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Evidence for scale-dependent topographic controls on wildfire spread

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Abstract. Wildfire ecosystems are thought to be self-regulated through pattern–process interactions between ignition frequency and location, and patterns of burned and recovering vegetation. Yet, recent increases in the frequency of large wildfires call into question the application of self-organization theory to landscape resilience. Topography represents a stable bottom-up template upon which fire interacts as both a physical and an ecological process. However, it is unclear how topographic control changes geographically and across spatial scales. We analyzed fire perimeter and topography data from 16 Bailey ecoregions across the State of California to identify spatial correspondence between ecoregional fire event and topographic patch size distributions. We found both sets of distributions followed a power-law form and were statistically similar across several orders of magnitude, for most ecoregions. As a direct test of topographic controls on fire event perimeters, we used a paired *t*-test across ~11,000 fires to identify differences in topographic attributes at fire boundaries versus fire interiors. Statistical significance was determined using 500 iterations of a neutral landscape model. Level of topographic control varied significantly by ecoregion and across topographic features. For example, north–south aspect breaks, valley bottoms, and roads showed a consistently high degree of spatial control on wildfire perimeters. Topographic controls were most pronounced in mountainous ecoregions and were least influential in arid regions. Ridgetops provided a low-level control across all ecoregions. Spatial control was strongest for small (10^0–10^2 ha) to medium (10^3–10^4 ha) fire sizes, suggesting that controls were scale-dependent rather than scale-invariant. Roads were the dominant control across all ecoregions; however, removing roads from the analyses had no significant effect on the overall role of topography on wildfire extinguishment in this analysis. This result suggested that certain topographic settings show strong spatial control on fire growth, despite the presence of roads. Our results support the observation that both bottom-up and top-down factors constrain fire sizes and that there are likely scaling regions within fire size distributions wherein the dominance of these spatial controls varies. Human influences on fire spread may either diminish or enhance the role of some bottom-up and top-down factors, adding further complexity.

Key words: biophysical; complexity; disturbance; fire; landscape ecology; Scaling; self-organize; self-organized criticality; Topography.

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Introduction

Wildfire is the dominant disturbance agent in most western U.S. forests and rangelands. Prior to Euro-American settlement, patterns of forest and rangeland successional conditions emerged from interactions among wildfires, past burn severity patterns, biophysical environments, and vegetation regrowth. The resulting abundance, dispersion, and patch sizes of various successional conditions generally fell within a predictable range of variability (Taylor and Skinner 1998, Landres et al. 1999, Heyerdahl et al. 2001, Hessburg and Agee 2003, Veblen 2003).

In addition to sculpting successional conditions, historical wildfires provided a constantly evolving patchwork of burned and recovering patches that alternatively constrained and facilitated fire flow on the landscape. Overall, fires reduced forested area, thinned forests, and reduced surface fuels, which created a patchwork of landscape memories—conditions that, for a time, influence the growth and severity of future fires (Peterson 2002, Prichard et al. 2017). Patterns of biophysical environments added other positive and negative feedback to the landscape by means of spatial variability in insolation, gradients of edaphic environments, orographic effects, natural barriers to wildfire spread (e.g., rock, water, ice, bare ground), and the timing and distribution of ignitions (Beaty and Taylor 2001, McKenzie et al. 2006, Kellogg et al. 2008). Occasionally, large deviations in vegetation patterns occurred after very large weather-driven fire events, but systems generally rebounded to prior ranges of seral stage and fuel conditions (Nonaka and Spies 2005), unless there was a significant long-term change in climatic forcing (Keane et al. 2009). In this way, multi-scaled feedback—interacting with recurrent disturbances over space and time—resulted in fairly predictable ranges of vegetation succession and fuel conditions, which yielded self-regulating and self-organizing property of these systems.

In recent years, however, increases in the size and severity of western wildfires have led some to question the resilience of landscapes to future wildfires and other large disturbances (Stephens 2005, Westerling et al. 2006, Miller et al. 2009). Land management practices, including fire suppression, timber harvesting, land conversion to agriculture, development of extensive road networks, and livestock grazing have altered disturbance regimes, fuels, and vegetation patterns within many western U.S. landscapes (Fulé et al. 1997, Taylor and Skinner 1998, Hessburg and Agee 2003, Hessburg et al. 2005). Across large portions of the West, forested area has increased, forests are more homogenous in their structure and composition, forests are denser with a large proportion of stems in small size classes, and they are more prone to active and passive crown fire (Stephens and Lawrence 2005, Fry and Stephens 2006, Perry et al. 2011). Furthermore, trends in increased area burned are motivated by a warming climate, signaled by longer fire seasons, warmer winters, reduced mountain snowpack, earlier snowmelt and run-off, prolonged periods of intense drought, warmer mean annual and summer temperatures, and changes in the timing, amount, and distribution of precipitation (Westerling et al. 2006, Jolly et al. 2015). Thus, recent increased wildfire activity may be indicative of the breakdown in pattern–process linkages that historically maintained self-regulation in fire-adapted systems and that the dominance and degree of bottom-up and top-down spatial control on fire spread and extinguishment are not functioning as they have previously.

Patterns of wildfire event size distributions (FSD) have been used to infer ecosystem-level properties across the United States and elsewhere (Malamud et al. 1998, 2005, Ricotta et al. 2001, Boer et al. 2008). A key feature observed in many studies is the presence of power-law behavior in FSDs spanning several orders of magnitude. The parameters of observed distributions ostensibly match closely with those from simulated wildfire landscapes. By extension, researchers have forwarded a now popular theory on the origins of power-law behavior in natural wildfire systems termed self-organized criticality (SOC). Self-organized criticality theory holds that wildfire systems (1) are self-organized, where controls on fire spread rely on feedback between internal processes—ignition frequency and location, vegetation (e.g., fuel) regrowth, and its spatial patterning, (2) are scale-invariant, such that processes controlling small fires are the same as those controlling large ones, (3) build toward a critical state where fires of any size can result, and (4) interactions among internal system components lead to scale-invariant patterns and system-level behavior (i.e., the whole is greater than the sum of its parts; Turcotte 1999).

The simplicity of the rules governing simulated fires has been extended to natural wildfire systems, which suggests that the self-regulation, and by extension, the resilience in wildfire systems, is a fundamental and stable system property. However, recent evidence suggests that the negative feedback of past fires are variable, decay over time, and can fail under extreme weather conditions (Héon et al. 2014, Parks et al. 2015, 2018*b*, Holsinger et al. 2016), which has led some to question the importance of other feedback within the system in conferring resilience to wildfire systems.

Recent research has sought to identify the roles of top-down (exogenous) and bottom-up (endogenous) factors on wildfire spread across various fire-adapted ecosystems, both in the United States and across the globe. Results from these studies suggest that complex interactions exist between bottom-up and top-down forcings, each of which can exert varying degrees of dominance over space and through time. Bottom-up factors generally include (1) the ignition source, ignition density, and spatial distribution, (2) fuel types, amounts, and spatial arrangements, and (3) topography, which interacts with fire behavior and vegetation patterns. Top-down factors are those that emanate from without, but which condition vegetation and fuel patterns across large areas. These include broad geomorphic and geologic conditions, long-term climatic patterns, and weather conditions (Parks et al. 2012).

Wildfire is at once a physical and an ecological process that operates across spatial scales. At fine scales (e.g., an individual flame), combustion is a function of the presence of an ignition source, available fuel, and adequate oxygen. At larger spatial scales, fires are governed by long-term climate, fire weather, patterns of surface and canopy fuels, and patterns of past disturbances and topography, all of which can contribute to fire severity and the likelihood of fire spread in a given area (Moritz et al. 2005). These factors are not independent of one another, but are highly interactive, co-dependent and correlated over space and time, making generalizations of observed relationships difficult.

Of these factors, topography represents the most stable template upon which vegetation (and fuels) dynamics, climate, weather, and fire may respond. Regional fire history studies have helped elucidate the role topography plays in spatially varying fire-return intervals (Beaty and Taylor 2001, Heyerdahl et al. 2001). For instance, north slopes generally have lower levels of solar radiation and are therefore cooler, moister, and more productive than neighboring southerly slopes, which can lead to more extended fire-return intervals than their southerly counterparts, and higher fire severity. At fine scales, topographic features such as cold-air drainages can create microclimates where fire behavior can change markedly (Whiteman et al. 2001).

Wind patterns are also influenced by topography during a fire (Sugihara 2006). Diurnal patterns of upslope and up valley winds can accelerate fire spread and drive severity patterns. Channeling of wind flow into canyons and other natural chimneys can greatly increase the speed and severity of fires. In rugged topography, wind patterns are more complex and less predictable lending to uncertainty in short-term wind patterns. Topography also directly facilitates fire spread through convective pre-heating of fuels upslope from a flaming front, or it can provide barriers to spread where headwalls, scree slopes, or rock outcrops exist. These features can also create fire refugia, where extended fire-free periods create uniquely durable vegetation patterns on the landscape (Camp et al. 1997, Krawchuk et al. 2016).

Thus, topography can influence wildfire spread and extinguishment directly by driving wind flow patterns, providing physical barriers to spread, and influencing convective heating during a wildfire event, and also indirectly by influencing long-term climate, vegetation, and fuels.

Given the potential influence of topography on wildfire spread, we sought concrete statistical evidence for the degree and spatial scales of topographic controls on wildfire sizes. We analyzed fire perimeter and topography data from 16 Bailey ecoregions across the State of California to identify spatial correspondence between ecoregional fire event (FSDs) and topographic patch size distributions (PSDs). We first fit power-law models to ecoregional FSDs and topographic PSDs (sensu Moritz et al. 2011). Topographic patches included north and south aspect patches, and those of ridgetops and valley bottoms. We then statistically compared ecoregional FSDs and PSDs to identify spatial correspondence between them.

As a more direct measure of topographic control, we compared topographic features at fire boundaries and within fire interiors for ~11,000

fires, and used neutral landscape modeling to test the null hypothesis of no difference in topographic influence at fire boundaries and within fire interiors. A significant difference would indicate topographic controls on fire extinguishment. We further hypothesized that roads were also barriers to fire spread, directly through the disruption of fuel continuity, and indirectly through their use during fire suppression.

We used a multi-regional and multi-scaled assessment approach to evaluate topographical controls on wildfire extinguishment to ask the questions: (1) Are drivers of fire extinguishment scale invariant? (2) Are topographic controls dominant across all fire sizes? (3) Are all topographic features equally influential? and (4) Do controls from topography vary by ecoregion?

Methods

Study area description

The State of California is comprised of 16 Bailey ecoregions (Bailey 1995), which range from xeric desert ecosystems in the southeast, to fog belt coastal redwood forests in the northwest (Fig. 1). Across the State, wildfire regimes are integral to most vegetation types (Parisien and Moritz 2009), and regimes vary considerably by ecoregion (Sugihara 2006).

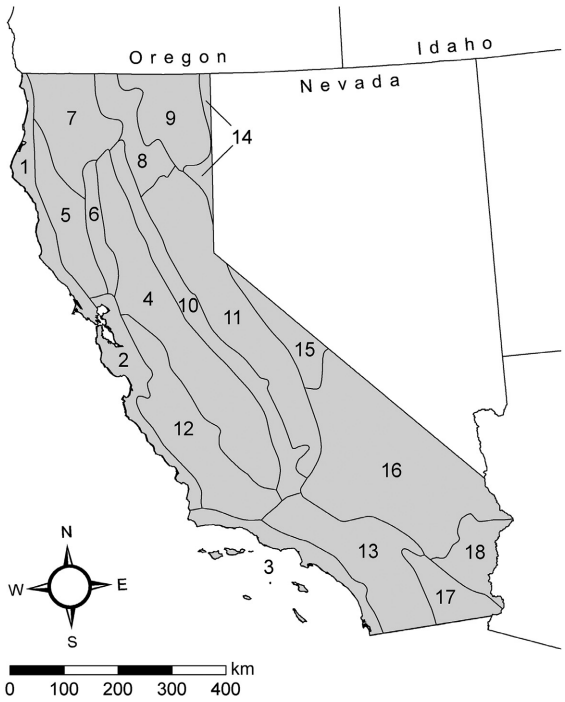

Fig. 1. Bailey Sections within California, USA. See Table 1 in text for Section details.

Main climatic gradients exist across the broad latitudinal gradient of cooler and moister conditions to the north, and warm and dry conditions in the south. Likewise, a longitudinal gradient exists, revealed by strong marine conditions in the west, and a dry continental climate in the east (Table 1). Local climatic variation derives from broad elevation gradients in the Klamath, North and South Coast, Sierra Nevada, Transverse, and Peninsular Mountain Ranges.

Data

Bailey's ecoregion data.—We downloaded a shapefile for the Bailey ecoregions hierarchy from the US Forest Service website: http://www.fs.fed.us/rm/ecoregions/products/map-ecoregions-united-states/. Bailey ecoregions (Bailey 1995) were developed for the conterminous United States to identify areas of similar biogeoclimatic conditions. Top levels of the hierarchy were delineated based on climate zones, and lower levels incorporated physiography, biota, topography, and soils. The Section level is the lowest in the hierarchy, and it incorporates an intersection of all factors. We chose it for all subsequent analysis because topography is used in Section delineation, and stratification by Section showed the most significant differences in fire size distributions, when considering the Division, Province, and Section levels (Moritz et al. 2011).

Topography data.—We obtained a 30-m digital elevation model (DEM) for California from the National Elevation Dataset (https://lta.cr.usgs.gov/NED). Within a geographic information system (GIS), we calculated several topographic features, including aspect, slope, and a topographic position index. Using these derived measures, we developed four topographic rasters that were summarized to each individual fire. These were as follows: (1) north–south aspect breaks (binary raster), (2) a ridge index (continuous raster, 0 [mid-slope and below]–100 [ridge]), (3) a valley index (continuous raster, 0 [mid-slope and above]–100 [valley]), and (4) a ridge-valley index (continuous raster, 0 [mid-slope]–100 [ridge or valley]). The ridge and valley indices were derived from the topographic position index calculated at several

Table 1. Bailey Section-level characteristics.

ID (See Fig. 1)	Bailey (1995) Section	N fires	Mean annual precipitation (mm)†	Mean maximum temperature (°C)†	Road density‡	Riley (1999) topographic roughness§¶	Mean slope (°)
12	Cent. Coast Range	1130	412.4	23.2	1.48	465.7	3.55
2	Cent. Coast	286	690.3	20.8	3.75	326.4	3.43
4	Great Valley	700	383.8	24.4	2.42	55.8	0.39
7	Klamath	838	1679.8	17.5	1.10	928.1	7.52
9	Modoc	468	455.0	15.3	1.06	578.6	2.47
16	Mojave	111	147.8	25.7	0.82	512.5	3.30
15	Mono	125	281.1	17.1	0.71	924.1	4.91
5	No. Coast Range	663	1424.3	20.0	1.75	661.1	5.81
1	No. Coast	295	1484.9	19.0	1.97	369.2	4.04
6	No. Int. Coast Range	276	757.2	22.3	0.92	474.1	4.18
14	NW Basin Range	114	333.2	15.8	0.92	664.9	3.18
10	SN Foothills	1534	760.1	22.2	1.69	558.1	4.38
11	Sierra Nevada	1891	1055.1	14.9	1.04	1197.3	6.89
3	So. Coast	998	428.8	23.1	6.07	259.3	2.91
13	So. Mtn. Valley	3695	398.2	24.1	2.76	620.6	4.60
8	So. Cascade	234	1022.2	15.4	1.53	770.7	4.21

† Calculated from (PRISM Climate Group 2013) 1-arc second climate normal data.
‡ Calculated using TIGER roads data.
§ Calculated using 1000-m statewide DEM.
¶ Calculated using the methods of Riley (1999), where TRI = $\sqrt{\sum \left(x_{ij} - x_{00}\right)^2}$ and x_{ij} is the elevation of each nearest-neighbor cell-to-cell x_{00}.

spatial scales (annular neighborhoods with 250-, 500-, and 1000-m outer radii). Aspect breaks were resampled to 60 and 90 m resolutions.

The statewide DEM was further used to develop topographic patches of continuous aspect, slope, and curvature. Aspect patches were developed by classifying the continuous aspect raster into north (270–90), south, and flat topographies, which were converted to polygons in the GIS. The same was done for slope (flat, 0%; shallow, 0–30%; steep, >30%) and curvature (flat, concave, and convex).

Road data.—A 2012 TIGER (topologically integrated geographic encoding and referencing) digital roads shapefile was downloaded for the entire State of California (https://www.census.gov/geo/maps-data/data/tiger-line.html). The shapefile was then converted to a 90-m binary raster (1 = road, 0 = no road) for further processing.

Wildfire perimeter atlas.—We used an atlas of georeferenced fire perimeters for California, for the years 1950–2012, accessed from the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (CDF-FRAP 2012, http://frap.fire.ca.gov/data/frapgismaps-subset). A total of 10,800 fire perimeters, ranging in size from 1 to 100,000 ha, were included in the database and used in analysis.

Statistical analyses

Comparison of scaling regions of topographic patch and fire size distributions.—Inverse cumulative distribution functions (iCDFs) were developed from (1) wildfire size distributions and (2) the topographic patches for each ecoregion. Power-law (Pareto) models were fit to both sets of distributions following the methods of Clauset et al. (2009), where maximum-likelihood estimation (MLE) was used to identify the best-fitting power-law model to all patches larger than a minimum patch size, and 2500 Monte Carlo simulations of the best-fitting model were run to assess significance of the model fit (Kolmogorov-Smirnov [KS] test, $P > 0.1$).

We then used a two-sample KS test to identify the range of fire event sizes and topographic patch sizes where the two distributions were not significantly different. From a previous analysis (Moritz et al. 2011), we fit power-law models to ecoregional fire event size distributions using the methods of Clauset et al. (2009). A minimum fire size (i.e., x-min) was identified for each distribution, where the power-law model fit to all larger fires. In the current assessment, we used these x-min values as a starting point for identifying coherence among fire and topography distributions. All fires

and topographic patches were censored to include only patches within the range of patches above the *x*-min value for the ecoregion. We then sequentially clipped fires and topographic patches from the right tail of their respective distributions until a non-significant KS test ($P > 0.05$) was identified. This was repeated for aspect, slope, and curvature topographic patch types.

Neutral landscape modeling to assess topographic controls at fire boundaries.—The goal of this analysis was to assess significant differences in topography at fire boundaries compared to fire interiors. Fire boundaries were defined as the 100-m interior buffered off the delineated fire perimeter (Fig. 2). This buffer was chosen to represent the conditions experienced at the location of extinguishment, and to represent a fuzzy boundary that could account for inaccuracies in boundary delineation. Fire interiors were defined as the area within the fire boundary, as defined above (Fig. 2).

Topographic variables were summarized to both the interior and boundary areas separately using the zonal statistics tool within ArcGIS 10.1.1 (ESRI 2012). Summary statistics included the following: (1) the proportional area in north–south aspect breaks, (2) mean ridge index, (3) mean valley index, (4) mean ridge-valley index, and (5) the proportional area covered by roaded pixels. Given that road location is often topographically driven (Narayanaraj and Wimberly 2011), we reanalyzed the data by converting cells that corresponded to both road and topographic breaks to NA, which removed them from the re-analysis.

For each ecoregion, a one-sided, paired *t*-statistic was calculated separately for each topographic feature, across all fires within each ecoregion, and within four fire size classes 1–100, 100–1000, 1000–10,000, and 10,000–100,000 ha. Size classes were based on previously identified potential scaling regions (Moritz et al. 2011) in fire size distributions.

The null hypothesis for the *t*-test was that topographic breaks were equally common in fire interiors as compared to fire boundaries. A *t*-statistic of 0 would indicate equality in topographic features within the fire boundary and interior. A *t*-statistic greater than zero would indicate topographic features are more prevalent at the fire boundary. We used a paired *t*-test to standardize boundary topographies to the topography each fire experienced when actively burning, and because boundary topographies on their own may not be comparable across fires, but instead are context specific.

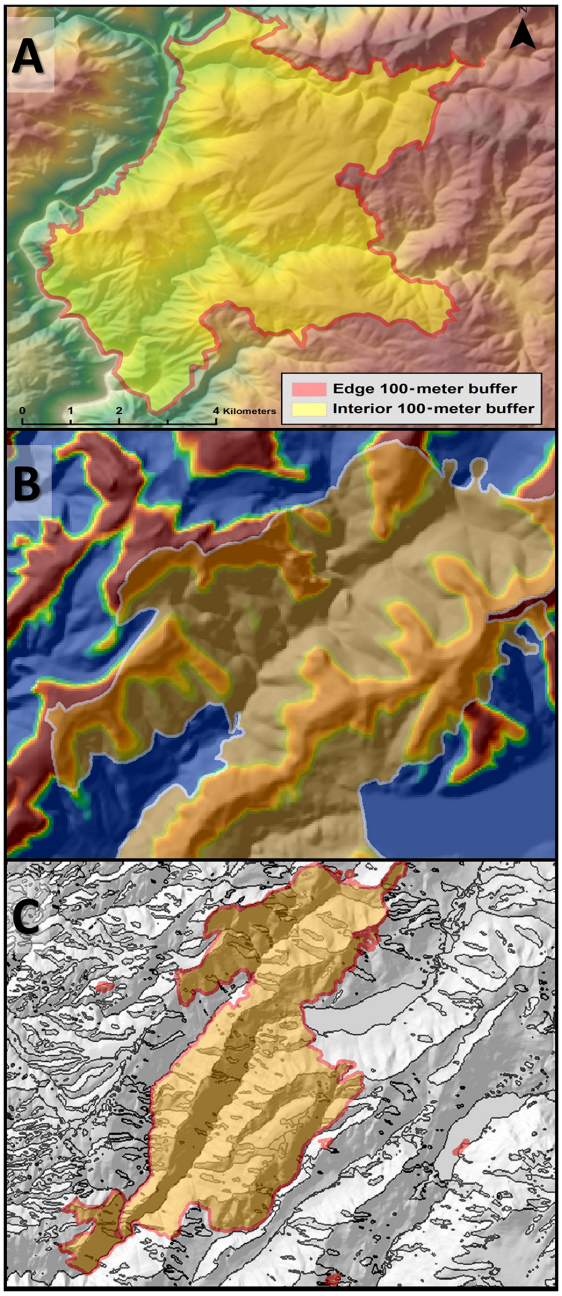

Fig. 2. (A) Example 100-m fire buffer and fire interior used for statistical analyses. (B) Example north–south aspect breaks (90 m resolution), and (C) example ridgetop index, red polygons (1000 m).

In lieu of using the *P*-values resulting from the standard *t*-test to evaluate significance, a neutral

modeling approach was used to assess significant differences between boundary and interior topographies for each topographic feature, ecoregion, and fire size class combination. Neutral modeling was favored over traditional *t*-test *P*-values due to the potential for spurious results related to the large differences in area covered by interior versus boundary areas. The neutral modeling proceeded as follows: (1) A *t*-statistic was calculated for observed fires for each topographic feature, ecoregion, and fire size class combination as described above (e.g., ridgetop topography for fires between 100 and 1000 ha within the Southern Cascades), (2) each fire was then randomly moved within its membership ecoregion, (3) each topographic feature was summarized to the boundary and interior regions, and (4) a paired *t*-statistic was calculated for each neutral model iteration. This process was repeated 500 times. The observed *t*-statistic from Step 1 was then compared to the distribution of *t*-statistics from the neutral model iterations from Step 4, and a *P*-value was calculated as the proportion of times a randomized *t*-statistic was greater than or equal to the observed *t*-statistic. Significance was assessed at $P \leq 0.05$. Random fire placements was restricted such that fire polygons could not intersect water bodies, rock, snow, ice, or other non-burnable surfaces.

All statistical analyses were conducted in the R statistical software (R Core Team 2018).

Results

Power-law model fits to topographic patch sizes

Power-law models provided good fits to the topographic patch data, in all ecoregions but the North Coast ($P = 0.09$; Fig. 3). Power-law shape parameters (aka, iCDF slope) varied between −0.72 and −1.07 (Fig. 3). Values <−1 (i.e., steep iCDF slopes) indicated that smaller patches were most influential to the shape of the power law: values = −1 indicated equal influence of larger and smaller patches, and values >−1 (i.e., shallow iCDF slopes) indicated that larger patches were somewhat more influential.

Comparisons between topographic and fire patch size distributions

Correspondence between topographic and fire event PSDs was found across all ecoregions, but the spatial extent of these relationships varied by ecoregion and by topographic feature (Fig. 4). Correspondence between fire event and aspect PSDs was identified for medium fire sizes in five of 16 ecoregions, medium and large fires in nine of 16 ecoregions, and large fires in two of 16 ecoregions (Fig. 4). Results for slope patches were similar to aspect, but fewer large fires corresponded with slope PSDs (Appendix S1: Fig. S1). Curvature PSDs corresponded least well with fire size distributions, correspondence was generally found for only small and medium patch sizes, but correspondence was high for the Central Valley, and Basin and Range ecoregions (Appendix S1: Fig. S2). This resulted from the fact that curvature patches represented a finer scale dissection of topography as compared to aspect and slope patches, which resulted in fewer larger patches and steeper iCDF shape parameters for curvature PSDs.

Neutral landscape modeling

Evidence for topographic control on fire extinguishment was strongest for north–south aspect breaks (Fig. 5), valley bottoms (Appendix S1: Fig. S4), ridges and valleys combined (Appendix S1: Fig. S7), and roads (Appendix S1: Fig. S8). In general, ecoregions that exhibited the strongest topographic control on fire extinguishment included the Sierra Nevada, Sierra Nevada Foothills, Klamath, North Coast, North Coast Range, Central Coast Range, and Southern Mountain Valley. Sierra Nevada and Klamath ecoregions were the steepest, most rugged, and are among the most fire active of all California ecoregions (Table 1). The Southern Mountain Valley had the highest frequency of fires, and moderately high ruggedness and steepness. The Northern Coast Range ecoregion was among the steepest of ecoregions, but was only moderately rugged. The North Coast and Central Coast had fairly low ruggedness and steepness (Table 1).

Topographic control on fire spread was greatest in the small (10^0–10^2 ha) and middle fire size ranges (10^2–10^4 ha), but this was not the case for all ecoregions (Fig. 5; Appendix S1: Figs. S4–S8). In ecoregions where valley bottoms exhibited a high degree of spatial control on wildfire perimeters, the highest control tended to occur in the 10^2–10^3 ha fire event size class (e.g., Central Coast, Central Valley, North Coast Range, Northern Interior Coast Range, Central Coast Range,

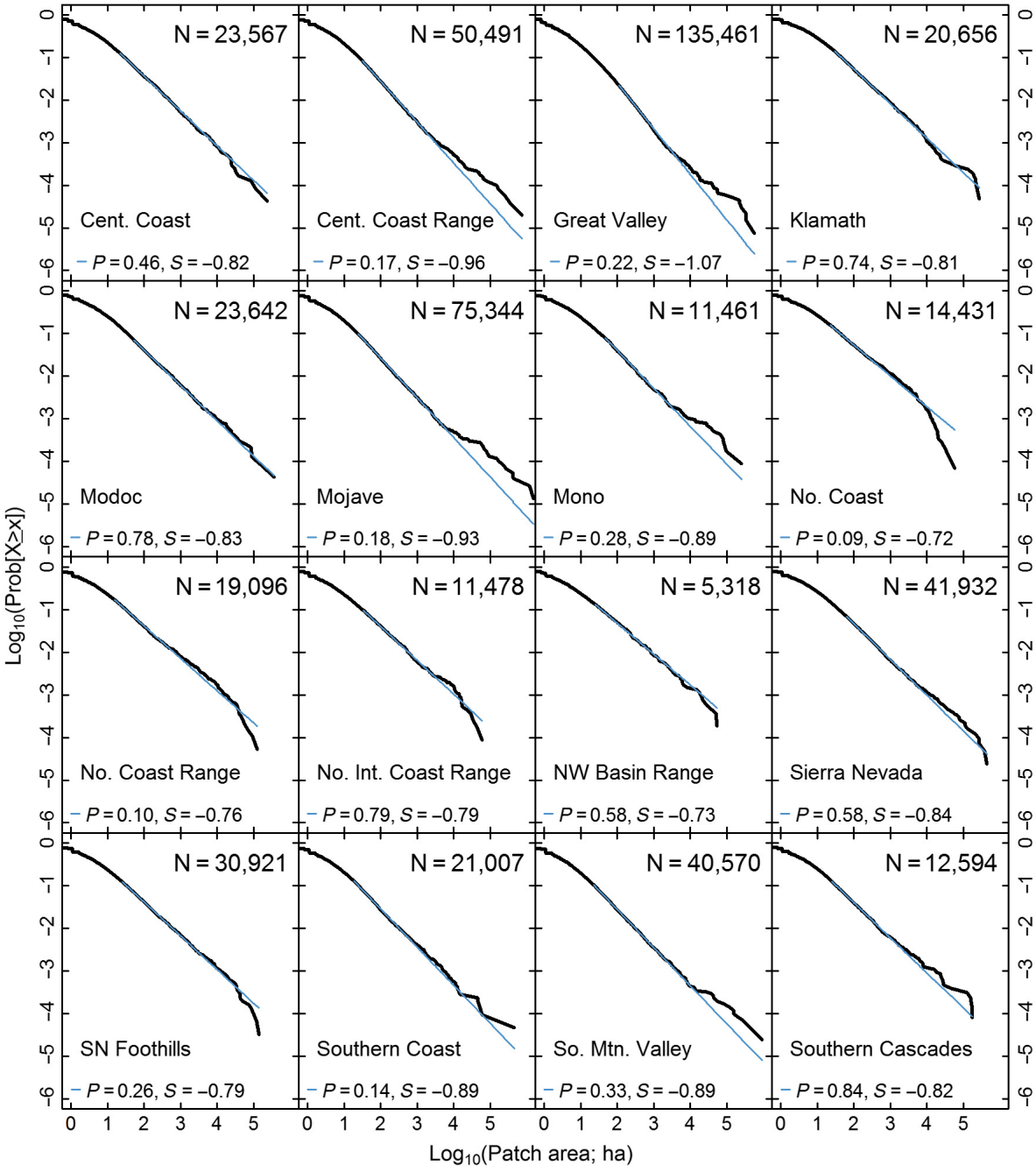

Fig. 3. Power-law (Pareto) model fits for observed aspect patch size distributions within Bailey Sections. Black lines are the observed distribution for aspect patch sizes, and the blue lines are the best-fitting power-law model. Aspect classes were north, south, and flat. S is the shape parameter of the power-law model, and *P* is the *P*-value. *P*-values >0.1 indicate a good fit to the power law.

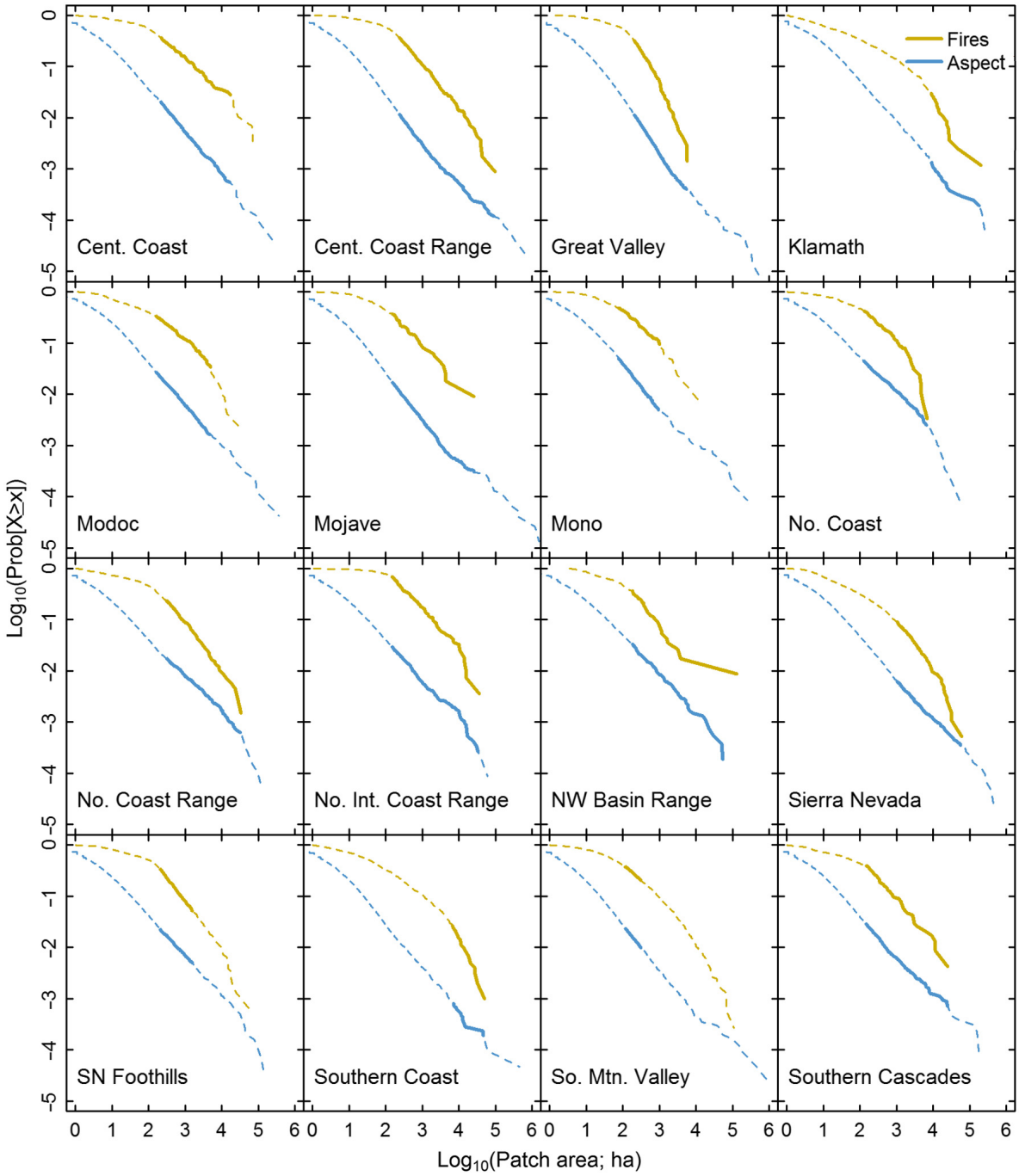

Fig. 4. Correspondence between wildfire event (gold lines) and north–south aspect (blue lines) patch size distributions. Bold solid portions of the lines indicate areas of correspondence among the wildfire and aspect distributions. Areas of correspondence were determined as follows: The *x*-min calculated for the wildfire size distribution (see text) was used to set the minimum patch size, and the right end was set by sequentially clipping patches from the right tail of the distributions until a two-sample Kolmogorov–Smirnov test shows no difference.

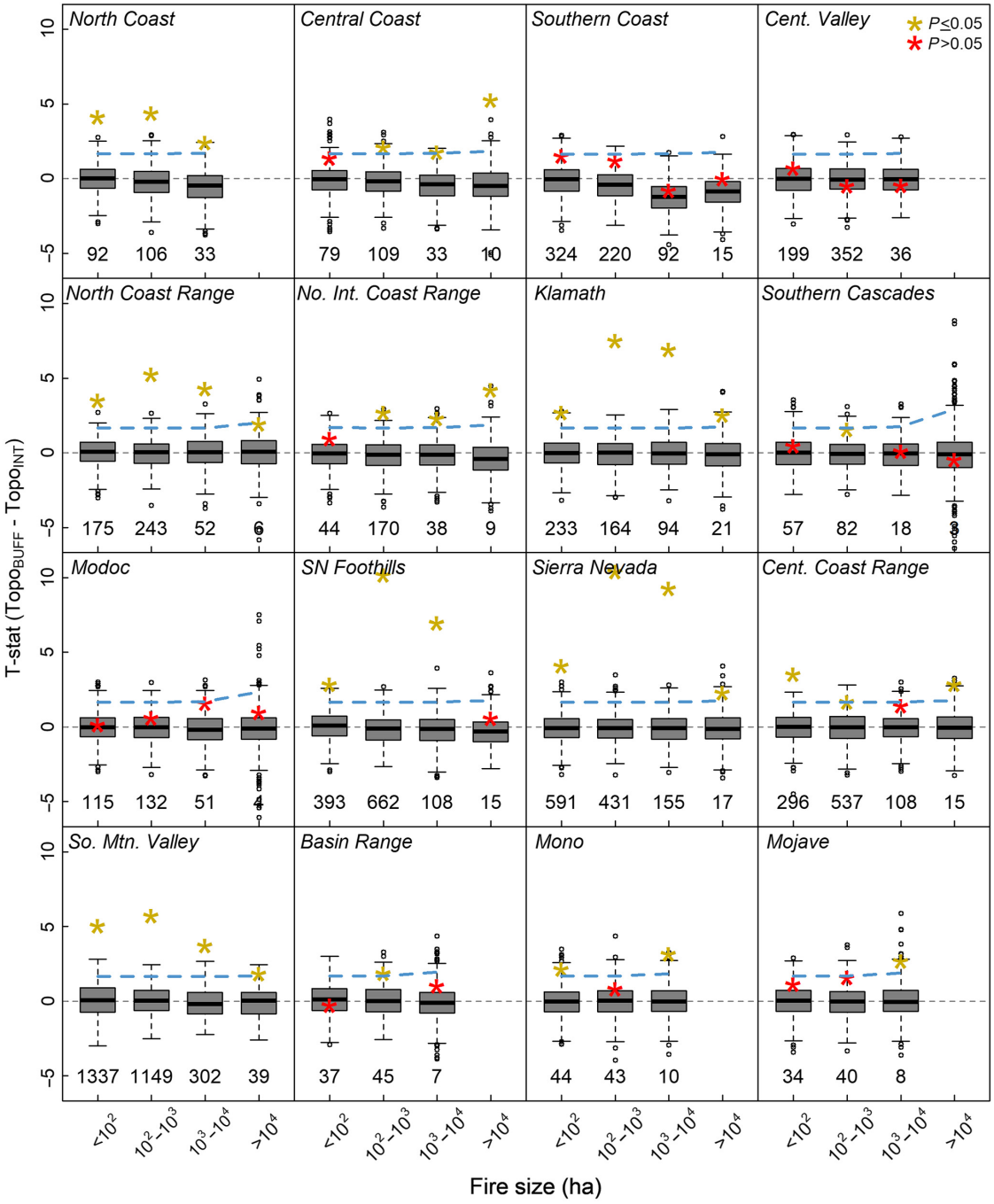

Fig. 5. Statistical comparisons of the proportion of 60 m pixels in north–south aspect at fire edges compared to fire interiors for Bailey Sections. Stars represent *t*-statistics from a one-sided, paired *t*-test on observed fires within each fire size class. *t*-statistics were compared to a distribution of *t*-statistics calculated from 500 neutral model iterations. *P*-values represent the proportion of times that neutral model *t*-statistics were greater than observed. Gold stars represent significant topographic control, and red indicate non-significance. The gray dashed line represents where boundary and interior topographies are equal, and blue dashed lines represent the T_{crit} value signifying significance for a traditional *t*-test for reference. Numbers below the box plots represent the sample size.

Klamath, and Sierra Nevada Foothills). North–south aspect breaks were more influential to the extinguishment of small- to medium-sized fires. Topography exhibited the least control on large fires across all ecoregions and for all topographic features (Fig. 5; Appendix S1: Figs. S4–S8).

Consistent with what we expected, ridgetops exhibited little control on fire extinguishment (Appendix S1: Fig. S6). Ridgetop environments are those where the compression of wind flow is often the greatest, regardless of initial velocities. Removing the influence of roads on the ridgetop assessment did not influence this result. However, when ridges and valleys were combined, evidence for topographic control increased for most ecoregions, largely influenced by inclusion of valley bottom environments (Appendix S1: Fig. S7).

Roads had the most consistent association with fire boundaries across all ecoregions and for most fire size classes (Appendix S1: Fig. S8). Control on fire extinguishment by roads was generally strongest for 10^2–10^4 ha fire sizes. Removing roaded pixels from the topographic features generally led to slightly higher significance for valley bottoms (Appendix S1: Fig. S5) and slightly lower significance for north–south aspect breaks (Appendix S1: Fig. S3); however, trends were similar between the analyses with and without roaded pixels.

The level of overlap among roads and topographic features varied across ecoregion. Roads intersected with aspect breaks disproportionately in coastal and coastal range ecoregions and in other densely populated regions such as the Great Valley (Appendix S1: Fig. S9). In general, roads did not intersect with valleys and ridgetops, but where there was disproportionate intersection, it was more pronounced on mid-slopes (e.g., lower valley bottom and ridgetop scores; Appendix S1: Fig. S9); that is, most roads were not located in valley bottom or ridgetop patches.

Discussion

Several studies have either identified or alluded to a role for topography in shaping fire patterns across the western United States, for both historical (Taylor and Skinner 1998, Beaty and Taylor 2001, Heyerdahl et al. 2001, Iniguez et al. 2008, Kellogg et al. 2008, Flatley et al. 2011, Krawchuk et al. 2016) and contemporary wildfires (Rollins et al. 2002, Narayanaraj and Wimberly 2011, Parks et al. 2012, Holsinger et al. 2016). Our contribution to this literature was as follows: (1) to analyze a large number of fires (>10,000 perimeters), across a relatively long time period (1950–2012), including mixed land ownerships, over broad environmental gradients, (2) to take a multi-scaled approach to contrasting topographic controls across fire sizes, and (3) to compare the influence of several different topographic features on fire growth and extinguishment.

We found direct empirical support for topographic controls on wildfire extinguishment across California, and the strength of control varied by ecoregion, topographic feature, and fire size. Topography exerted the greatest control in mountainous regions, and as expected, controls were strongest for small- to medium-sized fires, and weakest for large events.

Wildfire systems are complex and adaptive, composed of many interacting components, that when combined, promote non-linear responses to inputs, feedback between the system and the environment, establishment of lagged system memories, where past disturbances influence future behavior, and emergent behavior. Such systems are intrinsically difficult to study given these properties, and past efforts have relied on comparisons of natural systems with computer simulations (Malamud et al. 1998, 2005, Moritz et al. 2005). Within the SOC literature, cellular automata models with simple guiding principles were found to produce fire size distributions similar to those of natural fire regimes, and from these, authors ascribed mechanistic properties to natural systems. Specifically, authors compared slope parameters from power-law distributions observed across a wide range of simulations and global fire regimes to conclude a universal mechanism (i.e., SOC) for scale-invariant patterns. Such patterns resulted only from factors endogenous to the system (i.e., spatial patterns of fuel and ignitions) and required no fine-tuning of parameters. Under SOC, processes that governed model behavior at fine scales also operated at large scales, thus leading to scale-invariant power-law behavior. The simplicity of the SOC model has carried over into other natural and social systems (Turcotte 1989, 1999, Bak 2013).

Previous studies have called into question the claim of scale invariance across fire size

distributions (Ricotta et al. 2001, Boer et al. 2008, Moritz et al. 2011, O'Donnell et al. 2014), suggesting process domains may exist where dominant controls vary by event size. We first sought to identify common scaling regions among wildfire event and topographic PSDs to provide indirect evidence of a role for topography as a bottom-up driver of fire regimes across the state. The surprising similarity in the distributions across several orders of magnitude suggested that topography may be a main contributing factor to observed scaling behavior in wildfire distributions (Moritz et al. 2011). Accordingly, topographic PSDs themselves exhibited power-law behavior across many orders of magnitude. Boer et al. (2008) found similar scaling behavior between fire event sizes and the magnitude of weather events during burn periods in Australian forests. The authors suggested that a variety of factors acted upon fire spread and that their relative effects and interactions varied across scales. They concluded that exogenous forcings may be most influential for larger fires where scale invariance is expressed, which represented the majority of area burned. Our analyses focused on topographic effects, yet we found results similar to Boer et al. (2008), but for a bottom-up rather than top-down forcing factor. While bottom-up factors in wildfire systems are generally thought to contribute to local-scale heterogeneity in fire patterns, our findings suggest they may play a more prominent role, even at larger spatial scales (Figs. 3, 4). These findings suggest that interactions among terrestrial and meteorological systems may jointly influence wildfire spread across a middle-numbers scaling region. Both studies indicate that fuel patterns alone cannot describe observed scale invariance in fire size distributions, as previously suggested (Malamud et al. 1998, Ricotta et al. 2001, Moritz et al. 2005). Alternative mechanisms that incorporate bottom-up and top-down factors should be further investigated (McKenzie and Kennedy 2012).

We next looked for statistical evidence for bottom-up controls on fire spread and extinguishment to directly test the proposition of scale-dependent topographic controls, similar to previous studies (Narayanaraj and Wimberly 2011, Holsinger et al. 2016). We found that where control was exerted, the strength of control was dependent upon fire size, with greatest controls on small to medium fire sizes (Fig. 5; Appendix S1: Figs. S3–S8). The lack of control for the largest fires matched the prevailing understanding of wildfire systems. Large fires are generally driven exogenously by extreme weather events, endogenously by large-scale fuel continuity (i.e., contagion), or by both (Keane et al. 2002, Westerling et al. 2006, Flatley et al. 2011, Stephens et al. 2014, Jolly et al. 2015). Regardless of the mechanism, large fires are examples of a breakdown in pattern–process linkages, where the dominance of spatial controls shifts to a smaller number of driving factors. Features, such as topography, fuel reduction treatments, and past fires, appear to be less effective at controlling large fires burning under extreme fire weather conditions (Parisien et al. 2011, Stephens et al. 2014). Small fires generally occur under moderate-fire weather conditions, where fire spread is inhibited and/or initial attack is successful. Topography was shown to exert control on these fires in some circumstances, but not others. Spatial controls can be somewhat random and dependent upon the proximity of ignitions to various impediments to fire spread. However, interactions among other landscape components are generally not exhibited for small fires. Medium-sized fires (10^2–10^4 ha) are generally associated with scaling behavior in California ecosystems (Moritz et al. 2011). These fires generally burn for several days and experience a range of biophysical conditions, given their size. At this scale, interactions among weather, the biophysical environment, past disturbances (fuel succession), and their interactions contribute to fire patterns. Our results suggest a role for topography in mediating fine- and mesoscale wildfires. In some ecoregions, including the Sierra Nevada, Sierra Nevada Foothills, Klamath, Central Coast, and Coast Ranges sections, topographic control was strongest for these fires, depending on the topographic feature.

The strength of topographic constraints on fire spread may be dependent on top-down factors too, such as climatic gradients, which can influence tree growth and wood decomposition, availability of fuels to promote fire growth, and longevity of previous burns to inhibit fire spread (Parisien and Moritz 2009); that is, exogenous top-down forcing likely mediates the overall contribution of bottom-up factors on shaping fire patterns. By partitioning the State of California into ecoregions, we directly compared the effect

of top-down climatic factors on the relative influences of bottom-up factors. In ignition-limited ecoregions dominated by large-scale high-severity events, topographic controls may be limited, as these events are generally weather and fuel driven under extreme conditions. However, our results were somewhat equivocal regarding the relationship between topographic controls and climatic gradients, because topography appeared to be most effective in topographically complex ecoregions. Topography had the least influence on arid ecoregions, including Northwest Basin Range, Mojave, and Mono Sections. These environments represent fuel-limited systems at the extreme end of the climatic range where recurring wildfires are possible (Parisien and Moritz 2009) and where fire patterns are more likely related to the distribution of fuels. However, the patterns of topographic control were not as clear for ecoregions with higher annual precipitation. Precipitation was generally highest in mountainous ecoregions, somewhat confounding the underlying process driving the level of topographic control. Of the ecoregions that experienced >1000 mm of annual precipitation (Table 1), the Klamath and Sierra Nevada regions exhibited the strongest topographic controls, the Southern Cascades exhibited relatively weak control, and the North Coast and Northern Interior Coast Range exhibited moderate control.

Similar ecoregional results were found for dominant topographic controls on historical wildfire regimes in the Klamath (Taylor and Skinner 1998) and Sierra Nevada regions (Beaty and Taylor 2001). More recent studies have found topography as a key driver of burn severity patterns in California (Kane et al. 2015, Estes et al. 2017, Parks et al. 2018*a*). Parks et al. (2018*a*) used boosted regression tree analysis to relate fuels and biophysical variables to fire severity in ecoregions across the western US. The authors found that the importance of topographic predictor variables was relatively low overall compared to fuels, climate, and fire weather variables, but topography was found most influential for the Klamath, Central Coast, North Coast, and Sierra Nevada regions and lowest for the Southern Coast. While not directly comparable to our results, we found a similar ecoregional ordering of the strength of topographic control on fire extinguishment.

Dominant physiognomic type may also influence the strength of topographic controls across ecoregions. For instance, topography was not found influential in the Southern Coast ecoregion where chaparral shrubland is the dominant lifeform. Much has been written regarding the main controls on wildfire regimes in this region (Minnich 1983, Minnich and Chou 1997, Moritz et al. 2004, Goforth and Minnich 2007, Keeley and Zedler 2009), leading to much debate over the dominance of bottom-up (e.g., fine-scale patch mosaics) versus top-down (e.g., Santa Ana winds) controls on fire regimes. This ecoregion is characterized by low topographic complexity, a high density of roads, and a high incidence of wildfire (Table 1). Our modeling results suggest that roads (Appendix S1: Fig. S8), but not topography (Fig. 5; Appendix S1: Figs. S3–S7), were strong drivers of fire extinguishment. Likely, the dominance of roads as a controlling mechanism is related to firefighting activities given the high population densities, preponderance of residential communities, and subsequent firefighting response (Syphard et al. 2007). Regardless, topography does not appear to contribute additional significant bottom-up control in the chaparral-dominated Southern Coast ecoregion regardless of fire size or topographic feature.

The strength of topographic controls in our study also varied by topographic feature. A somewhat surprising finding of our analysis was the significantly stronger control observed at valley bottoms as compared to ridgetops. Fires generally spread more quickly uphill on steep slopes through the process of convective upslope heating (Sugihara 2006). Ridgetops can provide a natural break to fire advancement as the slope lessens, where topographic shoulders exist, and where they create aspect breaks upon which vegetation and fuels can change abruptly, and may contribute to heterogeneity in vegetation patterns through changes in soil properties. However, we found that ridgetops provided minimal control on fire spread across all ecoregions. This may due to the way in which ridgetops influence fires. Ridges do not always provide hard breaks for fire spread, rather fires cross over ridges and continue downhill under decelerating winds. In this sense, ridgetops may indirectly influence the effectiveness of nearby valley bottoms under certain wind and fuel conditions.

Valley bottoms exhibited strong spatial control on fire perimeters for most ecoregions. Valleys are generally associated with higher soil moistures, lower insolation, and higher terrain shading, which may lead to slower rates of spread. Fuel breaks provided by streams, lakes, and/or riparian areas may also halt fire spread and contribute to the strong influence observed by valley bottoms (Camp et al. 1997). In comparison, Narayanaraj and Wimberly (2011) analyzed fire extinguishment for six fires in central Washington State and found that fire boundaries were negatively associated with streams, which the authors suggested was a result of a positive association with ridgetops, though this inference was not tested.

Previous studies on historical reconstructions of fire regimes found that topography exhibited strong controls on mean return intervals in steeply dissected terrain (Taylor and Skinner 1998, McKenzie et al. 2006, Iniguez et al. 2008, Kellogg et al. 2008, Bigio et al. 2016). However, it is unclear whether these results hold for modern-era fires and across gradients of anthropogenic and ecological influence. Human interactions can diminish the role of the biophysical environment on ecological processes including wildfires (Forman and Godron 1986, Veblen et al. 2000, Syphard et al. 2007, 2017). For example, in the United States, 95–98% of annual wildfires fires undergo successful initial attack, which has drastic implications for vegetation patterns resulting from a lack of fire disturbance, and on subsequent fire size and behavior (Veblen et al. 2000, Keane et al. 2002, Hessburg and Agee 2003, Hessburg et al. 2005, Stephens et al. 2014). While these effects are widespread in California, the most populous state in the country, a high concentration of the wildland–urban interface across the coastal and interior regions provides additional pressures on agencies to remove fire from the landscape (Syphard et al. 2007).

In our study, human influences are included implicitly and explicitly in our analyses. By taking an ecoregional approach, we not only looked at variations in environmental gradients, but also across gradients of potential human influences. We also directly tested the influence of humans on fire extinguishment by including/excluding roads in our analysis, which were most consistently associated with fire boundaries across all ecoregions (Appendix S1: Fig. S8). This is comparable to the findings of Narayanaraj and Wimberly (2011), who found roads consistently had the largest influence on fire extinguishment compared to all other factors tested. In our study, roads exhibited the strongest control on small- and medium-sized fires, similar to topography, but evidence for control was also observed for the largest size class, though effect sizes were lowest for these fires. In terms of the large fire response, many large fires burn over the course of several weeks, yet the majority of the area burned occurs over the course of a few burn periods (Peterson et al. 2014). This suggests that the weather and fire behavior conditions at fire perimeters differ substantially from those occurring during large burn days, thereby allowing for successful direct attack. As previously stated, roads often serve as tie-in points for suppression activities, which could be the cause of the large fire response to roads in our analysis.

One potential implication of our results is that human-derived landscape features in California may diminish the role of topography and potentially other biophysical factors (Syphard et al. 2017) on regulating wildfire dynamics. Nonetheless, our results show that topography plays a dominant role in California. Roads are known to follow topographic features, such as valley and ridges, which might have influenced our results had we not controlled for them. However, removing roads from the landscape in our analyses did not significantly change the relative influence of topography. Narayanaraj and Wimberly (2011) found high variability in dominant factors associated with wildfire boundaries and that roads consistently had the largest influence, but other factors such as topography, heat load, vegetation type, and cover also contributed significant control. Other studies have looked at fires in Wilderness Areas, where human influences are minimized, and found that topography was a main determinant of fire spread and extinguishment, and that effects varied across regions (Rollins et al. 2002, Holsinger et al. 2016). We looked across a wide range of population densities in California and found that the influence of topography varied across gradients of topography and climate, but not human population (Table 1).

Our findings suggest a strong role for topography in shaping fire patterns across disparate ecoregions; however, we encountered some limitations that are noteworthy. The level of accuracy

in mapping wildfire perimeters is likely inconsistent across fires over space and time. We addressed this in our analysis in two ways: (1) we used a 100-m buffer on fire perimeters to include conditions surrounding, but not directly at the fire boundary, and (2) we eliminated fires from the database that occurred prior to 1950, a period of known, low-quality fire perimeter mapping. The 100-m fire perimeter buffers also allowed us to assume that fire extinguishment is not an instantaneous occurrence, but takes place over a length of space and period of time, reflecting that perimeters are actually gradients of conditions with fuzzy boundaries rather than hard edges. In this assessment, we looked only at the interactions among topographic facets with fire and ignored other potential biophysical drivers, fuels, and weather conditions. Our analyses required us to overlook much of the complexity incorporated in regional-level wildfire systems in order to directly explore a role for topography, and future work should incorporate other factors such as fuels, weather, climate, management, and past disturbances into a more comprehensive analysis (Holsinger et al. 2016). Finally, we summarized the effect of topography across fire boundary and interior areas, but we acknowledge that the relative influence of topography will vary along a fire perimeter, and evidence of control does not imply full control across the entire boundary.

Conclusion

With wildfires becoming larger, more severe, and more costly in recent years (Westerling et al. 2006, Miller et al. 2009), understanding the mechanisms that determine fire growth and extinguishment is crucial in terms of both developing a theoretical understanding of system-level dynamics, and practical guidance for identifying opportunities for forest restoration and suppression activities on the landscape. We found that topography was an effective barrier to spread in many ecoregions, primarily for small- to medium-sized fires. Topographic controls appear to be a reliable component of bottom-up wildfire regulation under certain climatic and weather conditions. Arid environments were least influenced by topography, but broad climatic gradients reflected in ecoregions appeared to have little additional influence on the role of topography. Rather, topographic controls were strongest in rugged terrain across precipitation and temperature gradients.

Our results draw into question the prevailing theory of SOC as applied to natural wildfire systems. Instead of being scale-invariant systems, we suggest that fire size distributions exhibit multiple scaling regions (Ricotta et al. 2001, Boer et al. 2008, Moritz et al. 2011, O'Donnell et al. 2014) due to the interactions between exogenous (e.g., climate, weather) and endogenous (e.g., ignitions, topography, fuels) factors occurring across several spatial scales. We identify quantitative evidence that one of these endogenous factors, topography, plays a central role in scaling behavior over several orders of magnitude. Lack of topographic control observed for large fires suggests that these events are likely driven by extreme weather and/or highly contagious fuels, which, when combined, can lead to a breakdown in pattern–process linkages and possibly represent a separate process domain. Furthermore, roads, an additional bottom-up control, were consistently associated with fire boundaries across ecosystems and their presence may somewhat diminish the role of other factors associated with the natural biophysical template on wildfire patterns. Given the broad environmental gradients and highly varied vegetation types examined in this study, our results are likely applicable to other fire-dependent systems.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2443/full