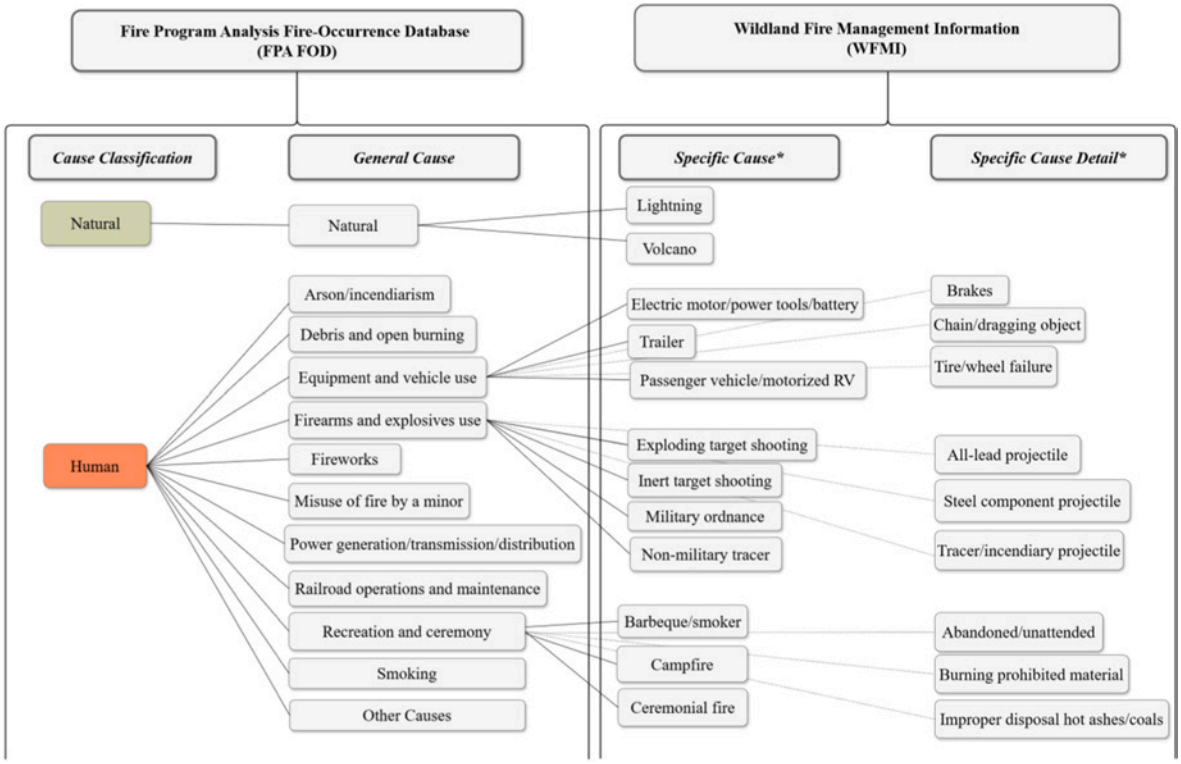

Fig. 2. Ignition cause information available from the combined use of the Fire Program Analysis Fire-Occurrence Database (FPA FOD) and the Wildland Fire Management Information (WFMI) system. *Due to the sheer quantity of *Specific Cause* and *Specific Cause Detail* categories, only a few examples for three select *General Causes* are shown for illustrative purposes. See Supplementary Materials, Table S1 for the full classification schema. Solid lines represent directly nested categories, whereas dotted lines indicate categories nested within a higher-level category.

"Dumped hot coals in the bed of a tree base" and "Cleaning out fire pit ring, threw out hot coals" were both reassigned under the NWCG *Specific Cause Detail* of *Improper disposal hot ashes/coals* (Fig. 2, Table S1).

We explored which specific activities were primarily driving human-caused wildfires, including recreation. However, some ignitions, though recreation-related, were not always directly categorized under the NWCG's *General Cause Recreation and ceremony*. The *Specific Causes* nested under this category are primarily focused on ceremonial and campfire use, and do not include options for recreational firearms use (nested instead under *General Cause Firearms and explosives use*) or recreational equipment and vehicle use, like off-highway vehicles (nested under *General Cause Equipment and vehicle use* (Fig. 2, Table S1). We infer that such ignitions were still recreation-related, despite being categorized differently.

2.3. Analyses

We applied a multi-scale analysis, whereby we focused first on wildfire causes across all BLM NCLs. Then, we conducted more detailed analysis in NCLs dominated by human-caused ignitions. We discuss each of these steps in more detail below. We present the results from the singular NCL with the most human-caused ignitions, and thus the most data to analyze, in the main manuscript, and provide results for others in the supplemental.

Analysis at NCL system level: Using the combined FPA FOD and WFMI cause information, we summarized fire activity in each BLM NCL. Using the BLM NCL abbreviations, we quantified the total count of human- and natural-attributed ignitions documented at each site between 1992 and 2020. We then quantified the total count of fire causes in each NCL at increasing levels of specificity: *General Cause, Specific Cause,* and *Specific Cause Detail* (Table S1) to identify patterns of human-caused ignitions. To normalize comparisons, and account for both variations in total fire counts and NCL size, we calculate the percentage contribution of each ignition cause within each site. We also explored ignition time series and spatial patterns, ordinal date of fire, and mean fire size per cause under *General Cause*, *Specific Cause*, and *Specific Cause Detail*, where possible. To assess temporal trends in ignition frequency, we employed negative binomial regression. Wildfire ignitions are discrete count data. While Poisson regression is often used for count data, preliminary analyses indicated overdispersion, with variance exceeding the mean, indicating that a negative binomial model was more appropriate. Simple linear regression was not suitable as ignition counts are non-continuous and non-negative. Furthermore, linear models assume normally distributed residuals, assumptions violated by overdispersed count data such as these. Previous studies have used regression analyses to explore wildfire frequency over time (Faivre et al., 2014; Li and Banerjee, 2021; Westerling, 2016) . We applied negative binomial linear regression models to four levels of analysis at the NCL system level: 1) total ignition count, 2) natural-ignition count, 3) human-ignition count, and 4) human-ignition count for the 16 NCLs when the MONE case study was excluded. We used the *MASS* package in R (version 4.3.1 (2023-06-16 ucrt)) (Ripley et al., 2024), and we present the slopes and p-values estimated from these regression analyses.

Analysis at NCL individual level, specifically those dominated by human-caused ignitions: We found 5 sites that were dominated by human-caused ignitions: Morley Nelson (MONE), San Juan Islands, Santa Rosa-San Jacinto Mountains, Sonoran Desert, and Mojave Trails. The MONE had the highest number by far (2087 incidents), excluding military-related ignitions. Due to its inordinately high number of human-caused ignitions compared to other units, we primarily focused our analyses on the MONE. Not only is the MONE a hotspot for understanding how human activities contribute to ignitions, the MONE experiencing these higher levels of recreation-related ignitions may serve as an early indicator of transformations that may emerge in other NCL units in the future, as recreational use continues to expand across public lands. Consistent with the NCL system-level ignition analyses, we

calculated the percentage contribution of each NWCG *General Cause* category, along with the more detailed percentage breakdowns by *Specific Cause* and, where possible, *Specific Cause Detail*. To explore seasonal patterns of recreational firearm-related shooting, we examined ordinal dates for ignitions classified under the *General Cause* of *Firearms and explosives use*, and the *Specific Causes* of *non-military tracer, inert target shooting*, and *exploding target shooting*. Lastly, we compared mean fire size (km^2) between natural- and human-ignitions and identified the General Cause categories associated with the largest average fire size among human-attributed ignitions.

3. Results

3.1. Patterns of wildfire causes across BLM NCLs

3.1.1. Natural caused ignitions dominated NCLs

Natural ignitions dominated 71 % of the NCL units (12 out of 17), with the highest frequency of natural ignitions in Grand Canyon-Parashant, followed by Grand Staircase-Escalante (Fig. 3). Human-caused ignitions were the main cause of wildfires in 29 % of the NCL units (5 out of 17): Morley Nelson (MONE), San Juan Islands, Santa Rosa-San Jacinto Mountains, Sonoran Desert, and Mojave Trails.

Natural-caused ignitions accounted for 73 % of all NCL unit ignitions between 1992 and 2020 (2257 incidents), while only 27 % were human-caused (851 incidents). Fires attributed to natural ignitions were also found to be larger in size than human-caused fires across the NCLs. Mean size of natural-caused fires across all units was 2.49 km^2 (standard deviation (SD) = 30.72), compared to the mean fire size of all human-caused ignitions at 0.82 km (SD = 8.19). The MONE unit accounted for 25 % of all NCL unit recorded ignitions, and 63 % of all recorded human-caused ignitions. Due to our stark finding that the MONE outlier is a heavy contributor to human-caused ignitions, even when excluding military-related ignitions, we gave particular focus to this unit above others to explore human-caused ignitions on public lands.

Since 1992, annual ignition frequencies across NCL units have shown an upward trend, irrespective of their cause, though this increase was not statistically significant (slope = 2.25, $p > 0.05$) (Fig. 4a–c). Annual ignitions attributed to natural causes have been consistently greater in number than those attributed to human causes. Excluding the MONE case study from human-ignition trends reveals a strong, significant increase in human-caused ignitions across the remaining 16 units, indicating that the overall upward trend is not solely driven by MONE (slope = 1.11, $p < 0.05$) (Fig. 4d).

3.1.2. General and specific causes vary across NCLs

Natural-caused ignitions were more frequent than human ignitions. Of the human-caused ignitions, the more common FPA FOD *General Causes* across the NCLs were *Firearms and explosives use, Equipment and vehicle use*, and *Recreation and ceremony* (9 %, 7 %, and 4 %, respectively). Ignition causes varied widely across the NCLs (Fig. 5), though the units' establishment dates are important to consider. Between its establishment in 2013 and 2020, for example, the San Juan Islands (SJIS) National Monument in Washington recorded 39 ignitions, primarily from Recreation and ceremony (41 %), followed by Equipment and vehicle use (33 %), and just 3 % from natural causes. Comparatively, between 2000 and 2020, the Santa Rosa-San Jacinto Mountains (SRSJ) National Monument recorded 166 ignitions, of which 42 % were due to natural causes. Of the SRSJ human-caused ignitions, the leading *General Causes* were *Equipment and vehicle use* (19 %), *Recreation and ceremony* (17 %), and *Arson/incendiarism* (11 %). *Equipment and vehicle use* was the leading *General Cause* of ignitions in both National Monuments: Mojave Trails (80 % of ignitions, though with only 15 total incidents) and Sonoran Desert (59 %, with 29 total incidents).

3.2. Specific activities' influence on wildfire patterns in the MONE NCA

3.2.1. Human-caused ignitions dominated the MONE NCA

Between MONE's NCA designation in 1993 and 2020, and excluding military-related incidents, a total of 788 ignitions were recorded in this area. Of these, 68 % were attributed to human causes (536 incidents) and 32 % were attributed to natural causes (252 incidents). Natural ignition frequency peaked in 1997 and has declined gradually over time with only 2 incidents recorded in 2018 and none documented since. Among all NCL units, MONE recorded the highest number of human-caused ignitions, which accounted for 25 % of all documented ignitions, irrespective of cause, and 63 % of all documented human attributed ignitions. MONE had the highest total ignition density of 0.32 incidents per km^2, followed by Grand Canyon-Parashant with 0.17 incidents per km^2. MONE also led in human-caused ignition density, with 0.22 ignitions per km^2, significantly outpacing natural ignitions, which occurred at a rate of 0.1 incidents per km^2. Of the 788 ignitions recorded in the MONE, 34 % were attributed to *Firearms and explosives use*, and 14 % to *Equipment and vehicle use* (Fig. 6).

61 % of the MONE ignitions documented over the analysis period had additional fire-cause information detailed under WFMI *Specific Cause* and *Specific Cause Detail* (Table 1). Of the incidents with additional WIFMI narrative, the top *Specific Cause Detail* by percentage were also nested under *Firearms and explosives use*: specifically non-military tracer

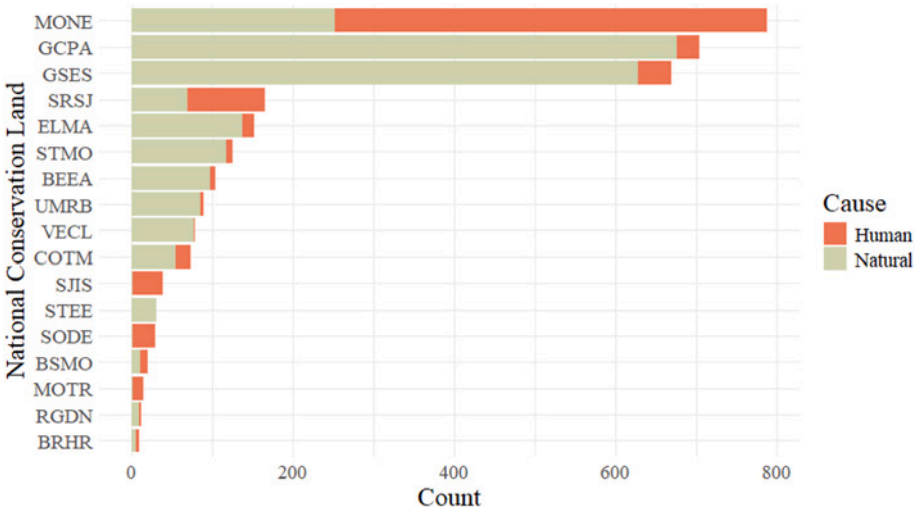

Fig. 3. Total count of human (excluding military-related) and natural ignitions documented in each NCL unit between 1992 and 2020. Refer to Fig. 1 for abbreviations.

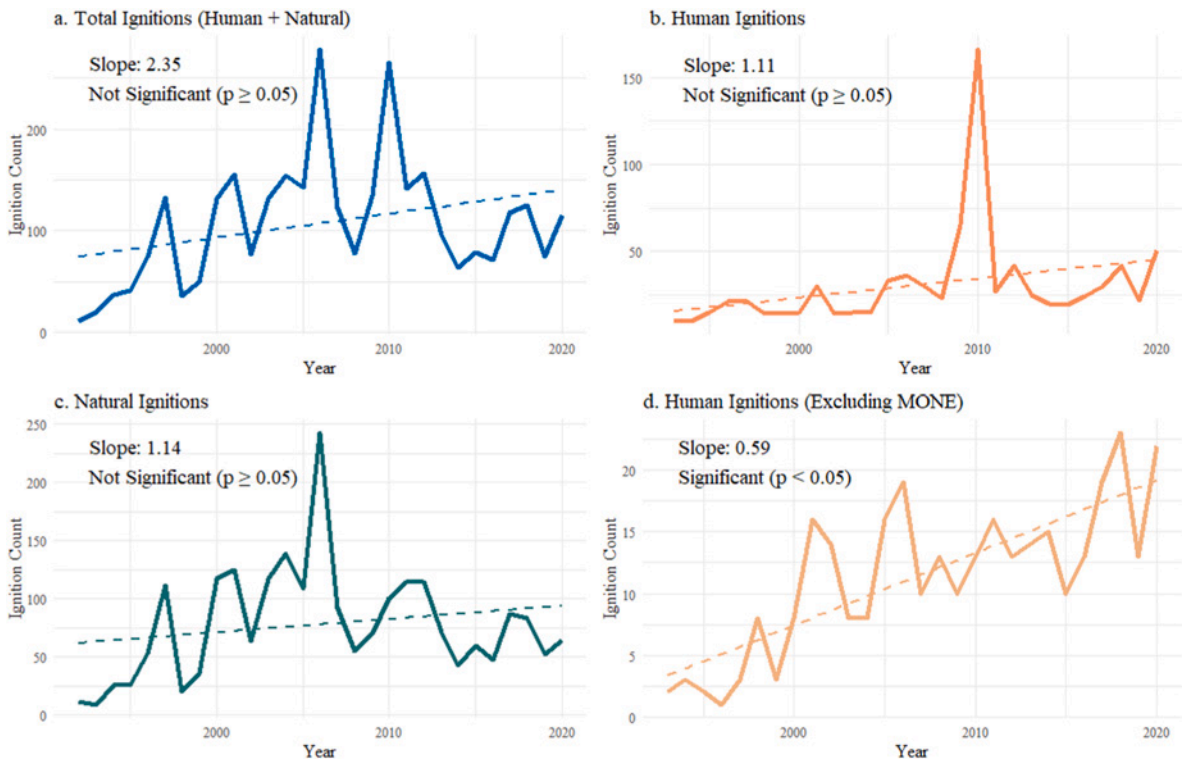

Fig. 4. Time series of ignition count across all 17 NCL units as a function of year for (a) total ignitions, (b) human ignitions, (c) natural ignitions, and (d) a comparison excluding human-caused ignitions in MONE, illustrating trends across the remaining 16 NCL units with the MONE outlier removed.

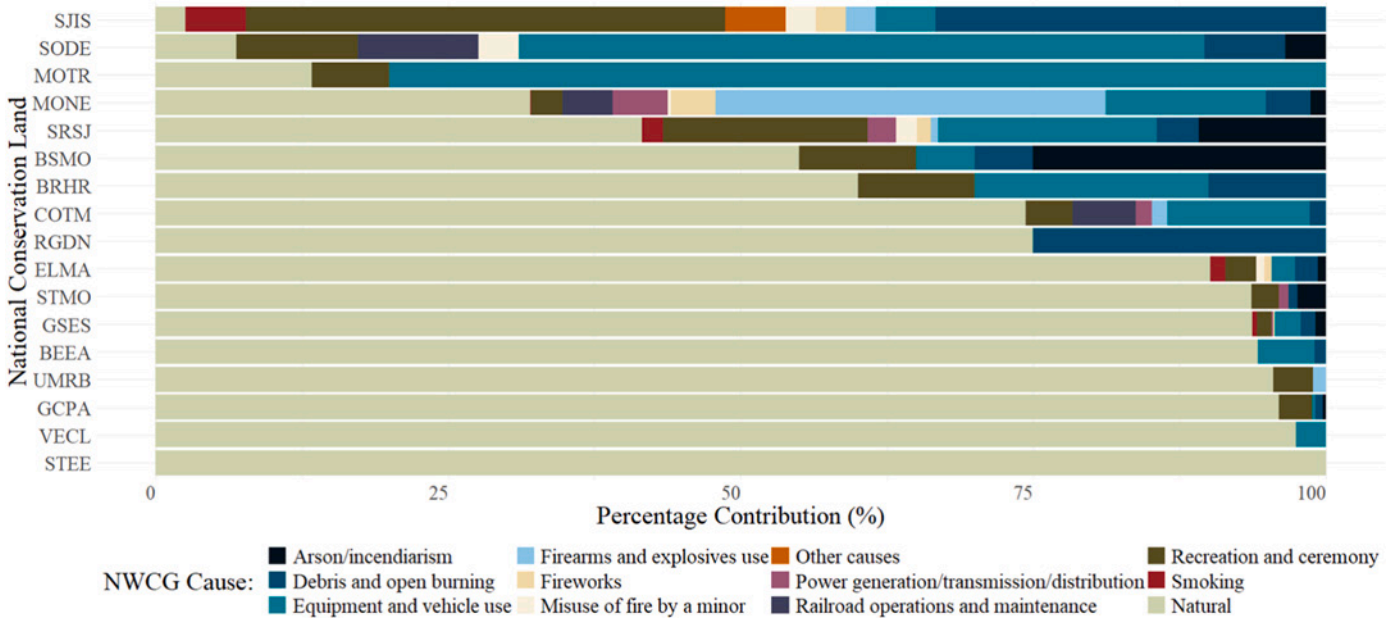

Fig. 5. Percentage contribution of General Cause for all ignitions in each BLM NCL. Refer to Fig. 1 for abbreviations.

(40.8 %), followed by inert target shooting (6.2 %). Following this were passenger vehicle/motorized recreational vehicle (RV) (6.2 %) and exhaust system (5.8 %), nested under *Equipment and vehicle use*. 5 % were attributed to *Fireworks*, followed by 4.2 % to campfires, nested under *Recreation and ceremony*. Additionally, 2 % were attributed to animal contact, categorized under the *General Cause* of *Power generation/transmission/distribution*. All incidents involved birds, including raptors and corvids, both coming into contact with, and being shot down from, powerlines.

3.2.2. *Human ignition patterns in MONE*

Human-ignitions showed strong interannual patterns and variability. Annual frequency was highest in 2010 and lowest in 2014. In both 2019 and 2020, all documented ignitions in MONE were human-caused, with 29 incidents recorded in 2020 alone.

Human ignitions showed strong intra-annual patterns. MONE ignitions attributed to *Firearms and explosives use* occurred primarily between the months of June and September (Fig. 7a). Explorations of the ordinal day of ignitions revealed that MONE ignitions attributed to non-

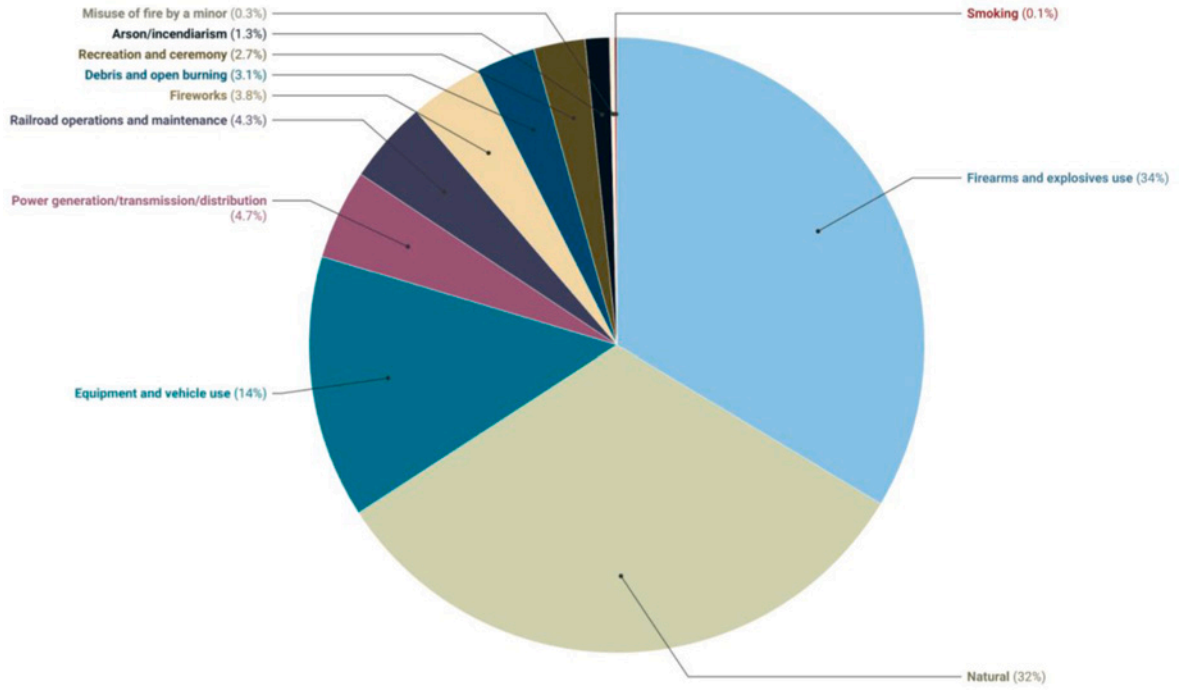

Fig. 6. Proportion of MONE ignitions under *General Cause* categories.

military tracers and exploding targets occurred between May 10th and October 20th (Fig. 7b–d), falling within the Idaho BLM fire prevention order; national or regional regulations that aim to reduce wildfire risk on public lands by prohibiting certain activities, such as incendiary devices, open fires, fireworks, and target shooting.

Within the MONE unit, human-caused ignitions attributed to *Firearms and explosives use* and *Equipment and vehicle use* exhibit spatial clustering, especially surrounding recreational dirt trails and major roads. Ignitions linked to non-military tracers were mostly concentrated within the active military area, despite being documented as civilian recreation, while inert target shooting-caused ignitions were widely distributed across the MONE.

3.2.3. *Natural ignitions in MONE*

The trend observed at the NCL level - where fires attributed to natural causes were larger than those caused by humans, both in terms of fire size and total burned area - also held true for the MONE; although natural ignitions were less frequent than human-caused ignitions in the MONE, they were responsible for significantly more area burned. On average, naturally ignited fires were significantly larger, with a mean size of 3.04 km^2 (SD = 10.97), compared to 0.38 km^2 (SD = 2.4) for human-caused fires—making natural fires roughly 10 times larger in area. The largest area burned by natural ignitions occurred in 1996, totaling 324 km^2.

Between 1993 and 2020, twelve human-caused fires exceeding 4.05 km^2 (1,000 acres) were recorded in the MONE. The largest was the 1996 Sinker Butte fire, attributed to *Equipment and vehicle use*, specifically an exhaust system, which burned over 36 km^2. The second largest, the 2015 Celebration fire, was attributed to *Recreation and ceremony*, specifically a campfire, and burned over 27 km^2. In the MONE, the largest mean fire size was linked to ignitions from *Recreation and ceremonial* activities (1.7 km^2), followed by *Power generation/transmission/distribution* (1.4 km^2), and *Fireworks* (0.49 km^2). *Firearms and explosives use* ignitions averaged 0.1 km^2, while *Railroad operations and maintenance* had the smallest mean fire size, at 0.09 km^2.

4. Discussion

We present the first exploration of ignition sources on public lands using a combination of ignition data sources. We asked first: What are the patterns of human versus natural ignitions across BLM NCLs? and second, focusing on the MONE: Which specific activities are the primary drivers of human-caused wildfires within BLM NCLs? Addressing these knowledge gaps can contribute to both refining existing, and informing new, educational and outreach content and regulatory approaches targeted to address human behaviors and minimize human-caused ignitions on public lands. Due to historical reporting inconsistencies, our analysis may not fully capture all incidents, leading us to believe that this account is likely conservative.

4.1. *Fire causes on public lands: Natural vs. human*

Our findings that natural ignitions predominated public lands and occurred more frequently than human ignitions (73 % natural), contrast with the well-documented national trends, which indicate that 84 % of ignitions are typically human-caused (Balch et al., 2017). Regionally, however, our findings support the previously documented general pattern of elevated natural ignitions in the Intermountain western US (Balch et al., 2017). The dominance of natural ignitions on public lands may be due to comparatively fewer people in these areas, but could also be due to an improved capacity to accurately attribute ignition sources on public over private lands. Often occurring in more remote, densely vegetated and less populated areas, natural ignitions have the capability to spread naturally across larger areas. In support of previous research at the national and regional (western US) scale (Abatzoglou et al., 2016, 2018; Cattau et al., 2020; Nagy et al., 2018), we found that natural fires were often much larger in size, burning more acres than human-caused fires. Climate and fuel variability are primary drivers of natural ignitions, evidenced by the strong correlation between annual area burned and interannual climatic variables influencing fuel abundance and flammability (Abatzoglou et al., 2016). Live fuel moisture content, notably dry, flammable vegetation, has been shown to increase the likelihood of natural ignitions, especially in shrub-dominated areas (Rao et al., 2023). The prevalence of fire-prone ecosystems like sagebrush

Table 1
Percentage of human-caused ignitions in the MONE NCA, according to detailed narrative from the Wildland Fire Management Information (WFMI) system, between 1993 and 2020. Ignitions related to military activities and operations excluded.

General Cause	Specific Cause/Specific Cause Detail	Percentage (%)
Arson/incendiarism	Device	0.42
	Hot set	0.21
	Vehicle arson	0.21
Debris and open burning	Open trash burning	1.46
	Other land clearing	2.49
Equipment and vehicle use	Brakes	1.04
	Chain/dragging object	0.42
	Electric motor/power tools/ battery	0.83
	Exhaust system	5.82
	Heavy equipment & implements	0.42
	Inert target shooting	0.21
	Other (remarks required)	0.42
	Other mechanical failure	0.83
	Passenger vehicle/motorized recreational vehicle (RV)	6.24
	Sparks/metal fragments from cutting/welding	0.42
	Tire/wheel failure	0.83
	Trailer	0.21
	UAS/model rockets & airplanes	0.21
	Unknown (remarks required)	3.74
Firearms and explosives use	Blasting	0.42
	Exploding target shooting	1.66
	Flares/fusees	0.21
	Inert target shooting	6.24
	Non-military tracer	40.75
	UAS/model rockets & airplanes	0.21
Fireworks	Fireworks	4.99
Power generation/ transmission/distribution	Animal contact	2.08
	Electrical transmission/ distribution systems	5.61
Railroad operations and maintenance	Brakes	2.91
	Exhaust particles	2.49
	Rail grinding	0.21
	Track replacement	0.42
	Unknown (remarks required)	1.04
Recreation and ceremony	Campfire	4.16
	Improper disposal hot ashes/coals	0.21

steppe across public lands in the western US likely contributes to the higher incidence of natural ignitions in these regions.

Public lands may represent a growing contributor of human-caused ignitions. Our key finding —that even when the MONE case study is excluded, the remaining 16 NCLs still exhibit a strong, significant increase in human-caused ignitions—supports this, indicating that the upward trend in human-started fires is not solely driven by MONE. Moreover, the trend suggests that NCLs may be departing from regional patterns, which are typically dominated by natural ignitions. MONE may represent a potential future scenario for other NCLs, where increased recreational activities contribute to elevated wildfire risk, as outdoor use of public lands continues to rise. In addition, recreational shooting may increase across public lands under the 2025 Expanding Public Lands Outdoor Recreation Experiences (EXPLORE) Act, which requires the BLM and Forest Service to establish at least one shooting range in their respective districts freely available and accessible to the public (U.S. House of Representatives, 2024). Nationally, human-ignition hotspots have been found to be strongly related to anthropogenic presence, especially close to high road density areas and near and within the wildland-urban interface (WUI) (Narayanaraj and Wimberly, 2012). The WUI, where properties and vegetation intersect and intermingle, acts as a major source of human-caused ignitions, associated with greater numbers of threatened residential structures and higher suppression costs (Mietkiewicz et al., 2020). While still relatively infrequent, our findings demonstrate that human-caused ignitions have become an increasing occurrence on public lands in the last few decades, which supports trends observed at the national level (Balch et al., 2017; Nagy et al., 2018). The broader impacts of human-caused ignitions vary significantly depending on the context. In the WUI, such ignitions threaten communities and residential properties, whereas on public lands, these ignitions threaten valuable ecosystem functions, habitats, biodiversity, and grazing and recreational opportunities. Ignitions on public lands in the western US likely also exacerbate sagebrush habitat fragmentation and range contraction, with cascading effects on sage-obligate species. As wildfire activity continues to shift, and climate change amplifies fuel and ignition risks, growing numbers of human-caused ignitions are expected to further transform public lands.

4.2. Recreation-related activities contributed to human-caused ignitions in the MONE

MONE had unique human-caused wildfire patterns and trends, with 68 % of unit incidents attributed to human causes. The semi-arid climate that characterizes this unit may contribute to its heightened sensitivity to ignitions compared to other NCLs. Additionally, the expansion and spread of cheatgrass is likely accelerating the invasive grass-fire cycle, altering both fire frequency and size. These dynamics, in tandem with other drivers, have already contributed to the fragmentation of remaining sagebrush steppe ecosystems, and may help explain the higher human-caused ignition frequency observed in MONE (Holbrook et al., 2016; Pilliod et al., 2017). Compared to other NCL units, the pattern in MONE aligns more closely with national trends showing that most wildfires in the US are human-caused (Balch et al., 2017; McGranahan and Wonkka, 2024; Nagy et al., 2018), yet contrasts with the predominance of natural ignitions typically observed in the interior West. Although generally smaller than natural fires, human-caused fires are increasing in size and burning over longer season lengths at both national regional scales (Balch et al., 2017; Cattau et al., 2020; Dennison et al., 2014; Nagy et al., 2018; Westerling, 2016). Human-caused ignition patterns in the MONE demonstrated these trends, and as such, we suggest that this NCA represents a potential future state of other public lands in the West—where wildfires from recreational shooting are likely to increase over time under the EXPLORE Act. Recreational use of firearms and explosives use, specifically non-military tracers and inert target shooting, accounted for 41 % and 6 % of ignitions in the MONE unit, respectively. The rise in recreation-related firearms ignitions suggests higher visitation to the NCA, potentially driven by population growth in the Treasure Valley and Boise Metropolitan Statistical Area (Requena-Mullor et al., 2023). The MONE, easily accessible from these regions, may have experienced more recreation, with consequences such as heightened potential for human-caused ignitions, invasive species introduction and spread, grass-fire cycle acceleration, unauthorized trail development, and landscape degradation.

Our findings highlight the popularity of recreational shooting in MONE, supporting previous research that documented common practices such as legal target shooting of static targets and the hunting of Piute ground squirrels (*Urocitellus mollis*), for which open shooting is permitted, despite being a valued prey resource for raptors (Aberg, 2023; Thomason et al., 2024). Illegal shooting of protected nongame birds, particularly raptors and corvids, has also been documented in MONE (Aberg, 2023), despite the area's designation for raptor protection and conservation. Illegal shooting has been found to peak between March and May coinciding with the highest levels of recreational shooters in the NCA and occurring in high-use areas, although not exclusively (Aberg, 2023; Thomason et al., 2024). Illegal target shooting of birds along powerlines has been documented here, challenging the common assumption that birds die primarily from powerline electrocution (Aberg, 2023). Not only did our analyses demonstrate fires result from individuals shooting powerlines down (6 % *inert target shooting*), we speculate that 2 % of *animal contact* fires, nested under the *General Cause* of *Power Generation/Transmission/Distribution*, could be the result

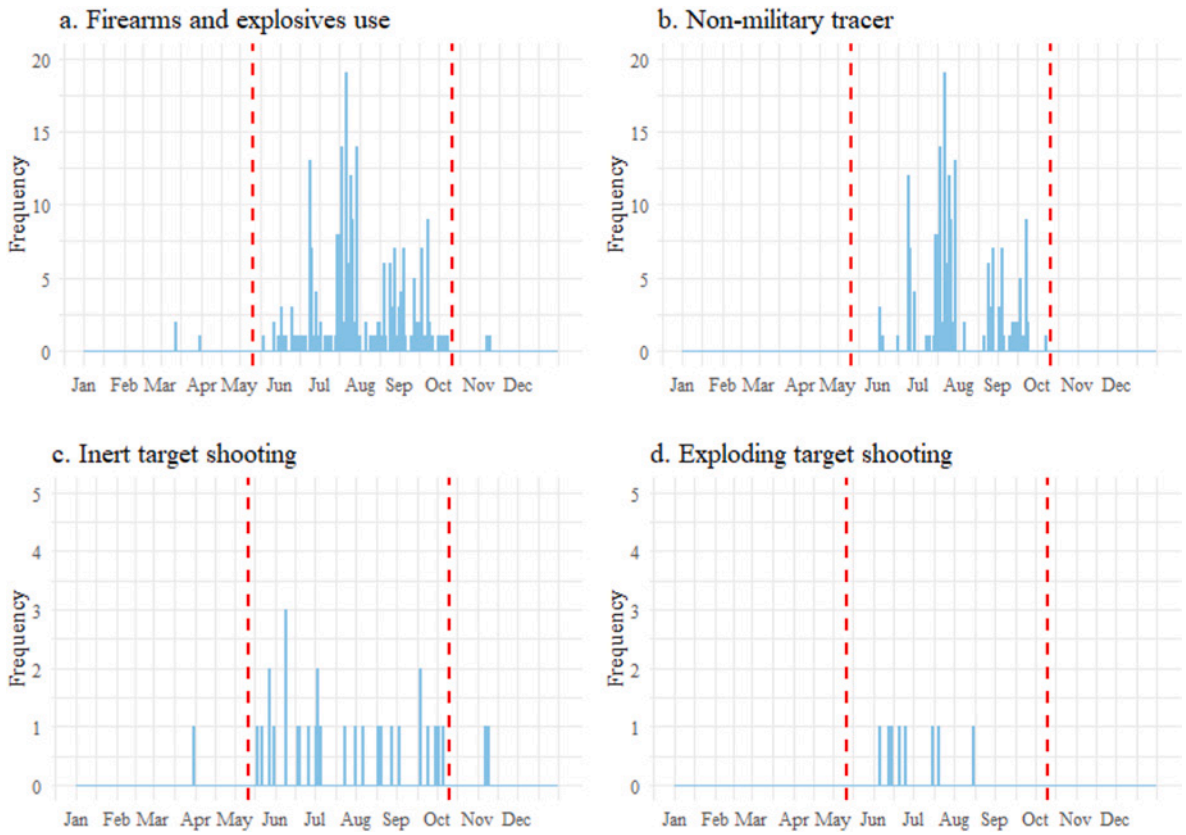

Fig. 7. Date of human-caused ignitions in MONE attributed to (a) *General Cause* of *Firearms and explosives use*, and specific causes of (b) non-military tracer, (c) inert target shooting, (d) exploding target shooting. The red lines represent the dates of the BLM Fire Prevention Order, from May 10th to October 10th.

of illegal shooting of nongame birds based on accompanying WFMI Remarks, such as: 'Burned hawk found in origin area under power pole'. Firearms use is permitted on all BLM-administered public land, however, unlike other NCLs, numbers of gun shops and shooting ranges surrounding this unit are high, with approximately 20 gun shops within 45 miles of the MONE. The rise in recreational shooting within the MONE has been linked to increases in certain practices, such as dumping, shooting at trash, and wildlife poaching. Furthermore, we demonstrate that firearms and explosives use in MONE have occurred during the Idaho BLM Fire Prevention Order from May 10 to October 10, raising questions about the enforcement and effectiveness of fire prevention orders, with the caveat that the implementation date of this order is unclear. Targeted mitigation efforts will be needed to reduce ignitions attributed to *Firearms and explosives use* in this unit, and this is especially critical in light of MONE's most recent South Travel Management Plan (TMP) decision in February 2024 which will increase recreation to this area through the designation of 236 new motorized route miles and 37 non-motorized route miles in northern Owyhee County, providing access to 453.6 km^2 (112,087 acres) of BLM-managed public land (Appelhof, 2024). We expect that the new recreational routes will intensify the rising trends of human-caused ignitions, especially those due to *Firearms and explosives use* and *Equipment and vehicle use.* While this issue is currently most pronounced in the MONE, similar patterns may emerge in other public lands over time as recreational demands increase.

There is a need to focus on reducing ignitions caused by recreational shooting, particularly target shooting and tracers. Efforts to reduce wildfire risk from shooting may include improving educational messaging to explicitly target recreational shooters, with messaging such as 'avoid shooting in windy conditions to minimize risk of igniting fires with hot bullet fragments', or 'choose targets that are made of safer, less combustible materials'. Efforts may also involve encouraging recreational shooters to carry fire suppression tools and be prepared to extinguish any fires that may result from their activities (Nelson, 2025). We demonstrate the need for safe fire-proof bullets for use in firearms and shooting ranges, especially in arid, fire-prone areas like the sagebrush steppe. These suggestions apply to public lands broadly, not just BLM units (Edgeley et al., 2025). We encourage public land agencies to address human-caused ignitions more proactively and as a matter of urgency, especially those caused by recreational shooting.

4.3. Reporting procedures influence historical fire reports

Our findings may represent a conservative estimate of human-caused ignitions due to historical reporting inconsistencies and underreporting. Historical fire reports rarely include the *Specific Cause Detail* and narrative necessary to fully attribute fires, especially those attributed to *Firearms and explosives use*, which was only included as a NWCG *General Cause* in 2020 (Short and Finney, 2022). As such, it is likely that historically there are higher numbers of *Firearms and explosives use* ignitions, but that these have been attributed to a different cause (Short and Finney, 2022). The ambiguous fire-cause categories in historical reporting systems (e.g., Miscellaneous as a *General Cause)* may simultaneously underestimate firearms-related wildfire events in earlier years and exaggerate the increase observed in recent years, as reporting standards have changed (Short and Finney, 2022). Historical data inconsistencies, together with evolving fire cause reporting standards, can introduce uncertainty into observed trends.

Accurately attributing human-caused ignitions in detailed reporting is challenging. Detailed fire cause reporting can benefit our understanding of human-caused ignition trends and impacts, especially for future monitoring of firearms related wildfires (Short and Finney, 2022). Our work provides support for the updated NWCG fire cause standard that recognizes *Firearms and explosives use* as a *General Cause*. However,

we suggest additional improvements to the NWCG fire cause standard to a) include more categories nested in *Specific Cause* under certain *General Cause*, and b) to permit selecting multiple categories during reporting, such as *Recreation and ceremony* and *Firearms and explosives use*. The current NWCG reporting standards make it challenging to specifically attribute ignitions to recreation-related activities, leading to uncertainty. For example, ignitions caused by all-terrain vehicles are nested under *Equipment and vehicle use*, yet such motorized vehicles are commonly used for recreational purposes. The *Recreation and ceremony General Cause* focuses more on campfires and smokers, and does not include options for ignitions caused by recreational vehicles or recreational shooting. The NWCG standard does include an *Activity/Group* attribute that could help identify occurrences of equipment and vehicle or firearms use associated with "recreation" but Activity/Group entries are currently optional even in the latest federal reporting systems (NWCG, 2020b). Permitting the selection of multiple causes of making identification of Activity/Group required in the reporting process may reduce uncertainty around ignition causes and improve ignition attribution, helping to better understand the diverse range of human ignition causes on both public and private lands.

In addition to accurately attributing ignition cause under *Specific Cause Detail*, fire reports can include information on whether or not an ignition occurs in a *Special Area*, such as a National Monument, Area of Critical Environmental Concern, or Recreation Area. Despite all occurring on public lands, 55.4 % of all reported ignitions (745 incidents) were categorized as *No Special Area Type designation*. Specifying the type of land on which an ignition is documented, along with specific details on varying causes, can contribute to our overall understanding of ignition drivers and causes. This, in turn, supports the development of more effective educational outreach and regulatory strategies aimed at influencing human behavior and reducing human-caused ignitions on public lands.

4.4. Future research

Future research could explore ignition causes on other federally managed public lands, such as other acres managed by the BLM, National Park Service, US Forest Service, Fish and Wildlife Service, Department of Defense. We did not explicitly explore the level to which each agency reports ignitions, but there is likely bias across these agencies. Differences in governance across federal land management agencies could be explored, specifically the extent to which this may influence ignition reporting procedures, ignition cause detail inclusion, and efforts to reduce human-caused ignitions. For example, previous research found that few BLM Resource Management Plans explicitly address increasing wildfire events in tandem with climate change (Brice et al., 2020). Exploration of public land management plans across agencies could contribute to a better understanding of how different agencies are addressing heightened human-caused ignitions from increasing recreation. Future research could explicitly compare across all US military training areas to explore military-related ignition trends over time. Consideration of additional broader impacts of human-caused fires is also needed, such as suppression funding, wildfire smoke, and destruction to trails and other recreation-related infrastructure. Lastly, future research into safer, less-flammable ammunition for firearms and shooting ranges is needed, especially in the context of arid shrub steppe landscapes.

5. Conclusions

Our multi-scale analysis revealed that natural ignitions have consistently dominated public lands, however human-caused ignitions, while less frequent overall, have increased significantly in frequency since 1992, indicative of a potential departure from regional ignition trends. Strongly dominated by human-caused ignitions, the MONE was an exception, with pervasive ignitions attributed to recreational-related firearms and explosives use. The dominance of natural ignitions may reflect the remoteness of many public lands but also suggests the effectiveness of land management agencies to reduce human-caused ignitions. However, rising human-caused ignitions stemming from growing recreation and firearm use present an emerging wildfire risk to sagebrush steppe ecosystems, especially when combined with changes in climate, land use, and invasive species abundance. Our findings support the need for targeted mitigation to address high ignition risk from activities like recreational shooting, such as promoting safer, fireproof ammunition and designated shooting ranges. We endorse the revised NWCG fire–cause data reporting standards that will continue to make fire data more robust and recommend offering additional and more refined *Specific Cause* categories, or more widespread use of *Activity/Group*, to better capture the complexity of ignition sources nested under each *General Cause*. Additionally, our work highlights challenges of attributing ignitions that may have more than one cause. Permitting multiple cause selections during reporting could improve ignition attribution and support more accurate, robust fire data nationally that capture the wide array of human activities responsible for human-caused ignitions. Together, these recommendations can help support land management agencies in fulfilling their multiple-use mandate while contributing to a more resilient and sustainable public lands management strategy with reduced human-caused ignitions.

CRediT authorship contribution statement

Megan R. Dolman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karen C. Short:** Writing – review & editing, Methodology, Data curation. **Jodi S. Brandt:** Writing – review & editing. **Mark A. Finney:** Writing – review & editing. **T. Trevor Caughlin:** Writing – review & editing. **Megan E. Cattau:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.128564.

Data availability

Data will be made available on request.

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