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Extreme Fire Spread Events Burn More Severely and Homogenize Postfire Landscapes in the Southwestern United States

Jessika R. McFarland[1] | Jonathan D. Coop[1] | Jared A. Balik[1] | Kyle C. Rodman[2] | Sean A. Parks[3] | Camille S. Stevens-Rumann[4]

[1]Clark School of Environment & Sustainability, Western Colorado University, Gunnison, Colorado, USA | [2]Ecological Restoration Institute, Northern Arizona University, Flagstaff, Arizona, USA | [3]Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service, Missoula, Montana, USA | [4]Forest and Rangeland Stewardship and Colorado Forest Restoration Institute, Colorado State University, Fort Collins, Colorado, USA

Correspondence: Jessika R. McFarland (jessika.mcfarland@western.edu)

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ABSTRACT

Extreme fire spread events rapidly burn large areas with disproportionate impacts on people and ecosystems. Such events are associated with warmer and drier fire seasons and are expected to increase in the future. Our understanding of the landscape outcomes of extreme events is limited, particularly regarding whether they burn more severely or produce spatial patterns less conducive to ecosystem recovery. To assess relationships between fire spread rates and landscape burn severity patterns, we used satellite fire detections to create day-of-burning maps for 623 fires comprising 4267 single-day events within forested ecoregions of the southwestern United States. We related satellite-measured burn severity and a suite of high-severity patch metrics to daily area burned. Extreme fire spread events (defined here as burning > 4900 ha/day) exhibited higher mean burn severity, a greater proportion of area burned severely, and increased like adjacencies between high-severity pixels. Furthermore, increasing daily area burned also resulted in greater distances within high-severity patches to live tree seed sources. High-severity patch size and total high-severity core area were substantially higher for fires containing one or more extreme spread events than for fires without an extreme event. Larger and more homogenous high-severity patches produced during extreme events can limit tree regeneration and set the stage for protracted forest conversion. These landscape outcomes are expected to be magnified under future climate scenarios, accelerating fire-driven forest loss and long-term ecological change.

1 | Introduction

Forests across many regions of Earth are experiencing increases in wildfire activity, with significant impacts on ecosystems and societies (Bowman et al. 2020). Recent record-setting fire seasons in disparate regions of North America, Australia, and Europe have imposed immense costs on human health and lives, altered habitats, and disrupted ecosystem functions (Filkov et al. 2020; Leone et al. 2023; Jain et al. 2024; MacCarthy et al. 2024). Across a wide range of forest types, climate change and land use legacies have extended fire season lengths, produced more extreme fire weather, and increased the aridity and availability of fuels, leading to rising fire frequency, area burned, and in some regions, burn severity

(Abatzoglou and Williams 2016; Singleton et al. 2019). Where fire behavior and effects exceed the range of variability to which species are adapted, changing fire regimes can rapidly transform forest ecosystems, particularly under a warming climate (Johnstone et al. 2016; Coop et al. 2020; Turner and Seidl 2023).

Extreme wildfires, characterized by high intensity and unusually rapid spread (Duane et al. 2021; Tedim et al. 2018), are an emerging global phenomenon that challenges existing fire science and management. A focus on extremes highlights the disproportionate impacts of a small subset of the fastest (Balch et al. 2024), most intense (Cunningham et al. 2024), or most damaging fires to human communities (Bowman et al. 2017). Over the duration of any given fire, one or more days of exceptional fire growth (referred to here as *extreme fire spread events*) can have outsized effects on total area burned by individual fires and over fire seasons (Wang et al. 2021; Potter and McEvoy 2021; Coop et al. 2022; Brown et al. 2023; Balik et al. 2024). However, beyond area burned, the outcomes of such events on postfire landscapes, and their implications for forest resilience (the capacity for forest ecosystems to resist, recover or adapt after disturbance; Falk et al. 2022), have not been explicitly assessed. In particular, it is not known if extreme fire spread events burn more severely or produce different burn severity patterns than nonextreme events. As these events are expected to increase under future warming (Coop et al. 2022), understanding burn severity and postfire landscape outcomes may be critical to anticipating ecological impacts.

Burn severity patterns control important ecological processes in postfire landscapes. Fine-scale mosaics of varying burn severity can promote diversity in habitats, species, and ecosystem functions (Kolden et al. 2015; He et al. 2019; Jones and Tingley 2022). However, recent increases in area burned at high severity (Singleton et al. 2019; Parks and Abatzoglou 2020) may jeopardize forest resilience. Large high-severity patches can restrict postfire tree regeneration by reducing propagule availability, especially for obligate-seeding, nonserotinous conifers (Chambers et al. 2016; Kemp et al. 2019). High-severity patch patterns can also influence patterns of postfire tree regeneration—homogeneous high-severity patches further increase distances to live tree seed sources (Stevens et al. 2017; Singleton et al. 2021). Large, severely burned patches also interact with climatic drivers, enhancing postfire surface warming, with impacts on tree regeneration (Davis et al. 2019) and future fire activity (Zhao et al. 2024). Recent research has explored patterns of burn severity as a function of wildfire size, with increases in area burned associated with larger high-severity patch size, core area, aggregation, and reduced patch complexity (Potter 2017; Singleton et al. 2021; Buonanduci et al. 2023, 2024; Cova et al. 2023). However, the extent to which these patterns may be related to fire spread rates is unknown.

The purpose of this study was to contrast the landscape outcomes of extreme fire spread events with those of nonextreme events, and more generally, to assess relationships between daily fire spread rates and patterns of burn severity. Because the conditions that give rise to extreme events (e.g., continuous fuels, high fuel aridity, and high wind) also increase fuel consumption and fireline intensity (Turner et al. 1994), we expect daily fire growth rates to be positively associated with burn severity. Further, we expect the most extreme events to produce the largest, most homogeneous high-severity patches.

Growing availability of extensive, remotely sensed datasets and products, and improved methods to characterize daily fire growth, burn severity, and postfire landscape patch metrics facilitate effective analyses of the processes and patterns left by wildfire across large landscapes. Accordingly, the specific objectives of this study are as follows. First, we assess relationships between daily fire spread and burn severity using satellite-derived day-of-burning (DOB) maps and burn severity datasets. We categorize extreme fire spread events based on daily fire growth rates, following Balik et al. (2024), defining extreme fire spread events as >2 SD (standard deviations) from the mean daily growth rate, large fire spread events as 1–2 SD from the mean, and common fire spread events as ≤ 1 SD from the mean. We then test for differences in burn severity and the proportion of area burned severely (i.e., $>90\%$ overstory canopy mortality; Miller et al. 2009) between these event types, and as a function of daily area burned. Second, we assess relationships between spread event type, daily fire spread rate, and high-severity patch size and aggregation characteristics in the context of potential forest recovery. To accomplish this objective, we calculate a suite of landscape metrics (percentage of like adjacencies, distance to nearest live tree seed source, area-weighted mean patch size, and total core area) for high-severity patches, and examine how they vary with daily fire event size and categorical spread event types. We focus this study on forests of the southwestern United States, which are particularly vulnerable to ecosystem transformation catalyzed by severe fire, warming, and drought (Guiterman et al. 2022). Findings are intended to shed light on how changing burning conditions can lead to altered postfire landscapes, with implications for the resilience of fire-prone forests globally.

2 | Methods

2.1 | Study Area

Our study region comprises four forested EPA Level III ecoregions (EPA 2023) in the southwestern United States (Figure 1). This area is characterized as semi-arid, with strong spatial and topographic influences that create regional differences in weather and climate (Sheppard et al. 2002). Although seasonal droughts occurred in this region before the onset of anthropogenic climate change, the Southwest has experienced an intensifying megadrought within the last two decades (El-Vilaly et al. 2018; Williams et al. 2022). Yearly moisture availability in this region is largely provided by winter snowfall and seasonal monsoon events in middle to late summer (Sheppard et al. 2002), both of which can play important roles in modulating fire activity (Singleton et al. 2021).

Forests across the southwestern United States have been shaped by fire for millennia and represent a wide spectrum of forest types and historical fire regimes (Table S1). Common forest types include, but are not limited to, ponderosa pine (*Pinus ponderosa*), mixed-conifer (e.g., *Pseudotsuga menziesii; Abies concolor; Picea pungens*), aspen (*Populus tremuloides*), lodgepole

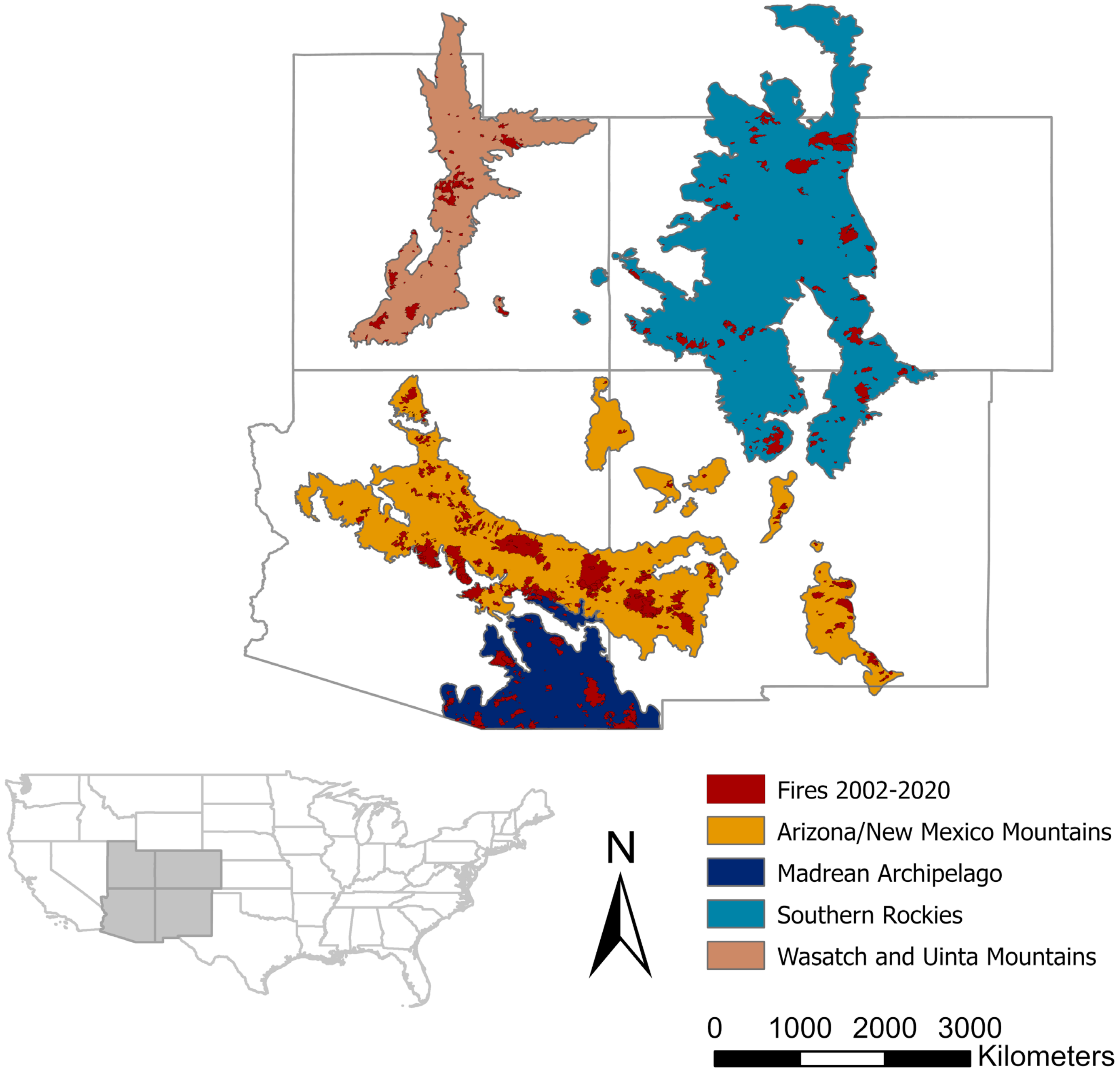

FIGURE 1 | Map of the southwestern US study area, large (>400 ha) fire perimeters (2002–2020), and the forested ecoregions included in this analysis (EPA 2023). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

pine (*Pinus contorta* var. *latifolia*), and spruce-fir (*Picea engelmannii; Abies lasiocarpa*). Historically, lower elevation ponderosa pine forests tended to burn frequently but at low severity, with fire spread often limited by the availability of fine fuels (Swetnam and Baisan 1996; Veblen et al. 2000). Higher elevation spruce-fir forests had infrequent but stand-replacing fires, typically limited by climatic conditions that control fire season length and fuel flammability (Sibold et al. 2006). Between these forest types, mid-elevation mixed-conifer forest fire regimes were variable and mixed in frequency and severity (i.e., mixed-severity; Schoennagel et al. 2011; Tepley and Veblen 2015).

Although forest types in the southwestern United States contain tree species with a wide range of fire-adapted traits, the compounding influences of climate change and land management legacies have driven departures from the historical range of variability in parts of this region (Dillon et al. 2011; Higuera et al. 2021; Parks et al. 2023). Prior to Euro-American settlement, lightning strikes and Indigenous land use practices had strong influences on local fire regimes (Allen 2002; Lake et al. 2017; Roos et al. 2022). However, these relationships and fire regimes were severely altered in many areas with the onset of settler colonialism and the displacement and genocide of Indigenous peoples (Liebmann et al. 2016; Roos et al. 2022). The combined effects of livestock grazing, extraction of large fire-resistant trees, cessation of Indigenous ignitions, and fire suppression policies have produced both fire deficits and fuel accumulations prone to anomalously severe, stand-replacing fire (Swetnam and Baisan 1996; Bowman et al. 2011; Parks et al. 2023; McClure et al. 2024).

2.2 | Day-Of-Burning Maps, Burn Severity, and Forest Cover

We used a suite of remotely sensed and spatial data products to measure daily fire progression, identify extreme fire spread events, and characterize subsequent patterns of burn severity and patch characteristics (Figure S1). First, we acquired fire perimeter data for large fires (> 400 ha) that occurred within our study area between 2002 and 2020 from the Monitoring Trends in Burn Severity program (MTBS) (Picotte et al. 2020). Next, we developed spatially continuous, DOB maps (Figure 2a) interpolated from MODIS and VIIRS fire detection data following the methods of Parks (2014) for each fire (30-m resolution). Briefly, this method uses fire detections to identify and map predicted days of burning, which are then constrained to final fire perimeters. Following previous studies (Coop et al. 2022; Balik et al. 2024), fire detections between midnight and 6 am were assigned to the previous DOB. Fires with < 10 unique detections were excluded from analysis. In total, we synthesized fire progression data for 623 fires comprising 4267 daily fire spread events.

We assigned each daily fire spread event into "extreme," "large," or "common" categories (Figure 2B) as follows: extreme events exceeded 4900 ha/day (> mean + 2 SD of all $\log_{10}$-transformed DOB areas), large events were between 1286–4900 ha

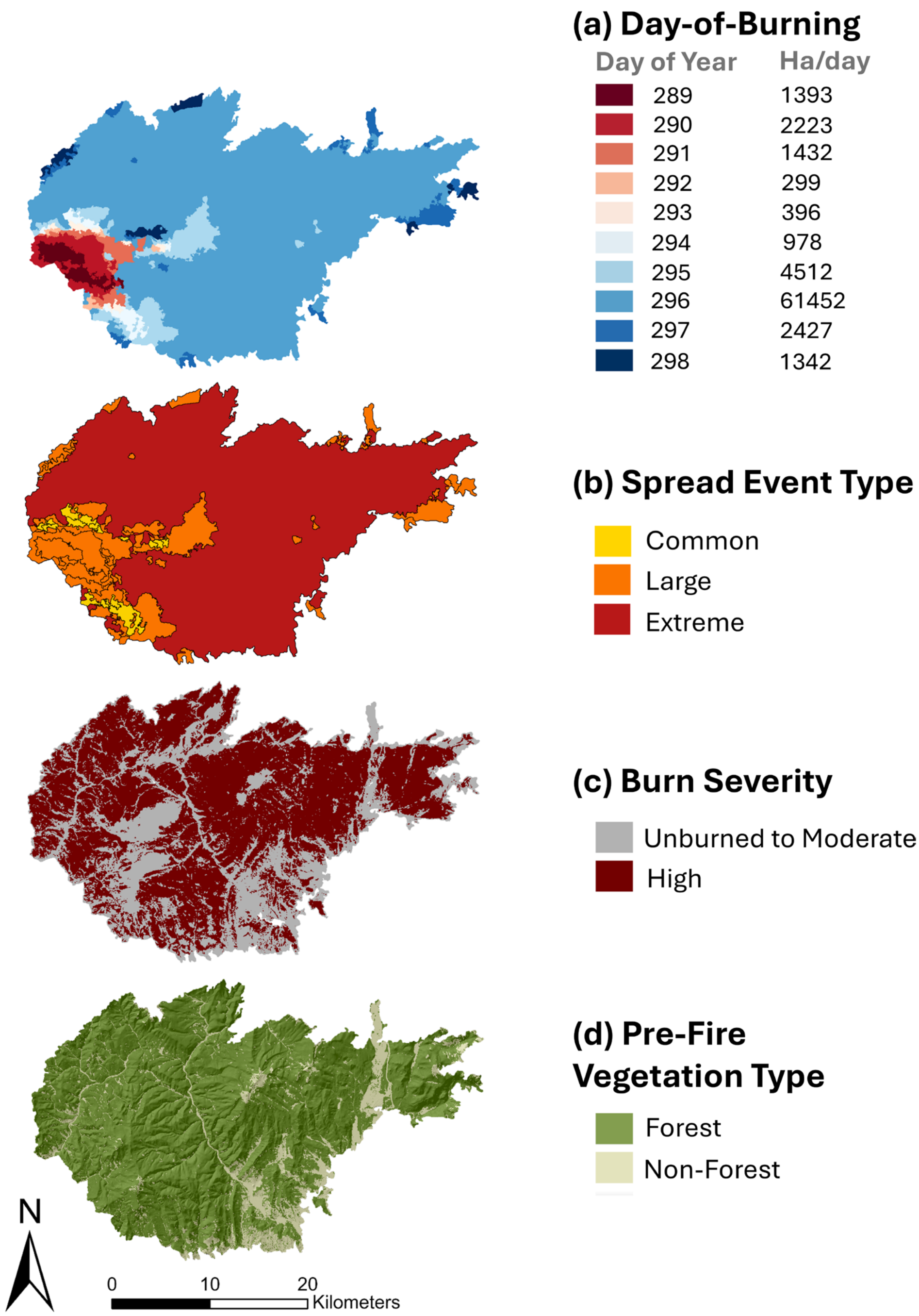

FIGURE 2 | Example shows the East Troublesome fire, depicting (a) daily fire progression, (b) categorical fire spread event types, (c) high-severity burn patches (red), and (d) prefire vegetation with topographic relief. The East Troublesome fire burned 78,000 ha in Colorado in October 2020.

(mean + 1SD < X < mean + 2SD) and common events were less than 1286 ha (< mean + 1SD). We also classified individual fires based on whether they included one or more extreme fire spread events. Of our 623 fires, 56 fires (~9%) featured one or more extreme fire spread events.

Gridded burn severity (30-m resolution) was measured as the predicted composite burn index (CBI), derived from Google Earth Engine (Gorelick et al. 2017) and the Random Forest model developed by Parks et al. (2019). This model uses pre- and postfire Landsat imagery, climate, and latitude to estimate field-measured CBI, which represents the cumulative aboveground effects of fire events on soils, surface fuels, and vegetation (Key and Benson 2006) on a scale from 0 (unburned) to 3 (highest degree of severity). We used a threshold of CBI ≥ 2.25 to categorize high-severity pixels (Miller and Thode 2007) and grouped pixels into high-severity patches (Figure 2C) using eight-neighbor contiguity. Because our study focuses on forests, we restricted our analyses to pixels identified as conifer, mixed-conifer, hardwood, and exotic tree-shrub classes in LANDFIRE existing vegetative type (EVT) data before the fire event (Toney et al. 2012; Figure 2D). We used the year of LANDFIRE data (2002, 2012, 2016, and 2020) that was closest to the pre-fire year.

2.3 | Landscape Metrics

We calculated a suite of landscape metrics for high-severity patches to characterize postfire burn severity patterns within each fire spread event (Table 1). Landscape metrics are a powerful way to describe landscape patterns and infer ecological processes (O'Neill et al. 1988; Cushman et al. 2008). We used the terra package for raster processing (Hijmans et al. 2022) and the landscape metrics package (Hesselbarth et al. 2019) in R (R Core Team 2022) to calculate high-severity metrics within each fire. Some metrics were averaged at the scale of daily fire spread events, and others were averaged within the fire perimeter itself (Table 1; Column "Unit of analysis"). All landscape metrics were calculated solely from pixels that were forested prior to fire, based on the most recent prefire Landfire EVT.

We extracted continuous CBI data from random points subsampled at 0.01% across all fires in our dataset (n = 308,404) to reduce pseudoreplication. Proportion of area burned at high severity and percentage of like adjacencies were used to examine the spatial pattern of high-severity patches within daily fire spread events. Percentage of like adjacencies summarizes the percentage of high-severity 30-m cells adjacent to other high-severity cells, ranging from 0% (uniformly spaced; all pixels in different patches) to 100% (highly aggregated; all pixels in one patch). Distance to nearest live tree seed source was calculated as the distance between points randomly sampled at 0.01% in each high-severity patch (n = 87,683) and the nearest forested pixel that was unburned or burned at low/moderate severity (CBI < 2.25). Total core area was calculated as the cumulative area burned at high severity per fire that was 3 pixels (~100 m) from a patch edge. This distance threshold was selected to represent potential seed dispersal limitations for nonserotinous conifer species in high-severity patches, as studies in the southern Rockies observe tree regeneration declines when live tree seed sources exceed distances of 50–100 m (Chambers et al. 2016; Korb et al. 2019).

2.4 | Analysis

We conducted statistical analyses of burn severity and landscape metrics at two scales: daily fire spread events within fires and fires themselves (Figure S1). To understand the influence of daily fire spread, we modeled burn severity (CBI), proportion of area burned at high severity, percentage of high-severity like adjacencies, and distance to nearest live tree seed source as a function of categorical daily fire spread event type (i.e., extreme, large, and common) and continuous values of daily area burned. Area-weighted mean high-severity patch size and total high-severity core area were calculated across the entirety of each fire event and compared between fires with and without at least one extreme spread event. This recognizes that high-severity patches may span multiple days of burning, and summarizing patch area metrics requires keeping whole patches intact.

To test relationships between landscape patterns and daily fire spread event size, we used linear mixed-effects models (LMEs), as implemented by the glmmTMB package in R (Brooks et al. 2017). We developed models for each landscape metric as a function of (a) fire spread event type and (b) continuous values of daily area burned (ha). Area burned was $\log_{10}$-transformed for each model. The proportion of area burned at high severity and the percentage of high-severity like adjacency metrics were modeled at the DOB scale, where we used daily fire spread event type or continuous values of daily area burned as fixed effects with fire ID incorporated as a random intercept term. Burn severity and distance to the nearest live tree seed source were analyzed at the 30-m pixel scale within daily fire spread events; thus, we modeled daily fire spread event type and continuous values of daily area burned as fixed effects while incorporating DOB within fire ID as a nested random intercept term. Finally, models predicting area-weighted mean high-severity patch size and total high-severity core area were analyzed at the scale of individual fires, with mean continuous values of daily area burned and fire event type as fixed effects. All analyses were conducted in R (R Core Team 2022). The data, models, and code that support the findings of this study are openly available at https://doi.org/10.5061/dryad.9kd51c5sr (McFarland et al. 2025).

3 | Results

The 623 fires included in our analyses burned a total of 3,965,585 ha between 2002 and 2020. The mean daily fire spread event size across the study area was 929 ha/day. A total of 1,449,957 ha (36%) area burned in extreme fire spread events (n = 140), 1,293,111 ha (33%) burned in large events (n = 550), and 1,222,517 ha (31%) burned in common events (n = 3577). Fifty-six fires contained one or more extreme fire spread events; these fires accounted for 2,209,691 ha (56%) of the total area burned. The mean daily fire spread rate for fires containing one or more extreme spread events was 2966 ha/day, as compared to 499 ha/day for fires that burned without an extreme event. Of the total area burned within our study area, 647,009 ha burned at high severity: 309,254 ha (48%) burned at high severity during extreme

TABLE 1 | List of burn severity and postfire landscape pattern metrics used in high-severity patch characteristic analysis. All metrics except CBI and the distance to the nearest live tree seed source were calculated using the landscapemetrics package in R (Hesselbarth et al. 2019).

Burn severity and postfire landscape pattern metrics	Description	Values	Unit of analysis	Application	Supporting literature
Burn Severity (CBI)	Above and below ground organic matter consumed by fire, ranging from 0 (unburned) to 3 (100% tree mortality).	0–3	Daily fire spread event (Subsampled [0.01%] 30-m pixel)	Assess the range of burn severity produced per daily area burned	Parks et al. 2019; Parks and Abatzoglou 2020; Rodman et al. 2023
Proportion Area Burned at High-Severity	The proportion of all forested pixels classified as high severity in a daily fire spread event.	0–1	Daily fire spread event	Compare forested area burned at high severity to total forest area burned per day	Potter, 2017; Cova et al. 2023; Williams et al. 2023
Percentage of High-Severity Like Adjacencies	The number of like adjacencies of high-severity cells, divided by the total number of cell adjacencies multiplied by 100.	0–100	Daily fire spread event	Demonstrates aggregation of high-severity pixels; higher values indicate high-severity areas are more likely to be proximate	Steel et al. 2018; Singleton et al. 2021; Crist 2023
Distance to Nearest Live Tree Seed Source	The distance of randomly distributed points in high-severity patches to the nearest forested pixel.	>0	Daily fire spread event (Subsampled [0.01%] 30-m pixel)	Summarize distances to forested pixels of unburned, low, and moderate severities to infer potential forest recovery	Steel et al. 2022; Buonanduci et al. 2023
Area-Weighted Mean High-Severity Patch Size (ha)	Summarizes each class as the mean of all high-severity patch areas.	>0	Fire	Assess mean high-severity patch size to infer ecological impacts	Harvey et al. 2016; Cova et al. 2023; Buonanduci et al. 2023
Mean High-Severity Total Core Area (ha)	The sum of core areas of all high-severity patches.	≥ 0	Fire	Assess total core area of high-severity patches (> 3 pixels; ~100 m) limited by seed dispersal	Harvey et al. 2016; Singleton et al. 2021; Buonanduci et al. 2023; Cova et al. 2023

daily fire spread events, 195,945 ha (30%) burned in large events, and 141,810 ha (22%) burned in common events.

3.1 | Daily Fire Spread Rate Predicts Burn Severity and Landscape Pattern

We found strong and statistically significant differences ($p < 0.05$) between landscape metrics for categorial fire spread events and daily area burned (Table S2). Burn severity and all landscape metrics analyzed on the scale of daily fire spread events increased with daily fire spread event type (e.g., extreme, large, or common) and daily area burned. Mean burn severity for extreme events was significantly higher (CBI = 1.62) than that in large (1.36) and common (1.07) spread events (Figure 3A; Table S2). Likewise, burn severity increased with $\log_{10}$-transformed daily area burned (Figure 3B; Table S2). The proportion of daily area burned at high severity also differed among daily fire spread event types (Figure 3C; Table S2). Mean proportion of area burned at high severity was significantly greater in extreme events (0.20) than in large (0.16) and common (0.11) events (Figure 3C; Table S2). The proportion of area burned severely also increased with $\log_{10}$-transformed daily area burned (Figure 3D; Table S2).

The percentage of high-severity like adjacencies (PLADJ) differed among daily fire spread event types. PLADJ of extreme fire spread events (65%) was greater than that of common events (56%), but did not statistically differ from large events (66%; Figure 3E; Table S2). However, PLADJ increased linearly with $\log_{10}$-transformed daily area burned (Figure 3F; Table S2). As PLADJ summarizes the percent likelihood of a high-severity pixel being adjacent to another high-severity pixel, these findings indicate that as daily fire spread events become larger, high-severity pixels become more highly aggregated. Finally, we found that the distance to the nearest seed source was greater in extreme events (159 m) than in large (115 m) and common (104 m) events (Figure 3G; Table S2). The distance to the nearest live tree seed source also increased with $\log_{10}$-transformed daily area burned (Figure 3H; Table S2).

3.2 | Fires Containing Extreme Events Have Larger High-Severity Patches With Greater Core Area

Similar to our daily fire spread results, both landscape metrics analyzed on the scale of individual fires showed strong and significant differences ($p < 0.05$) between fires with vs. without an extreme fire spread event and increased significantly with mean daily area burned. Both area-weighted mean high-severity patch size and total high-severity core area were an order of magnitude larger in fires with at least one extreme fire spread event compared to fires without extreme events. Area-weighted mean high-severity patch size was highest in fires with at least one extreme fire spread event compared to fires without an extreme event (1089 ha vs. 115 ha; Figure 4A; Table S3). Across fires, mean high-severity patch size also increased with mean $\log_{10}$-transformed daily area burned (Figure 4B; Table S3). Total high-severity core area (i.e., the amount of high-severity area > 100 m from patch edges) increased significantly in fires with extreme fire spread events compared to fires without an extreme event (2807 ha vs. 119 ha; Figure 4C; Table S3). Total high-severity core area also increased with mean $\log_{10}$-transformed daily area burned (Table S3; Figure 4D).

4 | Discussion

Between 2002 and 2020, the top ~3% of daily fire spread events accounted for 36% of the total forest area burned (965,585 ha) but nearly half (48%) of the total area burned severely. These findings reinforce the disproportionately large contributions of extreme spread events to the total area burned (Coop et al. 2022; Balik et al. 2024) but also provide new insight into critical fire effects and landscape outcomes such as area burned at high severity, high-severity patch size, and patch homogeneity. Patterns produced by extreme events at the daily level also scaled up to differences at the level of individual fires: fires that included extreme fire spread events had significantly larger high-severity patch sizes and high-severity patch core area. As such, our findings complement previous research on associations between fire size, proportion burned severely, and postfire landscape patterns (Cansler and McKenzie 2014; Cova et al. 2023; Buonanduci et al. 2023). The strong effects of extreme fire spread events may be an important driver of observed increases in total high-severity area and the percentage of fire burning at high severity, particularly in the southwestern United States (Dillon et al. 2011; Singleton et al. 2019; Parks and Abatzoglou 2020). Collectively, our findings highlight the outsized effect that extreme events have on landscape burn severity outcomes, with major implications for forest resilience in an increasingly fire-prone future (Rodman et al. 2023).

4.1 | Connections Between Forest Fire Spread Rate and Burn Severity

The positive relationship between daily area burned and burn severity may be a function of underlying processes that govern multiple aspects of fire behavior. For example, within forested landscapes, extreme spread events are generally associated with running crown fire that is both fast moving and severe by nature (Saberi et al. 2022). Weather, fuels, and topography are well understood to influence both fire spread and severity (Littell et al. 2009; Bradstock et al. 2010; Dillon et al. 2011; Holsinger et al. 2016), and combinations of fire-conducive conditions may thus produce both extreme events and severely burned landscapes. In particular, strong winds are well understood to drive the growth rates of extreme wildfire events (Castellnou et al. 2018; Potter and McEvoy 2021; Busby et al. 2023) and crown fire (Perrakis et al. 2023). Wind speed is also associated with larger, more aggregated high-severity patches (Wu et al. 2018).

Extreme events may also be linked to plume-dominated fire behavior and pyrocumulonimbus formation (Di Virgilio et al. 2019; Vaz et al. 2023) that can provide a positive feedback expanding the footprint of high-severity fire (Lydersen et al. 2017). High fuel loads and continuity, and low fuel moisture may further interact with extreme fire weather conditions to increase fire growth rates and area burned at high severity (Duane et al. 2021; Francis et al. 2023). In particular, mass fires

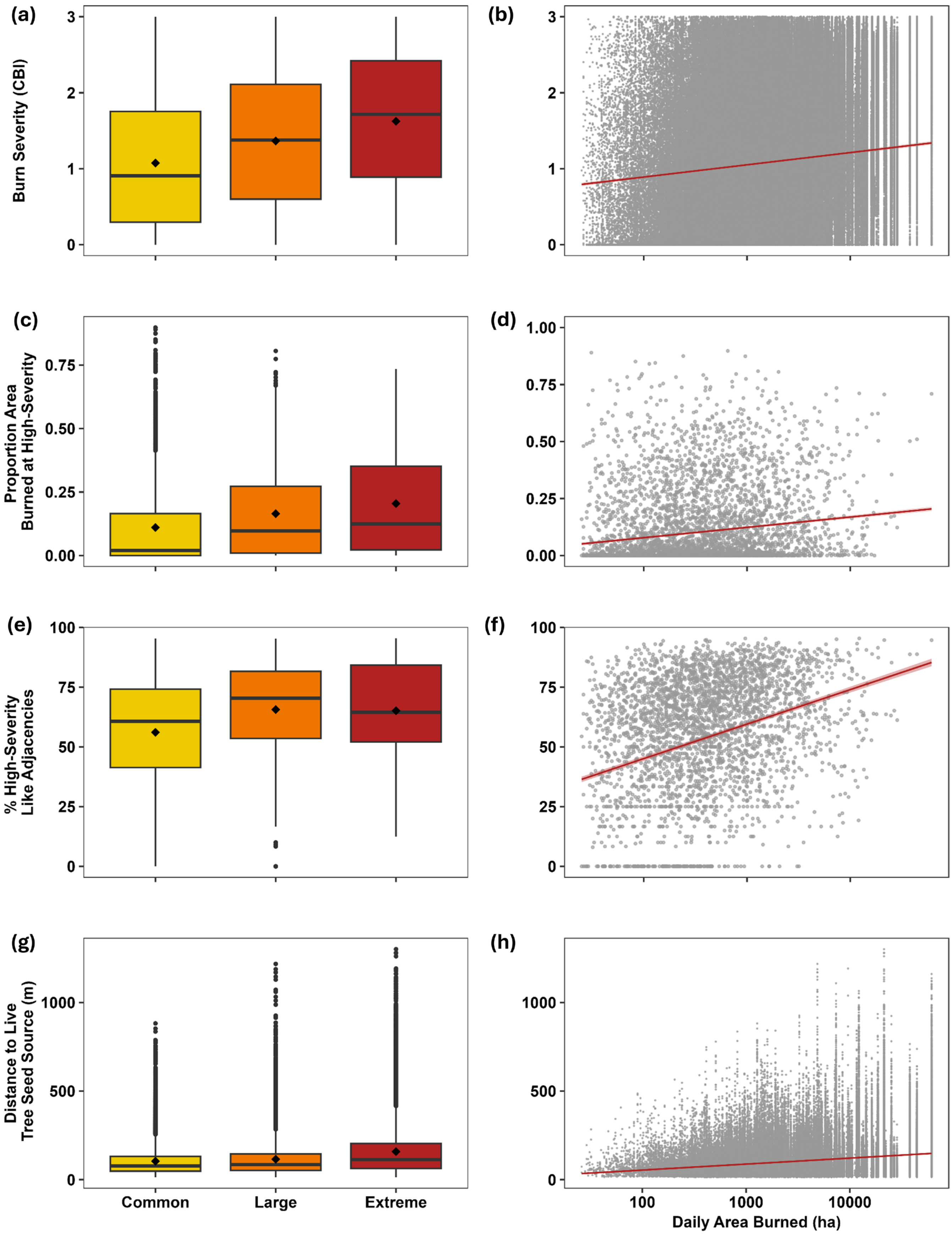

FIGURE 3 | Legend on next page.

FIGURE 3 | Boxplots and scatterplots showing relationships of burn severity and high-severity patch metrics with daily fire spread event size. We illustrate relationships between either fire spread event types (boxplots in left column) or daily area burned (scatterplots and LME trendlines in right column) with burn severity (A and B; 0.01% subsample), proportion of area burned at high severity (C and D), percentage of like adjacencies of high-severity areas burned (E and F), and distance to nearest live tree seed source (G and H; 0.01% subsample). Fire spread event categories are defined as common (yellow; ≤ 1285 ha), large (orange; 1286–4900 ha), and extreme (red; > 4900 ha/day) fire spread events based on statistical thresholds across all fires. In boxplots, black diamonds represent mean values. Scatterplots illustrate metrics plotted against daily area burned (ha), with the x-axis on a $\log_{10}$ scale. Trendlines on scatterplots include 95% confidence intervals.

occurring in fuel-rich landscapes and under especially fire-conducive atmospheric conditions can lead to near-complete consumption of available fuels (Finney and McAllister 2011). Finally, topographic factors such as slope inclination and aspect also shape fire behavior including rate of spread, energy release component, and severity (Holden and Jolly 2011; Evers et al. 2022). While our study is broadly focused on the landscape impacts of extreme fire spread events, there are a suite of environmental factors that influence fire spread and severity at finer spatial and temporal scales, highlighting critical future research directions.

4.2 | Postfire Landscape Patterns

Beyond burning more severely, we found that increasing daily fire spread rates were related to the proportion of area burned severely. Similarly, Birch et al. (2014) reported a correlation between the proportion of high-severity area burned and daily area burned in Montana and Idaho. In our study, extreme fire spread events had greater proportions of area burned at high severity compared to common and large events. Extreme and large events were also characterized by greater percentages of high-severity-like adjacencies. As daily fire spread rates increase, the area burned at high severity becomes increasingly aggregated into large, homogeneous patches. These findings are consistent with those of Singleton et al. (2021) who found that high-severity patches progressively aggregate with increasing fire size. While our research highlights that extreme fire spread events, as defined here, have outsized effects on burn severity and high-severity landscape configurations, so too did events in our large category that burned between 1286–4900 ha/day. Similar patterns produced by large and extreme events may be a function of landscape factors that constrain forest or fire patch size. In the southwestern United States, the total area available for continuous severe fire may ultimately be limited by the island-like nature of forests occupying discrete mountain ranges and plateaus separated by large treeless expanses. Even larger extreme events in contiguous forests elsewhere (e.g., in the boreal forest biome) may produce more extensive high-severity patches, highlighting an avenue for future research expanding these approaches to other ecoregions.

Extreme fire spread events created substantially larger high-severity patches with greater distances from surviving forest, highlighting major implications for postfire tree regeneration. Our results illustrate that fires that included one or more extreme fire spread events produced high-severity patches that were exponentially larger than fires that did not feature extreme events. Many aspects of postfire landscape pattern scale consistently with fire size (Buonanduci et al. 2023), facilitating predictions of future landscape outcomes under forecasted increases in fire activity (Buonanduci et al. 2024). Here, we found that mean high-severity patch size and total high-severity core area increased nonlinearly with fire size, suggesting that extreme fire spread events and the large fires they produce have disproportionate effects on forest persistence and postfire tree regeneration. Fires that included one or more extreme fire spread events were on average 12× larger than fires without such events (37,452 ha vs. 3086 ha). Consequently, fires with at least one or more extreme fire spread events produced 10× greater area-weighted mean high-severity patch size and over 20× greater total high-severity core area. Mean high-severity patch size and total high-severity core area have been found to increase with fire area in studies throughout the western United States (Harvey et al. 2016; Singleton et al. 2021; Buonanduci et al. 2023; Cova et al. 2023). We propose that this pattern is associated with the strong relationship between fire growth rate and burn severity. High-severity patch size, the product of area burned and burn severity, is thus expected to scale with fire growth rate. As extreme fire spread events constitute a disproportionate area burned within individual final fire perimeters (Potter and McEvoy 2021), fires including these events are not only larger but will contain larger high-severity patches.

4.3 | Extreme Fire Spread Events Undermine Forest Resilience

The extreme fire spread events we study here can catalyze major changes across ecosystems as forests are burnt severely and recovery capacity diminishes. First, increased area burned at high severity (CBI ≥ 2.25) drives greater short-term losses of forest and tree populations (Davis et al. 2023). Impacts to ecological processes include reduced carbon storage (North and Hurteau 2011), reduced wildlife habitat quality for some species (Jones et al. 2020; Driscoll et al. 2024), increased soil erosion (Robichaud and Waldrop 1994), and impaired watershed function (Neary et al. 2003; Stevens 2017). While some forest types in our study region (e.g., spruce/fir and lodgepole pine) are well adapted to infrequent, stand-replacing fire (Schoennagel et al. 2004; Margolis et al. 2007), the frequency of extreme wildfires has increased in temperate coniferous forests under a changing climate (Cunningham et al. 2024), and recent losses in some settings are exceeding rates observed over recent millennia (Higuera et al. 2021). Furthermore, for forest types adapted to frequent, low severity fire (e.g., ponderosa pine), recent increases in high-severity fire activity may surpass critical thresholds of resistance and resilience (Chambers et al. 2016; Singleton et al. 2019; Woolman et al. 2022; Falk et al. 2022). Thus, the six-fold increase in proportions of stand-replacing fire relative to precolonization periods in the southwestern United States

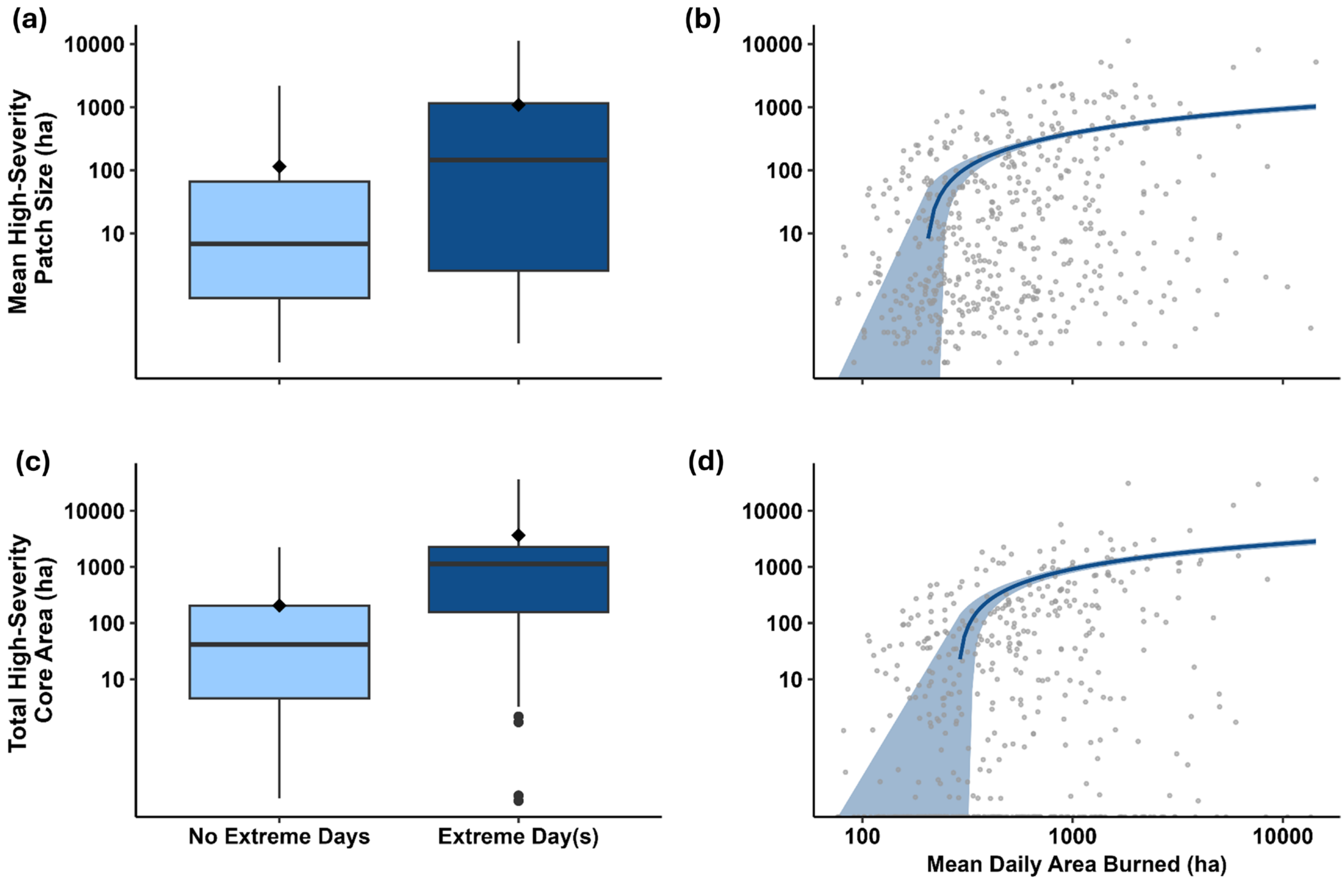

FIGURE 4 | Boxplots and scatterplots showing relationships between fire type, fire spread event size, and landscape metrics of high-severity patches at the fire level. We illustrate relationships between area-weighted mean high-severity patch size (A-B) and total high-severity core area (C-D) with fire spread event types (boxplots in left column) and daily area burned (scatterplots and linear trendlines in right column). Fire type is categorically represented by the boxplots as fires with one or more extreme fire spread events (dark blue; "Extreme Day(s)") or fires without an extreme fire spread event (light blue; "No Extreme Days"). Central horizontal lines within the boxplots depict median values, black diamonds represent means, and points represent outliers. Geometric means were plotted instead of arithmetic means to account for $\log_{10}$-transformed Y axes. Scatterplots illustrate metrics plotted against $\log_{10}$-transformed mean daily area burned (ha). Trendlines on scatterplots include 95% confidence intervals.

(Parks et al. 2023) sets the stage for extensive and potentially persistent forest losses.

The postfire landscape patterns associated with extreme fire spread events we report here can severely constrain postfire recovery for a wide range of obligate-seeding species, particularly nonserotinous conifers that dominate most of our forested study area. Most telling are the distances to nearest live tree seed sources in extreme fire spread events, which highlight disproportionately greater distances from potential seed sources and reduced propagule availability. Regeneration of wind-dispersed conifers in the western United States becomes increasingly limited as distances to live trees exceed 50–100 m (Chambers et al. 2016; Stevens-Rumann and Morgan 2019). Within high-severity patches, the mean distance to the nearest seed source after extreme fire spread events was 159 m, and the median distance was 113 m, suggesting that the majority of high-severity patch area generated from extreme events experience reduced seed rain, limiting postfire colonization of obligate-seeding tree species. While distances to seed sources varied significantly between large and extreme events, large fire spread events had a median distance of 85 m, highlighting potential regeneration declines even under comparatively lower fire spread rates. These findings clearly demonstrate that as daily fire spread rates increase, postfire forest recovery will likely decline without substantial investments in management interventions to reduce fuels and fire severity. Furthermore, increased high-severity patch homogeneity also suggests that patches are less likely to support unburned or low severity refugia that can support forest resilience by sustaining individual obligate tree species and promoting tree regeneration (Coop et al. 2019; Rodman et al. 2023). Platt et al. (2023) found that forested fire refugia have generally maintained consistent proportions over time and across fire sizes; however, the maximum distance to refugia has increased over the last several decades (Platt et al. 2023), which could be associated with increased fire size, high-severity patch size, and patch homogeneity. Further work exploring the relationships between fire spread rates and refugia could provide important insights into long-term predictions of forest resilience in an increasingly fire-prone future.

Large high-severity patches accelerate risks for long-term forest losses and vegetation type conversion. In addition to the reduction in live tree seed sources and greater seed dispersal distance requirements, increased competition with other species in severely burned patches reduces the likelihood of the re-establishment of prefire forest types (Donato et al. 2016; Coop et al. 2020). These delays are compounded by climate change as warmer and drier conditions generally reduce forest recruitment (Stevens-Rumann et al. 2018; Kemp et al. 2019; Davis et al. 2023) while facilitating the establishment of opportunistic species with different regeneration strategies and climate adaptations (e.g., resprouting woody species, xeric shrubs and herbs, or invasive annual grasses; Brown and Johnstone 2012; Hansen et al. 2016; Stralberg et al. 2018; Coop et al. 2020). Beyond the effects on forests, altered burn severity patterns associated with daily fire growth influence a range of plant and animal species, as well as myriad ecological processes. While heterogeneity in burn severity patterns supports species biodiversity across different types of habitat and taxa (Ponisio et al. 2016; Kelly et al. 2017; Jones and Tingley 2022), large and homogeneous high-severity patches can lead to declines in avian community richness (Steel et al. 2022), pollinator abundance (Tarbill et al. 2023), and arboreal mammal presence (Chia et al. 2016). Finally, large high-severity patches can amplify local warming effects and produce positive feedbacks enhancing fire likelihood (Zhao et al. 2024). Accordingly, as the disproportionately large high-severity patches produced by extreme spread events occupy an increasing fraction of postfire landscapes under a warming climate, they imperil a suite of forest ecosystem values and forest-obligate biota.

4.4 | Implications for Forest Stewardship in an Era of More Extremes

Extreme fire spread events are projected to become more common under continued climate warming (Coop et al. 2022). Predicted increases in extreme fire spread events and commensurate increases in high-severity landscape burn patterning are expected to lead to outsized forest losses and reduced recovery capacity. As regions around the world struggle with the acceleration of extreme wildfire events (Bowman et al. 2017; Duane et al. 2021) and high-severity fire impacts on forests (Wu et al. 2018; Tran et al. 2020; Nolè et al. 2022; Rodman et al. 2022), our research foretells threats to forest resilience for obligate-seeding, nonserotinous forest types.

Fuels reduction through prescribed burning and mechanical thinning can, in some settings, mitigate high-severity fire (Prichard and Kennedy 2014; Davis et al. 2024) and increase the likelihood of forest persistence through extreme fire spread events (Lydersen et al. 2017; Walker et al. 2019). However, the efficacy of traditional fuels treatments may also be challenged by larger fires burning under increasingly extreme fire weather, highlighting an important direction for research. Furthermore, though these management strategies may be paramount to sustaining forests and forest regeneration capacity over the next few decades, their effectiveness may eventually be diminished by ongoing climate change (Davis et al. 2023). A growing proportion of the landscape occupied by large, high-severity patches compels attention to postfire landscape management. Recent reviews have highlighted prioritization schema and a suite of strategies, including novel reforestation practices and protection of postfire forest (Stevens et al. 2021; Larson et al. 2022). However, in some settings, sustaining forest values in a more flammable future that increasingly imperils postfire regeneration may demand fundamental paradigm shifts that accommodate or even embrace change (Schuurman et al. 2020). As managers, scientists, and communities around the world navigate an era of more extreme events, innovative, adaptive, and collaborative processes will be crucial components of pathways toward sustaining resilient forest ecosystems.

Author Contributions

Jessika R. McFarland: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, writing – original draft, writing – review and editing. **Jonathan D. Coop:** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing – review and editing. **Jared A. Balik:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, supervision, validation, visualization, writing – review and editing. **Kyle C. Rodman:** conceptualization, formal analysis, methodology, project administration, software, supervision, validation, visualization, writing – review and editing. **Sean A. Parks:** conceptualization, formal analysis, investigation, methodology, project administration, software, supervision, validation, writing – review and editing. **Camille S. Stevens-Rumann:** conceptualization, methodology, project administration, supervision, validation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Data Dryad at https://doi.org/10.5061/dryad.9kd51c5sr. Fire perimeter data were provided by Monitoring Trends in Burn Severity (MTBS) at https://doi.org/10.5066/P9IED7RZ. Daily burned area was calculated using Moderate Resolution Imaging Spectroradiometer (MODIS) obtained from the NASA EOSDIS Land Processes Distributed Active Archive Center at https://doi.org/10.5067/FIRMS/MODIS/MCD14DL.NRT.0061 and Visible Infrared Imaging Radiometer Suite (VIIRS) daily fire detection data obtained from LP DAAC at https://doi.org/10.5067/FIRMS/VIIRS/VNP14IMGT_NRT.002. Existing vegetation type (EVT) data were obtained from Department of the Interior and U.S. Geological Survey's LANDFIRE at https://landfire.gov/vegetation/evt and were accessed for version years 2001, 2012, 2016, and 2020.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.