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"Rethinking megafires: defining severe wildfire events through the lens of high severity spatial pattern"

Table of Contents

List of Abbreviations

CCCSF	California Coastal Chaparral Forest and Shrub Province
CCR	California Coastal Range and Open Woodland
NRMF	Northern Rocky Mountain Forest
MRMS	Middle Rocky Mountain Steppe
SRMS	Southern Rocky Mountain Steppe
SS	Sierran Steppe
CMF	Cascade Mixed Forest
CC	Ecoprovince group encompassing CCCSF and CCR ecoprovinces
NMS	Ecoprovince group encompassing NRMF, MRMS, and SRMS ecoprovinces
MTBS	Monitoring Trends in Burn Severity
NBR	Normalized Burn Ratio
RdNBR	Relative Differenced Normalized Burn Ratio
SLC	Scan line correction, in reference to the failure associated with Landsat 7 in 2003
PLAND	Percentage of landscape
PCI	Patch cohesion index
PLADJ	Percentage of like adjacencies
AW	Area-weighted
SDC	Stand-replacing decay coefficient
SM	Severity metric

Abstract

Larger and more extreme fire events have become increasingly common, receiving significant attention from fire scientists and managers, and spurring the development of the term "megafire". This paper aims to examine the definition of a megafire by tracking the occurrence of megafires through time and exploring whether their spatial pattern of high severity patches is unique compared to fires of different sizes. To do this, the frequency of megafires and large fires from 1984 to 2017 is tracked, and a suite of landscape metrics measuring high severity spatial pattern are tested in fires of different sizes in US ecoprovinces, with the goal of understanding if spatial pattern of high severity fire is statistically different among fire size classes. It is found that megafire occurrence has increased over time, and that megafires contain larger high severity patches that are denser and more spatially cohesive relative to more moderately sized fires, and also that large fires and megafires exhibit similarities in spatial pattern. These results carry implications for post-fire vegetation regeneration, forest vegetation-type conversion, and overall ecosystem resilience, but also suggest that spatial pattern should be prioritized over fire size when classifying extreme fire events in western US ecosystems.

Introduction

In the past forty years, western United States forests have experienced a marked shift in fire regime, indicated by findings that in some regions, yearly area burned, length of fire season, and fire severity have increased (Westerling et al. 2006, Miller et al. 2009b, Dennison et al. 2014). Unprecedentedly large and extreme fires have occurred throughout the United States and the world, leading to the development of the term "megafire" and its surrounding body of literature (Keane et al. 2008, Lannom et al. 2014, Stephens et al. 2014, Barbero et al. 2015). A megafire is often defined as a fire that burns over 100,000 acres, but a definition based solely on size has been contested; some contend that a megafire should be defined by its rate of spread, suppression cost, structural damage, loss of life, or general societal impact (Buckland 2019, Stephens et al. 2014, Tedim et al. 2018).

Modern-day extreme wildfire events are the result of a number of compounding and interacting ecological factors. Beginning in the early 20th century, policies of widespread, categorical fire suppression and exclusion, along with practices of livestock grazing and forest harvesting, have worked to change the structure and functionality of western US forests. Previously, frequent, low severity wildfires maintained vegetation density and resource availability in forests, but years of fire exclusion have led to more widespread and intense disturbances from fire, pests and disease (Ferrel 1996, McCullough et al. 1998, Parker et al. 2006, Collins et al. 2011). Prolonged drought in many areas of the western US, especially California, provides abundant dry fuels, puts trees at greater risk of pest infestation, and facilitates a prolonged fire season (Mattson and Haack 1987, Williams 2013, Swain et al. 2014, Littel et al 2016). Land-use change, especially expanded development at the urban-wildland interface, puts property and life at risk, and necessitates wildfire suppression, eliminating wildfire management techniques that can buffer fire risks, such as controlled and prescribed burning (Cohen 2008, Stephens et al. 2014). In addition, impacts of climate change, including warming and altered precipitation regimes, may result in increased fire severity and incidence of large fire (Flannigan et al 2000, Barbero et al. 2015).

Wildfire severity is an important aspect of what makes extreme fire events an ecological concern. Stand-replacing fire, which occurs when a patch of vegetation experiences high-canopy mortality, is of particular interest, as it influences forest resilience (Stephens et al. 2016, Knox & Clarke 2011). A forest is resilient when its ecosystems persist over long periods of time and have the ability to recover from perturbations, especially wildfire (Holling 1973, Stephens et al. 2016). Resilience to wildfire in western forests is contingent on the ways in which vegetation regenerates post-fire; some species, such as lodgepole pine, quaking aspen, and oak, show strong resilience to perturbation due to their regeneration methods, which involve serotiny, underground root structures, and basal resprouting, respectively (Johnson & Fryer 1989, Nyland 1998, Espalta et al. 2002, Fraser et al. 2004, Harvey et al. 2016). However, many western forest tree types, including the numerous coniferous species that populate western forest stands, lack these regeneration strategies, and rely instead on methods of windblown, animal-aided, and slope-influenced dispersal (Kemp et al. 2015, Harvey et al. 2016). Regeneration potential for coniferous species that rely on dispersal depends heavily on distance to adjacent living stands, creating challenges for regeneration in post-wildfire landscapes that include large and simply-shaped high severity patches (Harvey et al. 2013, Harvey et al. 2016). Where dispersal potential is limited, forest resilience to wildfire decreases, as the potential for regeneration of the same species type is limited, while the likelihood of future stand replacing fire is increased (Coppoletta et al. 2016, Collins et al. 2017). Furthermore, the resilience of shrub dominated ecosystems, which depends on post-fire resprouting, can be hampered by high-frequency occurrence of high severity fire, which has become increasingly characteristic in modern fire regimes (Moreno & Oechel 1993, Safford & Van de Water 2014). Because of these feedback mechanisms, understanding the size and spatial configuration of high severity patches across western forest types is crucial to managing for forest resilience and avoiding deleterious effects of tree species assemblage alteration, vegetation type conversion, and ecosystem degradation.

With these ideas in mind, the questions of whether megafire occurrence is on the rise, and if the spatial pattern of patches burned at high severity can be a defining characteristic of megafires, arise. Therefore, this paper has two aims: (1) to track the occurrence of megafires, as commonly defined based on fire size, over time, and (2) to explore a more mechanistic definition of megafires, one that incorporates the spatial pattern of their high severity patches. These objectives are achieved using remotely sensed data alongside metrics of landscape pattern and fire severity, with the goal of elucidating significant differences in spatial pattern and severity of fires of different sizes across diverse western ecoprovinces. The spatial arrangement of high severity patches in large fires has implications for forest structure and function, vegetation regrowth and regeneration, ecological diversity and landscape heterogeneity, and habitat health (Parr & Anderson 2006, Davies et al. 2012, Kane et al. 2016, Ponisio et al. 2016); therefore, understanding their dynamics is important for management in the uncertain future of fire-prone ecosystems in the western U.S.

Methods

Geographic setting

The geographic distribution of megafires was first assessed using EPA Level II Ecoregions (Omernik 1987). It was determined that most megafires where high severity burn was observed fell within the Western Cordillera and Mediterranean California ecoregions, but in order to capture a finer ecological scale, Bailey's ecoprovinces (Bailey 1995) that overlapped the Western Cordillera and Mediterranean California regions were chosen as the ecological delineator of this study. Seven Bailey's ecoprovinces overlapped the original EPA Level II ecoregions: California Coastal Chaparral Forest and Shrub Province (CCCSF), California Coastal Range and Open Woodland (CCR), Northern Rocky Mountain Forest (NRMF), Middle Rocky Mountain Steppe (MRMS), Southern Rocky Mountain Steppe (SRMS), Sierran Steppe (SS), and Cascade Mixed Forest (CMF). Bailey's ecoprovinces that had similar ecological characteristics based on their published descriptions (California Coastal Chaparral and Shrub Province and California Coastal Range and Open Woodland (CCCSF-CCR), and Northern Rocky Mountain Forest, Middle Rocky Mountain Steppe, and Southern Rocky Mountain Steppe (NRMF-MRMS-SRMS)) were grouped together, resulting in four final ecological groups for analysis (Figure 1). For simplicity, these groupings will be referred to as ecoprovinces with the abbreviations CC, NMS, SS, CMF. Grouping the Bailey's ecoprovinces in this way effectively meant that the Western Cordillera ecoregion was split into three distinct groups (CMF, SS, and NMS), and that only fire prone areas of the Mediterranean California Level II ecoregion (i.e., areas outside California's Central Valley) were considered (CC). Details on temperature, altitude, precipitation, and common vegetation species for each ecoprovince can be found in Table 1.

Remote sensing imagery

To assess landscape metrics, remote sensing products were gathered from the Monitoring Trends in Burn Severity (MTBS) database (Eidenshink et al. 2007). MTBS technicians assess burn severity of western US wildfires greater than 1000 acres using the Normalized Burn Ratio (NBR) (Key & Benson 2005) and the Relative Differenced Normalized Burn Ratio (RdNBR) (Miller et al. 2009a) calculated on 30m resolution imagery from the Landsat Thematic Mapper and Enhanced Thematic Mapper Plus (U.S. Geological Survey 2016). Products of interest in this study were 6-class categorized burn severity images (classes included unburned to low, low, moderate, high, increased greenness, non-processing area mask), continuous RdNBR images, and burned area perimeters. MTBS data for all fires that occurred in states overlapping with Bailey's ecoprovinces of interest from 1984 to 2017 was downloaded. Three fire size classes were considered for this study: megafires (>100,000 acres), large fires (25,000-100,000 acres) and moderate fires (1000-25,000 acres). All megafires and large fires in each ecoprovince were analyzed. Because of the prohibitively large number of moderate fires in every ecoprovince, three random samples of twenty-five moderate fires were taken for each ecoprovince. The Bailey ecoprovince where each fire occurred was determined using the "Select by Location" tool in QGIS. The resulting dataset included information on start date, fire size, ecoprovince for each fire in the area of interest. Duplicates were removed and the dataset was filtered to only include wildfires (discarding prescribed, unknown, and wildland fire use MTBS fire categories). In each size class, only fires that exhibited high severity burn were included in analysis. All images that were affected by the 2003 scan line correction (SLC) failure of the Landsat 7 satellite were discarded, as calculated spatial patterns would be inaccurate on such imagery.

Landscape metrics

Landscape metrics (McGarigal 2013) for the high severity portions of each fire analyzed were calculated from MTBS categorical burn severity images using the *landscapemetrics* R package (R Core Team 2017, Hesselbarth et al. 2019). For each image, landscape metrics quantifying the proportion, spatial aggregation, and size of high severity patches were calculated (Table 2). Visual representations of a selection of landscape metrics used in this study can be found in Table 3.

<u>High severity proportion metrics (PLAND and patch density)</u>

Percentage of landscape (PLAND) is the proportional abundance of each patch type in the landscape, and here describes the percentage of each wildfire that burned at high severity. Patch density is the number of patches per hectare in each wildfire (McGarigal & Marks 1995). Patch density increases as more patches of the class of interest are found within the landscape. PLAND and patch density both describe high severity fire on a per-unit basis, allowing for comparison of metrics among wildfires of different size. These metrics differ in that PLAND describes the proportion of high severity fire area as a function of the total fire area, whereas patch density describes the prevalence of high severity patches in the landscape.

<u>Spatial aggregation metrics (Patch cohesion index, PLADJ, and clumpiness)</u>

Patch cohesion index (PCI) measures the physical connectedness of the corresponding patch type (Schumaker 1996). PCI increases as the patch type becomes more clumped, aggregated, and physically connected, and decreases as the class of interest becomes less physically connected. Percentage of like adjacencies (PLADJ) measures the degree of aggregation of the patch type of interest, and is calculated by summing the number of pixel edges that share an edge with a pixel of the same class and dividing by the total number of possible adjacencies (Neel et al. 2004). PLADJ increases as patch type aggregation increases. Clumpiness is also a measure of adjacency indicating the degree of aggregation of patches in a landscape, and is calculated by measuring the deviation of the PLADJ from that which would be expected under a normal distribution (Neel et al. 2004). Clumpiness increases as patches become more aggregated. PCI, PLADJ and clumpiness all measure cohesion, but differ in the ways that they are confounded by abundance of the class type in the landscape. PCI and PLADJ can be confounded when the abundance of the focal patch type in the landscape is large (>0.5), while clumpiness isolates the aggregation effect and is not affected by the shape of the landscape. Though no fires in the study exceeded 20% of high severity PLAND, multiple metrics were tested out of an abundance of caution against confounding effects (http://www.umass.edu/landeco/teaching/landscape_ecology/schedule/chapter9_metrics.pdf).

High severity patch size metrics (AW mean patch size and AW mean core area)

Area weighted (AW) mean patch size and AW mean core area were calculated to describe the size of high severity patches within wildfire landscapes. Area weighted means normalize metrics by the total area of the fire, giving greater weight to larger patches within the fire perimeter. Area weighted mean metrics calculated here describe the average patch area and core area in which a pixel in the landscape selected at random would be (Cansler & McKenzie 2014). In fires with many large patches, area-weighted mean patch size metrics will be considerably greater than regular means, but will provide a more realistic description of typical patch size across the landscape of the wildfire, as there is a greater likelihood that a randomly selected location in the landscape will come from a large patch (Harvey et al. 2016). AW core area was calculated as any area within a patch that was ≥150 meters (or 5 pixel lengths) from the patch edge. This distance represents the distance beyond which wind-dispersed conifer species are capable of spreading approximately 90% of their seed (Greene and Johnson 1996, Harvey et al. 2016).

Shape metrics (Perimeter to area ratio and stand-replacing decay coefficient)

Patch complexity was characterized by the perimeter to area ratio and the stand-replacing decay coefficient (SDC). Perimeter to area ratio was calculated and averaged across each wildfire. Large, simply shaped patches will have a low ratio, while more complex patches have higher ratio values. Low average ratios indicate an abundance of simply shaped patches, while higher ratios will indicate that patches are typically complex in shape. SDC is a parameter fit by nonlinear least squares estimation, which ranges from 0 to 1 and provides a single summary value of size and complexity of stand-replacing area for an entire wildfire. SDC is a function of a user-defined buffer distance (in this study, 30m was used) and the proportion of original stand-replacing area which exceeds the buffer distance inward from the patch edge (Collins et al. 2017, Stevens et al. 2017). Wildfires that exhibit large and/or less complex patches will yield small SDC values, while wildfires with smaller and/or more complex patches will yield larger SDC values.

Fire severity

To assess fire severity, the severity metric (SM) was calculated for each fire considered (Lutz et al. 2011). SM allows for a continuous measure of severity, contrasted with the categorical measure of severity used in landscape metric calculations, and is computed as one minus the normalized area under the cumulative severity distribution curve using RdNBR values (Lutz et al. 2011, Cansler & McKenzie 2014). SM values range from 0 to 1 and provide a single summary value of severity for an entire wildfire (Picotte et al. 2016). The area under the cumulative distribution curve of fires that burned at high severity will be smaller, yielding higher SM values for more severe fires (Cansler & McKenzie 2014). SM is a useful measure when comparing wildfire severity among regions with differing burn severity distributions, and was therefore useful in this study (Lutz et al. 2011). SM was calculated using the SeverityMetric tool in ESRI ArcMap (Lutz et al. 2011).

Statistical analysis

After the calculation of landscape metrics for each fire, summary statistics (mean, median, standard deviation, interquartile range) were compiled for each size class. Wilcoxon Rank Sum Tests were performed to determine where differences existed between size classes for each ecoprovince. The Wilcoxon Rank Sum Test is a non-parametric test that calculates pairwise comparisons between groups with corrections for multiple testing. Differences are significant when $p<0.05$. Pearson's correlation coefficients were calculated to determine associations between fire size and landscape metrics. All numerical data was square-root transformed before correlation analysis. All statistical tests were carried out using R statistical software (R Core Team 2017).

Results

Temporal analysis of megafire occurrence

A total of 3,263 wildfires, ranging in size from 1,001-565,115 acres, were found in the region of interest; of these, 60 (1.8%) were megafires. A steady increase in megafire occurrence since 1984 is seen; from 1984 to 2000, 12 megafires occurred, while 48 megafires occurred from 2001 to 2017 (Figure 2). Out of the 60 megafires in this region, 80% of total megafires occurred after 2000 and 41.6% of megafires occurred after 2010. This increase in megafire occurrence since 1984 is in agreement with previously reported increases in overall fire activity in the western US since the 1980s (Westerling et al. 2016).

Ecoprovinces differ in how often and when they have experienced megafires. Megafires appear to have been an occasional feature of pre-2000 fire regimes in the California Coastal Chaparral, Middle Rocky Mountain Steppe, Sierran Steppe, Cascade Mixed Forest and Southern Rocky Mountain Steppe, but each of these ecoprovinces has seen an increase in megafires occurrence since 2000. Northern Rocky Mountain Forest and California Coastal Range ecoprovinces, which had not experienced a megafire before 2000, see an emergence of megafire occurrences after 2000. Though the mechanisms behind megafire (and general wildfire) occurrence vary between ecoprovinces (Hessburg et al. 2019), both the uptick in and emergence of megafires suggest a shift in fire regime, with larger fire events occurring more often across ecoprovinces.

Occurrence of large fires in ecoprovinces was also tracked through time. Large fire occurrences became more frequent after 2000 in all ecoprovinces. Sierran Steppe and Middle Rocky Mountain Steppe ecoprovinces see a notable increase in large fires after 2000, while shrub dominated systems in California and the Northern Rocky Mountain Forest ecoprovince see a less-dramatic increase. Large fires in the Cascade Mixed Forest ecoprovince were especially frequent during 2015-2017.

Landscape metrics, severity, and fire size analysis

All large fires and megafires with viable imagery were considered for analysis, resulting in 9, 27, 10, and 6 megafires, and 44, 118, 83, and 30 large fires considered for the CC, NMS, SS, and CMF ecoprovinces, respectively. In total, 627 fires were considered for landscape metrics analysis. Comparison of landscape metric values across fire size classes within ecoprovinces can be found in Figure 3. Pearson correlation results can be found in Table 4, and Wilcoxon Rank Sum test results can be found in Tables 5 and 6.

<u>Proportion metrics</u>

Across ecoprovinces, mean total high severity acreage was greatest in megafires and decreased with smaller fire size class. CC megafires had the greatest mean total high severity acreage at 53788.4 acres; SS, NMS, and CMF megafire acreages were 43953.5, 43793.1, and 27750.4 acres, respectively. Patch density and PLAND are significantly greater in megafires and large fires than in moderate fires across all ecoprovinces. PLAND and patch density are greater in megafires than in large fires in NMS, as is patch density in SS. On average, PLAND was 2-4 times larger in megafires and large fires than in moderate fires, with CC megafires displaying the largest PLAND value at 8.78%. Patch density showed moderate correlations with both fire size and PLAND ($R = 0.579$ and 0.658) (Figure 4).

Cohesion metrics

PCI was greater in megafires than in moderate fires across ecoprovinces. Clumpiness was greater in megafires than in moderate fires in CC and NMS. PLADJ was greater in megafires than in moderate fires for all ecoprovinces except CMF. In NMS and CC, PCI was greater in megafires than in large fires. PCI was greater in large fires than in moderate fires across ecoprovinces, while PLADJ was greater in NMS and SS. CMF showed the greatest cohesion metric values across class sizes, but only showed statistically significant differences between megafire and moderate fire cohesion metrics for PCI. Associations between fire size and cohesion metrics were relatively weak, with R values ranging from 0.292-0.335; however, associations between PLAND and cohesion metrics were much stronger, with R values ranging from 0.618- 0.712 (Figure 5).

Patch size metrics

AW mean patch size and AW mean core area were significantly greater in megafires and large fires than in moderate fires across ecoprovinces. AW patch size and AW mean core area were greatest in CC megafires, with averages at 21,700 ac and 9,781 ac, respectively. These large mean values are likely due to the Cedar and Zaca fires, which each burned just under 20% of the landscape at high severity and in large patches. AW mean patch size was 3-70 times larger in megafires than in moderate fires (3-14 times larger excluding CC), while AW mean core area was 5-199 times larger in megafires than in large fires (5-30 times larger excluding CC). Both AW mean patch area and AW mean core area showed moderate to strong associations with fire size (R = 0.524 and 0.56) and PLAND (R = 0.754 and 0.726) across ecoprovinces (Figure 6).

Shape metrics

Perimeter-area ratio did not show any statistically significant differences among size classes of different ecoprovinces. Values ranged from 0.09-0.11, with little variation among size classes and ecoprovinces. Perimeter-area ratio did not have a strong relationship with fire size (R = -0.107), but did show a slight negative association with PLAND (R = -0.316) (Figure 7). SDC values were smaller in megafires than in moderate fires across ecoprovinces. No ecoprovince showed a significant difference in SDC values between megafires and large fires. SDC was significantly smaller in large fires than moderate fires in the NMS and SS ecoprovinces. Two-thirds of moderate fire groups showed larger SDC values than in large fires for the CC and CMF ecoprovinces. SDC showed moderate negative associations with fire size (R = -0.415) and strong negative associations with PLAND (R = -0.813) (Figure 7).

Severity metric

SM did not show any statistically significant differences among size classes of different ecoprovinces. In all ecoprovinces, Wilcoxon Rank Sum test results showed very high p-values (0.87-1), indicating a high degree of similarity in values, except for in the CMF ecoprovince, where p values were closer to showing a statistically significant difference (0.057-0.077). Mean SM was highest in CMF megafires with a value of 0.566, but the range among size classes and ecoprovinces was not large, with a minimum mean of 0.437 (seen in CC large fires).

Discussion

Taken together, these results indicate that megafires and large fires experience not only a larger amount of high severity effects, but that the spatial pattern of high severity is distinct from more moderately sized fires. This spatial pattern includes denser, more spatially aggregated high severity patches, with larger mean high severity patch sizes and core areas. Notably, these differences remain consistent over the large portion of the western US included in this study, which varies widely in dominant vegetation type, elevation, latitude, precipitation pattern, and fire regime. Although the total area of high severity and high severity spatial pattern varied across ecoprovinces, this study did not find a significant difference in severity metric across ecoprovinces. Though previous studies have reported an increase in fire severity over time in some western US regions, fire size does not appear to necessitate fire severity in this study area during this time period. Perimeter to area ratio was not shown to have a strong association with fire size, but showed a slightly negative association with PLAND. SDC tended to decrease with increasing fire size and PLAND, though a strong association with PLAND should be expected because the proportion of a wildfire burned at high severity is a component of the SDC calculation. Values of calculated shape metrics indicate that larger fires and fires with a greater proportion of the landscape burned at high severity typically show less patch complexity across ecoprovinces. Though these trends exist at the multi-ecoprovince level, important patterns may exist at the ecoprovince or sub-ecoprovince scale that were not assessed in this study due to low megafire sample size at a finer ecological scale.

Because the ecoprovince groups examined here are ecologically distinct, it can be expected that they will vary in their response to the spatial patterns of high severity left by megafires. In general, a heterogeneous burn pattern ranging in severity (including high severity) is important for forest resilience (Bowman et al. 2016). However, impacts associated with greater high severity AW mean patch size, AW mean core area, patch density, PLAND, PCI, and SDC (and perimeter-area ratio, though this metric was not particularly informative in this study) suggest that megafires may not always enhance the heterogeneity of post-fire landscapes in a positive way. Large patches burned at high severity pose challenges in landscapes where species that depend on dispersal from nearby live specimens, such as ponderosa pine, Douglas-fir, Engelmann spruce, are common, namely in the SS, NMS, and CMF ecoprovinces. Where large high severity patches are simple in shape and have a large core area, post-fire seedling establishment declines due to increased distance to seed source (Harvey et al. 2016). Cases such as these often lead to failures in regeneration of species that depend on dispersal, resulting in recolonization by a different tree species (such as quaking aspen or lodgepole pine), or persistence of early successional species and subsequent vegetation type conversion (such as from conifer to shrub dominated) (Cansler & McKenzie 2014). Changes in species dominance and vegetation cover type have implications for nutrient cycling and carbon sequestration, as well as wildlife viability. Shrub species in the CC ecoprovince may not be implicitly affected by large and aggregated high severity patches, but high frequency, high severity fire has been shown to have negative effects on shrub regeneration in chaparral biomes, leading to shrub stands that are fragmented and degraded, or converted to exotic grasslands (Safford & Van de Water 2014). For all ecoprovinces, large and densely-aggregated high severity patches will affect subsequent disturbance patterns, either by further pushing landscapes to new stable states, or by limiting future disturbance and thus enhancing resilience. Beyond changing the dynamics of natural forest disturbance and regeneration, large and cohesive high severity patches pose risks for forest fragmentation, post-fire erosion and water quality in affected watersheds, and consequently, human safety and comfort.

A final important finding in this study is that significant differences in spatial pattern exist not only between megafires and moderate fires, but also between large and moderate fires. Patch density, PCI, PLAND, AW mean patch area, and AW mean core area were all significantly greater in large fires than in moderate fires, while no landscape metric tested was consistently different between large fires and megafires across ecoprovinces. These findings indicate that megafires are not decidedly distinct from large fires in terms of spatial pattern, and are in agreement with rejection of the arbitrary 100,000 acre area value that is commonly used to signify a megafire. If landscape pattern of high severity burn is of concern to forest managers, they should be aware that both megafires and large fires consist of burn patterns significantly different than that of moderate fires, and take care not to focus solely on size when classifying an extreme fire event.

Conclusion

This study tracked an increase in megafire and large fire occurrence from 1984 to 2017 and found that during this period, a considerable majority of megafires occurred after 2000, with approximately 42% occurring from 2010-2017. In agreement with past findings, this indicates that megafires and large fires have become increasingly common in the twenty-first century. This study also sought to understand whether wildfire characteristics other than size alone could contribute to what defines a megafire. To test this, various landscape metrics that describe high severity patch size, patch aggregation, patch complexity, and total fire severity, were tested in moderate fires, large fires, and megafires; statistical tests for difference found that across ecoprovinces, both megafires and large fires have larger high severity patches, and that high severity patches are denser and more cohesive than in moderate fires, but also that megafires and large fires are not necessarily more severe than moderate fires. Though some of these relationships held when comparing large and megafires, it was found that megafires and large fires are more statistically similar than large fires and moderate fires. Therefore, this study highlights that wildfire spatial pattern of high severity burn is arguably more important than size when considering the ecological impacts of megafires, and that size should not be the only ecological qualifier for an extreme fire event. If extreme fire events become more frequent, ecological impacts such as forest loss due to vegetation type conversion and decline of tree species that depend on seed dispersal can be expected in ecoprovinces where trees are dominant, while landscape fragmentation and land degradation may be expected in ecoprovinces where shrubs dominate. Present-day extreme fire events are a result of a heavily altered fire regime, and understanding how they will shape western forests will be crucial for future ecological management.

Tables and Figures

Ecoprovince	Temperature (°F)	Precipitation (in)	Altitude (ft)	Dominant Species	Ecoprovince group
California Coastal Chaparral Forest and Shrub Province	50-65	10-50	0-2400	Chamise, manzanita, Monterey cypress, Torrey, Monterey and Bishop pine, California sagebrush, live oak, white oak, coyote bush, bush lupine	CC
California Coastal Range and Open Woodland	32-65	12-40	500-2500	California, canyon, and interior live oak, tanoak, California laurel, Pacific madrone, golden chinkapin, Pacific bayberry, chamise, manzanita, Christmasberry, California scrub oak, mountain mahogany	CC
Northern Rocky Mountain Forest	32-72	20-40	6000-9000	Douglas-fir, western redcedar, western hemlock, mountain hemlock, white pine, western larch, grand fir, ponderosa pine	NMS
Middle Rocky Mountain Steppe	32-68	10-30	3000-7000	Douglas-fir, grand fir, lodgepole pine, ponderosa pine, sagebrush	NMS
Southern Rocky Mountain Steppe	35-45	10-40	6000-14000	Engelmann spruce, ponderosa pine, Douglas-fir, aspen, lodgepole pine, mountain mahogany, scrub oak, pinyon pine, juniper	NMS
Sierran Steppe	35-52	10-70	1500-14000	Ponderosa pine, Jeffrey pine, Douglas-fir, sugar pine, white and red fir, incense cedar, digger pine, blue oak, manzanita, buckbrush, buckthorn, mountain hemlock, lodgepole pine, California red fir, white pine, whitebark pine, sagebrush-pinyon forest	SS
Cascade Mixed Forest	35-50	30-150	0-5000	Douglas-fir, western redcedar, western hemlock, grand fir, silver fir, Sitka spruce, Alaska-cedar, hemlock, redwood, silver fir	CMF

Table 1: Temperature, precipitation, altitude, and dominant species found in ecoprovinces assessed. These summaries are adapted from original Bailey's descriptions (Bailey 1995) provided by the USFS.

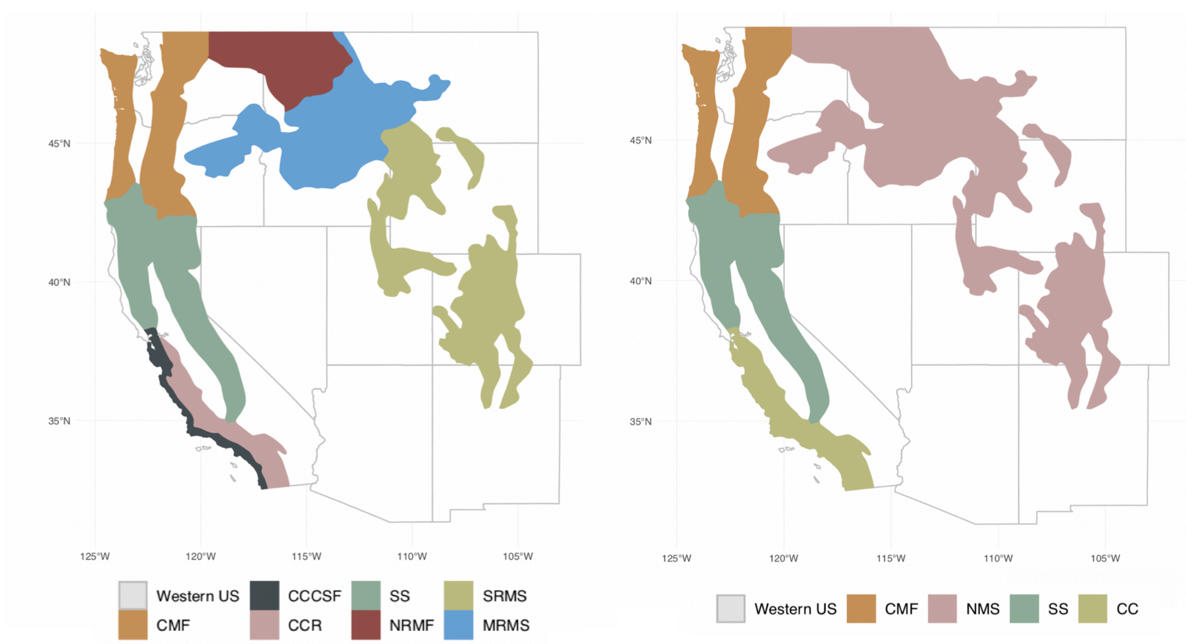


Figure 1: Map of study area, showing original Bailey's ecoprovinces (right) and grouped ecoprovinces (left).

Metric	Description	Citation

Proportion Metrics	PLAND	Proportional abundance of each patch type in the landscape; describes the percentage of each wildfire that burned at high severity	McGarigal (n.d.)
	Patch density	Number of patches per hectare	McGarigal & Marks 1995
Spatial Aggregation Metrics	PCI	Measures the physical connectedness of the corresponding patch type as a function of patch perimeter, patch area, and total landscape area	Schumaker 1996
	PLADJ	Measure of the degree of aggregation of the patch type of interest; calculated by summing the number of pixel edges that share an edge with a pixel of the same class and dividing by the total number of possible adjacencies	Neel et al. 2004
	Clumpiness	Measure of adjacency indicating the degree of aggregation of patches in a landscape; calculated by measuring the deviation of the PLADJ from that which would be expected under a normal distribution	Neel et al. 2004
High severity patch size metrics	AW mean patch size	Mean patch area across a fire, normalized by the total area of the fire	Cansler & McKenzie 2014; Harvey et al. 2016
	AW mean core area	Mean core area across a fire, normalized by the total area of the fire	Cansler & McKenzie 2014; Harvey et al. 2016
Shape metrics	Perimeter to area ratio	Ratio of patch perimeter to area	Harvey et al. 2016
	SDC	Measure of stand-replacing area size and complexity, fit by nonlinear least squares estimation; is a function of a user-defined buffer distance and the proportion of original stand-replacing area which exceeds the buffer distance inward from the patch edge	Collins et al. 2017; Stevens et al. 2017
Severity metric	SM	Continuous measure of severity across an entire fire; computed as one minus the normalized area under the cumulative severity distribution curve using RdNBR values	Lutz et al. 2011

Table 2: Summary of landscape metrics calculated

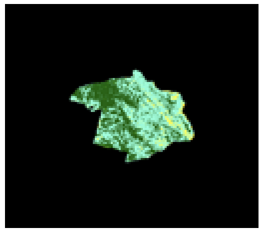
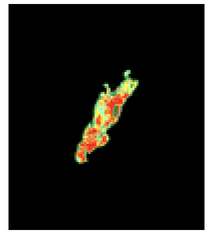
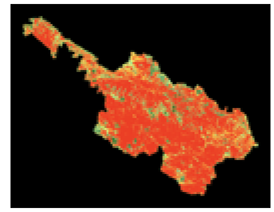
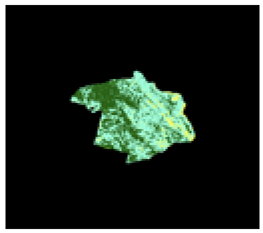
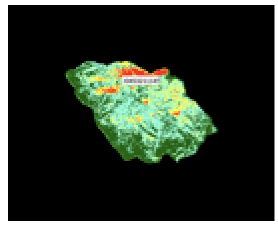
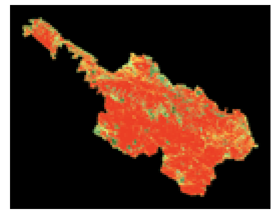
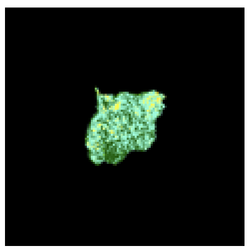
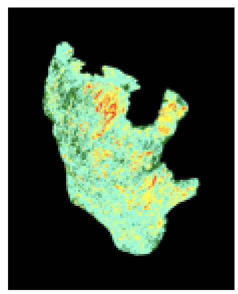
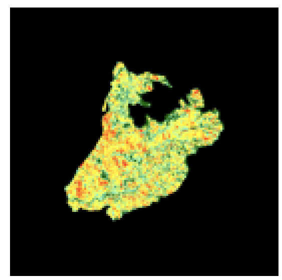
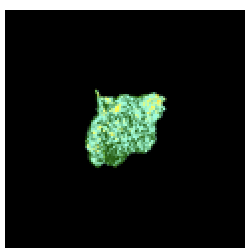
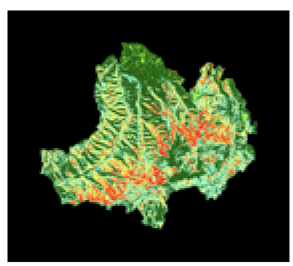
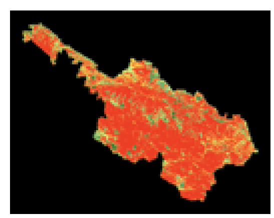
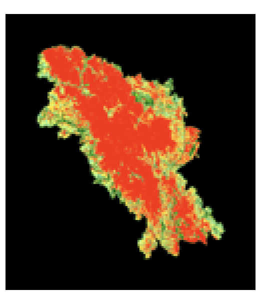
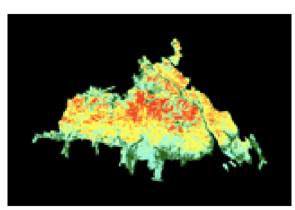
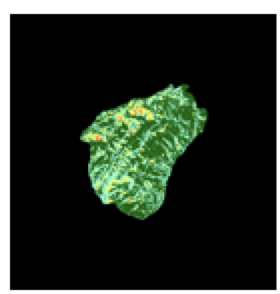
	Minimum	Median	Maximum
PLADJ	 1994 Soda Fire	 1995 Switchback Fire	 2007 Zaca Fire
AW Mean Patch Area	 1994 Soda Fire	 1985 Fountain Fire	 2007 Zaca Fire
Patch Density	 1989 Burrough Fire	 2001 St. Mary's Fire	 2006 Sierra Fire
PCI	 1989 Burrough Fire	 2005 School Fire	 2007 Zaca Fire
SDC	 1994 41 Fire	 2003 Grand Prix Fire	 1988 Unnamed Fire in California

Table 3: Visual representations of selected landscape metrics

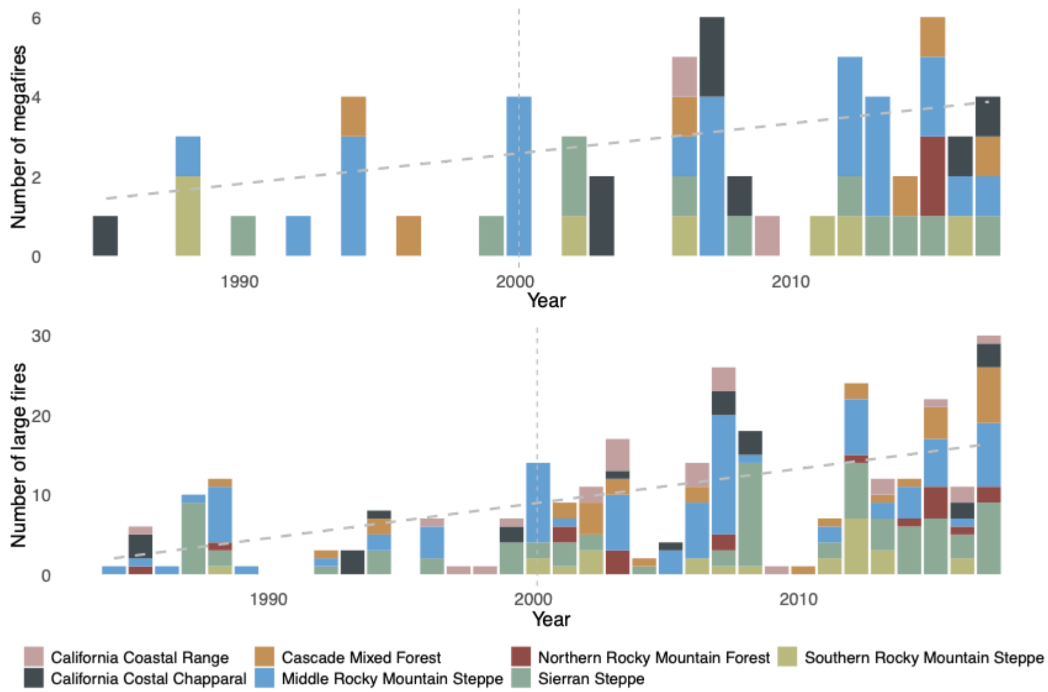


Figure 2: Increase in megafires and large fires seen over time by ecoprovince. Note different y-axis values.

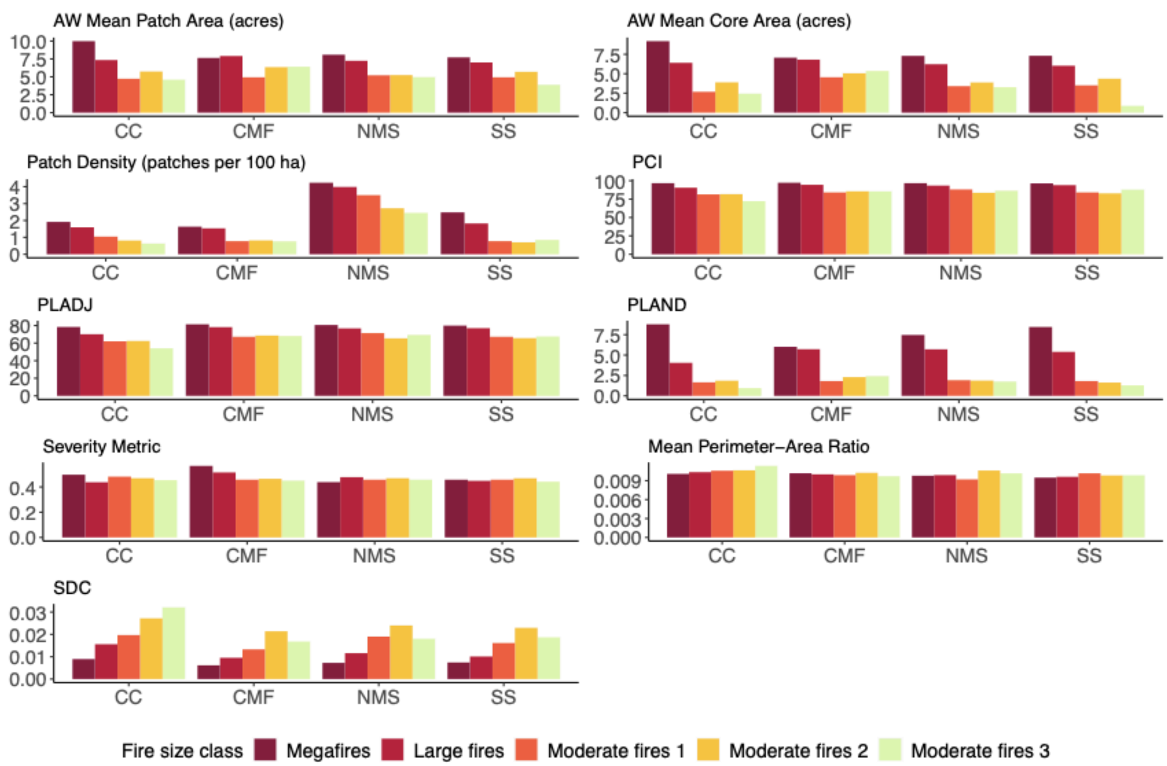


Figure 3: Mean landscape metric values for each fire size class within ecoprovinces. Note different y-axis values depending on range of landscape metric. AW mean patch area and AW mean core area values were log transformed for visual clarity.

		Fire Size	PLAND
Patch Density	***All***	**0.579**	**0.658**
	CC	0.528	0.688
	CMF	0.536	0.653
	NMS	0.526	0.572
	SS	0.7	0.745
Patch Cohesion Index	***All***	**0.335**	**0.618**
	CC	0.354	0.601
	CMF	0.386	0.728
	NMS	0.376	0.752
	SS	0.299	0.536
PLADJ	***All***	**0.346**	**0.721**
	CC	0.366	0.693
	CMF	0.36	0.765
	NMS	0.33	0.782
	SS	0.344	0.661
Clumpiness	***All***	**0.292**	**0.676**
	CC	0.317	0.653
	CMF	0.318	0.736
	NMS	0.273	0.737
	SS	0.277	0.594
AW Mean Patch Size	***All***	**0.524**	**0.754**
	CC	0.541	0.735
	CMF	0.518	0.84
	NMS	0.574	0.806
	SS	0.544	0.806
AW Mean Core Area	***All***	**0.56**	**0.726**
	CC	0.518	0.685
	CMF	0.593	0.833
	NMS	0.627	0.772
	SS	0.607	0.781
Mean Perimeter-Area Ratio	***All***	**-0.107**	**-0.316**
	CC	-0.181	-0.308
	CMF	-0.00619	-0.142
	NMS	-0.0665	-0.404
	SS	-0.137	-0.247
Stand-replacing decay coefficient	***All***	**-0.415**	**-0.813**
	CC	-0.412	-0.8
	CMF	-0.416	-0.816
	NMS	-0.402	-0.813
	SS	-0.472	-0.827

Table 4: Pearson correlation (R) values showing associations between fire size/PLAND and landscape metrics.

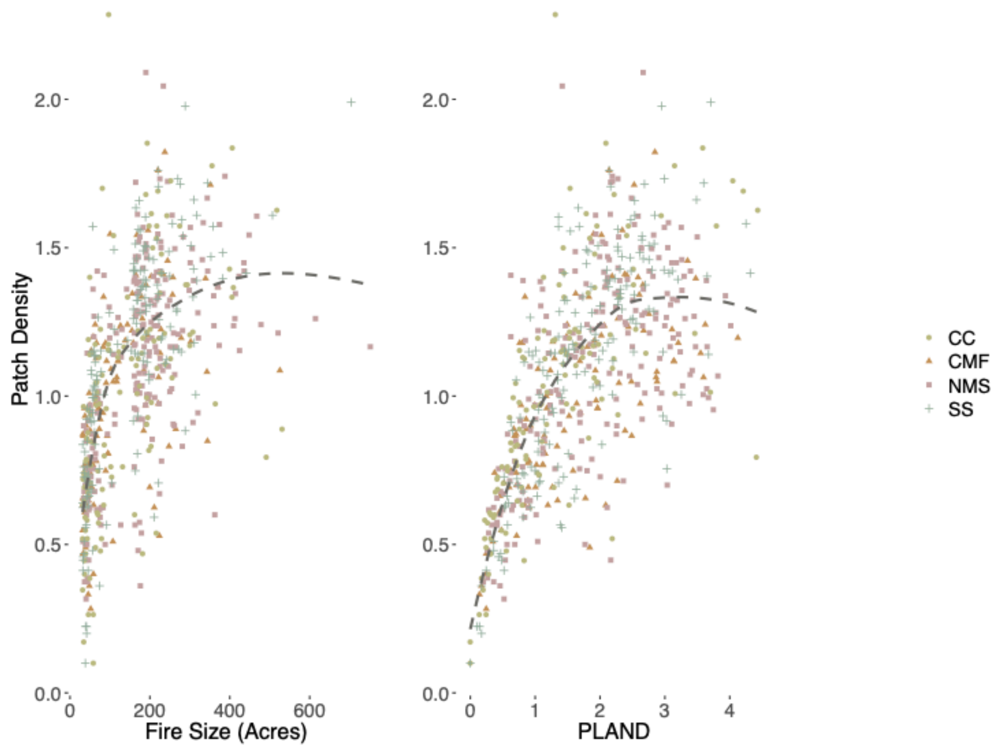


Figure 4: Relationships between fire size, PLAND and patch density. All values are square-root transformed.

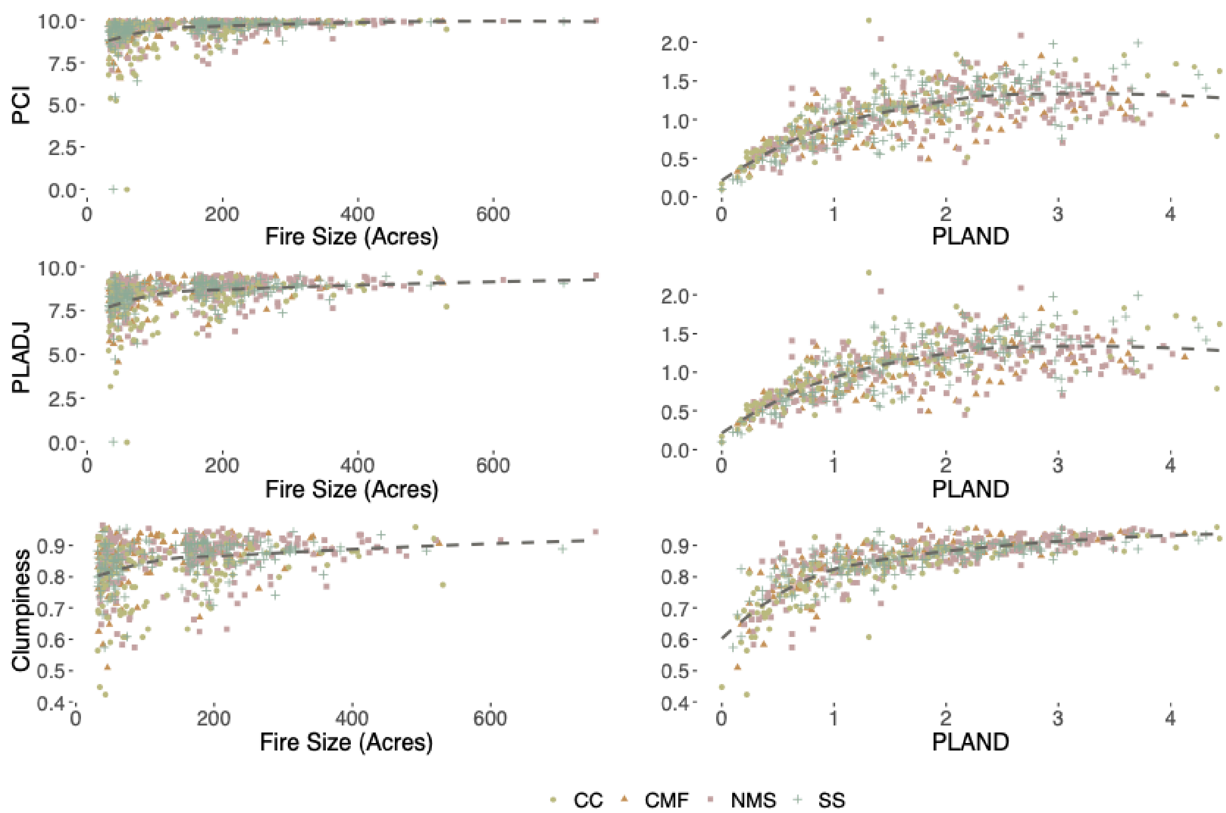


Figure 5: Relationships between fire size, PLAND and cohesion metrics. All values are square-root transformed.

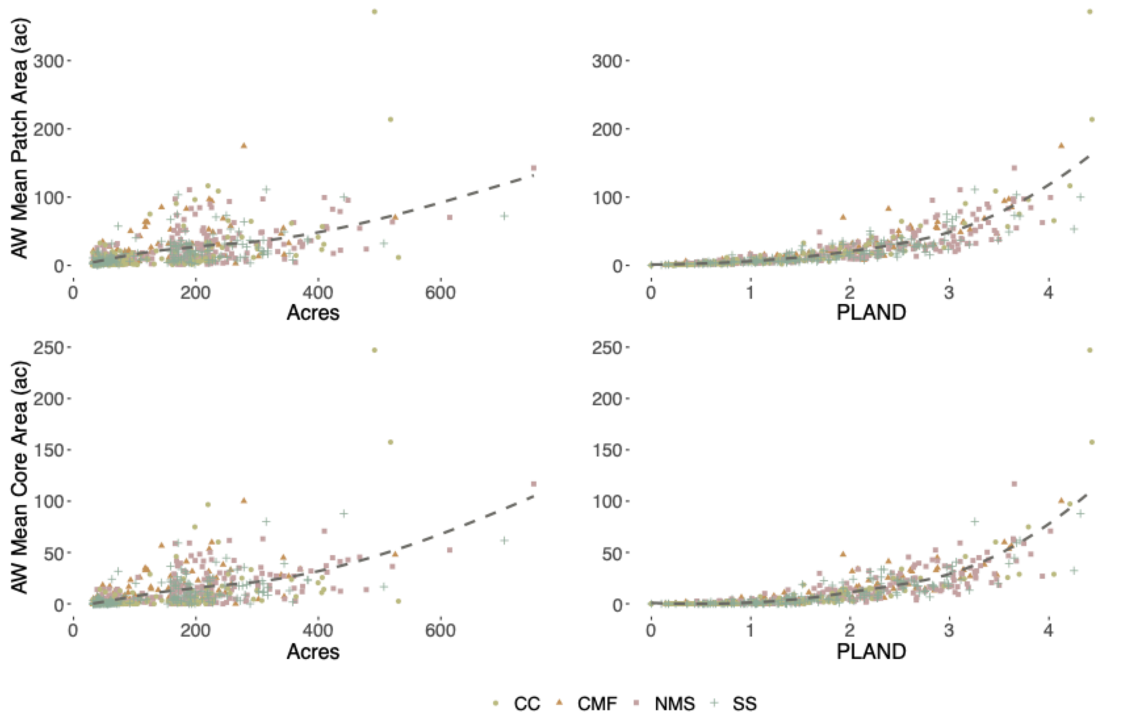


Figure 6: Relationships between fire size, PLAND and patch size metrics. All values are square-root transformed.

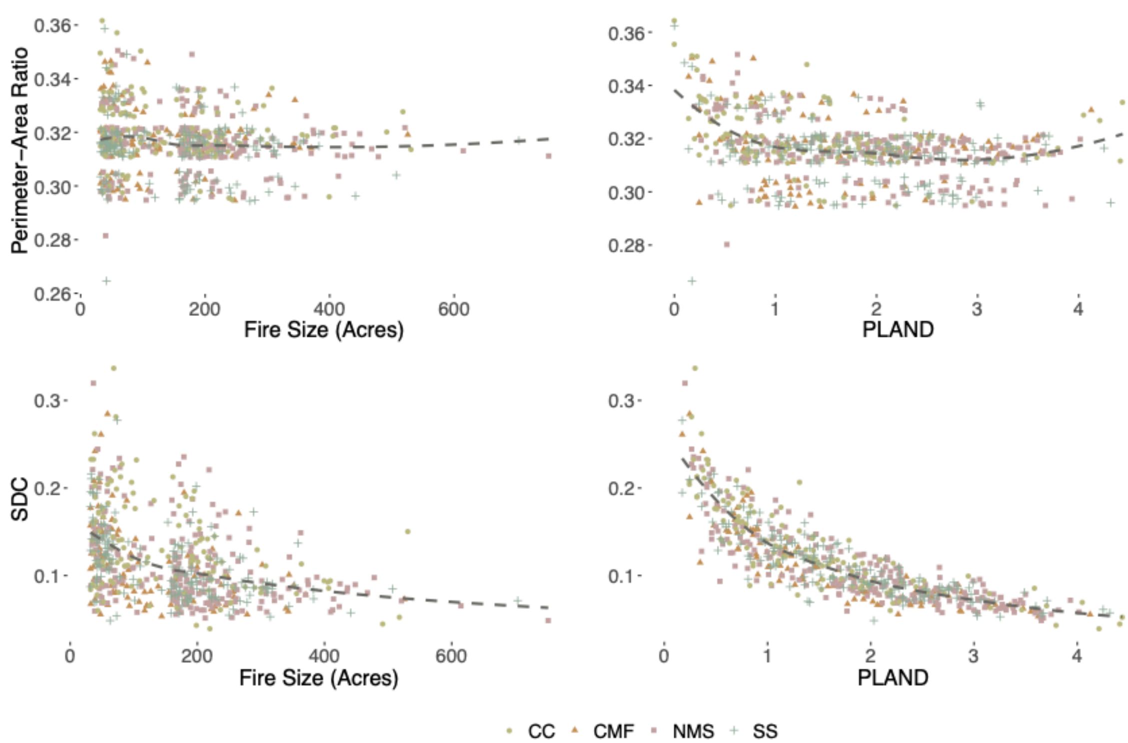


Figure 7: Relationships between fire size/PLAND and shape metrics. All values are square-root transformed. Perimeter-area points are jittered for visual clarity.

Bailey's Ecoregion	Landscape Metric	Class Size Comparison			
		Moderate-Mega 1	Moderate-Mega 2	Moderate-Mega 3	Large-Mega
CC	*Patch density **	0.0155	3.27E-03	6.70E-04	0.51338
	*Clumpiness **	0.033	0.048	0.033	0.155
	*Patch cohesion index ***	8.70E-04	1.19E-03	6.90E-04	0.03563
	*PLADJ **	0.016	0.018	0.006	0.098
	*PLAND **	3.82E-03	3.82E-03	3.40E-04	0.05565
	*Area weighted mean patch area ***	0.000024	0.0001	0.000024	0.022
	*Area weighted mean core area ***	0.00016	0.00026	4.50E-05	0.03147
	Mean perimeter-area ratio	0.68	0.4	0.33	0.68
	*Stand-replacing decay coefficient **	0.017	0.011	0.011	0.069
	SM	0.94	0.87	0.87	0.87
NMS	*Patch density ***	9.30E-09	3.50E-06	8.50E-08	0.048
	*Clumpiness **	0.043	0.03	0.037	0.444
	*Patch cohesion index ***	4.60E-06	1.20E-06	1.20E-06	0.01792
	*PLADJ **	0.0052	0.0027	0.0024	0.3115
	*PLAND **	2.10E-07	2.10E-07	2.10E-07	0.07
	*Area weighted mean patch area ***	3.30E-08	1.30E-08	1.30E-08	0.001
	*Area weighted mean core area ***	4.40E-08	6.40E-08	4.40E-08	0.00041
	Mean perimeter-area ratio	0.193	0.099	0.454	0.646
	*Stand-replacing decay coefficient **	2.40E-05	5.50E-05	2.40E-05	0.1031
	SM	0.8	0.71	0.8	0.65
SS	*Patch density ***	4.10E-07	2.70E-08	5.40E-07	0.0041
	Clumpiness	0.1426	0.0702	0.0027	0.4319
	*Patch cohesion index **	9.10E-04	7.70E-04	1.50E-05	0.27854
	*PLADJ **	0.01576	8.94E-03	4.10E-04	0.33377
	*PLAND **	1.50E-06	6.60E-06	9.10E-08	0.07
	*Area weighted mean patch area **	4.10E-05	3.10E-04	3.60E-06	0.11946
	*Area weighted mean core area **	0.00018	0.00018	9.40E-06	0.0939
	Mean perimeter-area ratio	0.66	0.66	0.66	0.92
	*Stand-replacing decay coefficient **	0.00354	0.00389	1.50E-05	0.12381
	SM	1	1	1	1
CMF	*Patch density **	0.01732	0.02056	0.01732	0.9835
	Clumpiness	0.1	0.14	0.1	0.73
	*Patch cohesion index **	0.0031	0.0146	0.0334	0.8226
	PLADJ	0.05	0.112	0.086	0.828
	*PLAND **	0.0068	0.0208	0.0434	0.9693
	*Area weighted mean patch area **	0.00016	0.01012	0.00807	0.26595
	*Area weighted mean core area **	0.0024	0.0024	0.0026	0.1116
	Mean perimeter-area ratio	0.74	0.74	0.74	0.74
	*Stand-replacing decay coefficient **	0.049	0.036	0.048	0.387
	SM	0.057	0.077	0.057	0.143

Table 5: Results of Wilcoxon Rank Sum tests for landscape metrics tested in each ecoprovince between megafires, moderate fires, and large fires. Landscape metrics for which there is a significant difference ($p < 0.05$) between each moderate fire group and megafires are denoted with a *, while a ** indicates that there is a difference between moderate and large fires and megafires.

Bailey's Ecoregion	Landscape Metric	Class Size Comparison		
		Moderate-Large 1	Moderate-Large 2	Moderate-Large 3
CC	*Patch density **	0.00067	4.20E-05	2.00E-06
	Clumpiness	0.282	0.191	0.033
	*Patch cohesion index **	2.68E-02	1.36E-02	8.70E-04
	PLADJ	0.133	0.072	0.006
	*PLAND **	9.66E-03	3.82E-03	2.90E-05
	*Area weighted mean patch area **	0.00211	0.00073	0.000024
	*Area weighted mean core area **	0.00056	0.00056	4.20E-05
	Mean perimeter-area ratio	0.94	0.4	0.26
	Stand-replacing decay coefficient	0.223	0.017	0.012
	SM	0.87	0.87	0.87
NMS	*Patch density **	9.30E-09	1.40E+00	2.40E-07
	Clumpiness	0.218	0.037	0.086
	*Patch cohesion index **	0.00062	0.00031	0.00028
	*PLADJ **	0.0401	0.0052	0.0086
	*PLAND **	2.50E-06	1.60E-06	1.00E-06
	*Area weighted mean patch area **	4.40E-05	2.40E-05	6.00E-06
	*Area weighted mean core area **	2.60E-06	3.20E-06	3.90E-07
	Mean perimeter-area ratio	0.08	0.091	0.478
	*Stand-replacing decay coefficient **	0.0011	0.0013	0.0011
	SM	0.8	0.8	0.71
SS	*Patch density **	4.10E-09	2.80E-09	8.10E-09
	Clumpiness	0.1186	0.0122	0.000095
	*Patch cohesion index **	7.70E-04	8.20E-05	2.90E-06
	*PLADJ **	0.00894	1.19E-03	2.80E-06
	*PLAND **	2.70E-07	9.10E-08	3.00E-09
	*Area weighted mean patch area **	9.70E-06	9.70E-06	3.50E-08
	*Area weighted mean core area **	1.70E-07	6.20E-07	1.00E-10
	Mean perimeter-area ratio	0.66	0.66	0.66
	*Stand-replacing decay coefficient **	0.0022	0.00044	2.10E-07
	SM	1	1	1
CMF	*Patch density **	0.00035	0.00035	0.00035
	Clumpiness	0.1	0.1	0.1
	*Patch cohesion index **	0.0031	0.0071	0.0043
	PLADJ	0.036	0.05	0.05
	*PLAND **	0.0005	0.0018	0.0032
	*Area weighted mean patch area **	0.0001	0.00231	0.0006
	*Area weighted mean core area **	0.0012	0.0012	0.0011
	Mean perimeter-area ratio	0.74	0.76	0.74
	Stand-replacing decay coefficient	0.06	0.02	0.036
	SM	0.109	0.309	0.057

Table 6: Results of Wilcoxon Rank Sum tests for landscape metrics tested in each ecoprovince between large fires and moderate fires. Landscape metrics for which there is a significant difference ($p < 0.05$) between each moderate fire group and large fires are denoted with a *.

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