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Article

Spatial Characterization of Wildfire Orientation Patterns in California

Ana M.G. Barros [1,*], José M.C. Pereira [1], Max A. Moritz [2] and Scott L. Stephens [2]

[1] Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Tapada da Ajuda, 1349-017 Lisboa, Portugal; E-Mail: jmocpereira@gmail.com

[2] Department of Environmental Science Policy and Management, University of California - Berkeley, 130 Mulford Hall, Berkeley, CA 94720-3114, USA;
E-Mails: mmoritz@berkeley.edu (M.A.M.); sstephens@berkeley.edu (S.L.S.)

* Author to whom correspondence should be addressed; E-Mail: barros.anamg@gmail.com;
Tel.: +00-0213-653387; Fax: +00-0213-653338.

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Abstract: Using 100 years of fire perimeter maps, we investigate the existence of geographical patterns in fire orientation across California. We computed fire perimeter orientation, at the watershed level, using principal component analysis. Circular statistics were used to test for the existence of preferential fire perimeter orientations. Where perimeters displayed preferential orientation, we searched for evidence of orographic channeling by comparing mean fire orientation with watershed orientation. Results show that in California, 49% of the burnt area is associated with watersheds, where fires displayed preferential orientation. From these, 25% of the burnt area is aligned along the NE/SW orientation and 18% in the E/W orientation. In 27 out of 86 watersheds with preferential fire alignment, there is also correspondence between mean fire orientation and watershed orientation. Topographic influence on fire spread and dominant wind patterns during the fire season can account for the consistency in fire perimeter orientation in these regions. Our findings highlight the historical pattern of fire perimeter orientation and identify watersheds with potential orographic channeling.

Keywords: wildfire perimeter orientation; orographic channeling; California; circular statistics; watershed

1. Introduction

Wildfires are a common occurrence across many ecosystems of the world [1–4]. Recurrent destruction of property, loss of lives and threats to conservation make headlines and create a passionate debate that challenges fire ecologists, scientists, managers and society to develop ways to coexist with fire-prone environments [5–9]. This is particularly true in the wildland urban interface (WUI), where large and devastating fires have deep impacts on people, emphasizing the need for effective wildfire risk management [5,10]. Such is the case in California, as in many other Mediterranean-climate regions, where highly fire-prone ecosystems coupled with the expansion of the WUI lead to major fires with large-scale losses [5–7].

Fire regimes in California vary by ecosystem, reflecting wide differences in population density, topography, vegetation and climate across the state [11]. In northern California, forests are dominated by mixed conifers and mixed evergreen hardwoods, while southern California coastal areas are dominated by chaparral and coastal sage scrub shrublands [12]. Chaparral also occurs in the foothills of the mountain ranges in the northern part of the state. Current fire regimes range from frequent low-severity fires in chaparral to mixed severity fires in many forests [12]. In California, humans have been present in the landscape for millennia, and their interaction with fire takes many forms, which have also changed in the course of time [12]. Human presence is linked with more ignitions, whether related with prehistoric inhabitants or associated with a growing WUI [13–15]. On the other hand, in many forests, fire suppression has been successful enough to generate high levels of fuel accumulation, thus increasing the likelihood of severe fires [16].

Across much of California, the Mediterranean climate, with hot and dry summers alternating with cool and moist winters, causes relatively slow decomposition of woody vegetation that results in fuel accumulation. In fact, given an ignition source and conducive weather, vast proportions of the state can propagate fire during the majority of the dry season [17]. Weather affects fire outcomes by altering fuel characteristics and the efficiency of heat transfer in combustion [18]. Wind speed directly affects spread rate and intensity by advection, and relative humidity affects moisture levels in dead fuel by hygroscopic diffusion and in live fuels by evapotranspiration [19]. At fine scales, the presence of topography (*i.e.*, slope steepness) has a similar, but less pronounced, effect than wind. On steep slopes, flames are brought closer to fuels, thus increasing the proportion of heat reaching the unburned fuel and facilitating combustion [19]. At coarser scales, complex terrain interacts with meteorological variables and generates effects, such as aerodynamic wakes, density-driven slope flows, channeling effects of upper level winds and flow acceleration over the crest of mountain ridges [20]. These flows, usually associated with mountainous terrain, can be conducive of extreme fire behavior [20].

Fuel treatments, with the objective of reducing forest fuel loads and, therefore, providing a defensible area for fire suppression activities, are used across large areas of California to manage fire risk [21–25]. Fuel treatment effectiveness strongly depends on their spatial layout, the level of suppression effort and weather conditions during the fire event, with effectiveness being reduced under severe fire weather [26,27]. Under moderate fire intensities and coupled with appropriate fire suppression, fuel managed areas can ameliorate fire behavior, reduce spotting, reduce fire severity and increase chances of fire control [28,29]. It has been shown that treatments should intersect the heading fire direction in order to maximize their effect in reducing fire spread rates and intensity [30–33]. Simulations have shown that as the head fire intersects treatments, deployed in an overlapping pattern, it is forced to flank, which contributes to a reduction of fire behavior [30,32,33]. Therefore, consideration of the most likely direction of fire spread will be critical when planning fuel treatments across a landscape.

Traditionally, fire statistics have focused mostly on the number of fires, total area burnt and ignition location, giving less consideration to fire shape. Nevertheless, a few studies have addressed the issue of geographical fire orientation. Barros *et al.* [34] analyzed fire perimeter orientation at the watershed level in Portugal using a fire atlas of 31-years. The authors showed that 84% of overall burnt area in the study period was associated with watersheds, where fires display preferential orientation. Haydon *et al.* [35] found a fairly good correspondence between wind direction and compass orientation of 196 fire perimeters that originated from 224 grassland fires over a period of 19 years in the Great Victoria Desert, Australia. Bergeron *et al.* [36] found that most of the distance covered by fires in the northwestern Canadian black spruce forest occurred in the northwest-southeast direction, and Parisien *et al.* [37] concluded that general trends in fire orientation within Canadian ecozones can be attributed to prevailing winds associated with dominant weather patterns.

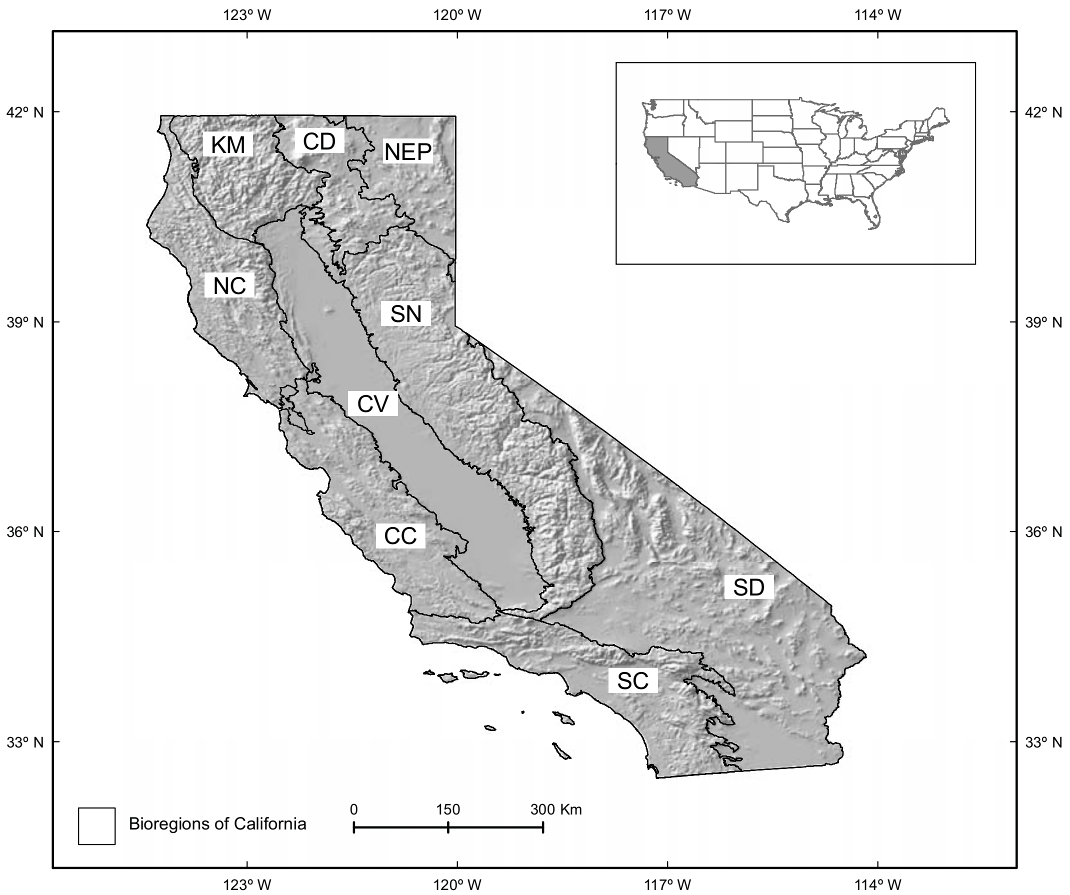
Characterizing landscape patterns of fire perimeter orientation may provide insights on the regional dominance of top-down (synoptic weather types, alternating drought periods), or bottom-up (topography, fuel type, load, connectivity, local meteorology) control of fires. Landscape level fuel management practices may be improved using historical data on fire orientation. Watersheds, where fires display alignment with topographic variables, may be indicative of topographic channeling, with the potential for eruptive fire behavior [38]. The objective of this study is to determine the existence of preferential fire orientation patterns at the watershed level in California, using a database of approximately 100 years of wildfire data. Specifically, we examined (i) whether fires display preferential alignment following a particular axis or if they are randomly oriented and (ii) whether there is a correspondence between the watershed and fire orientation, which may suggest evidence of orographic channeling.

2. Methods

2.1. Study Area

The study area corresponds to mainland California, comprising an area of roughly 423,696 km^2 along the western coast of North America (Figure 1). Bailey [39] developed a hierarchical ecosystem classification of California bioregions based on climate, continental position, elevation, vegetation characteristics and landforms. Sugihara *et al.* [2] combined the 19 sections of Bailey's ecoregion classification, as defined by Miles and Goudey [40], into nine bioregions based on generally consistent patterns of vegetation and fire regimes (Figure 1).

Figure 1. Shaded relief map of the California bioregions as defined by Sugihara *et al.* [2]. Delineation of the bioregions is based on common patterns of vegetation, topography, landforms and the ecological role of fire. North Coast (NC), Central Coast (CC), South Coast (SC), Klamath Mountains (KM), Southern Cascades (CD), Northeastern Plateau (NEP), Sierra Nevada (SN), Central Valley (CV) and Southeastern Deserts (SD).



California's coast comprises three bioregions: the North Coast (NC), Central Coast (CC) and South Coast (SC). The NC and CC are topographically diverse, ranging from flat terrain at sea level to steep mountains in the Coast Ranges, which consist of rugged, northwest-southeast oriented ranges. Vegetation varies between coastal scrub, chaparral, redwood forest, mixed conifer and mixed evergreen forest [41].

The South Coast (SC) bioregion is characterized by the Transverse Ranges, one of the few oriented east-west ranges in California, and a north-south oriented series of fault blocks, known as Peninsular Ranges. Both the Transverse and the Peninsular ranges define broad valleys, dissected by riparian corridors that influence the pattern and extent of fire spread [42]. The region supports low elevation vegetation that includes interior grassland, southern coastal scrub, chaparral, foothill woodland, mixed evergreen forest, and mixed conifer forest [42]. The SC bioregion comprises 8% of the state land area, but contains roughly 56% of the total human population. Being the bioregion with the highest population density, it also presents an extensive WUI, and the majority of contemporary burning is human-ignited [14].

East of the NC bioregion lies the Klamath Mountains (KM) bioregion, characterized by mountain ranges with steep and complex topography, intersected by several large river valleys, supporting a complex mosaic of vegetation types [43]. East of the KM bioregion is the Southern Cascades Range (CD) bioregion, a chain of volcanoes and volcanic flows with overall topography gentler than the Klamath Mountains and Sierra Nevada [44]. The northeastern corner of the study area forms the Northeastern Plateau (NEP) bioregion. Major vegetation types include juniper woodland, mixed Ponderosa pine and montane fir forest, among others [45].

The Sierra Nevada (SN) bioregion comprises a massive granitic block with a north-south trending orientation and an eastern escarpment that culminates in higher peaks [19]. The western slope of SN is relatively moderate and incised from north to south, with a series of almost parallel river canyons. The foothills are gentle broad valleys, while at mid-elevations, rivers cut deeper into canyons and ridges that run primarily east-northeast to west-southwest. At higher elevations, rugged mountain terrain dominates the landscape [19]. The lower montane zone consists of mixed conifers that transition to upper montane fir forest and montane chaparral at higher elevations. Ridge tops and the highest mountains support subalpine forest and shrublands [19].

The Central Valley (CV) bioregion is a wide, nearly flat and low elevation alluvial floor of sediments. Most of the valley floor and foothills have been converted to agriculture or urbanized, but they were previously dominated by a mixture of riparian forests and foothill woodlands, among other vegetation types [46].

The Southeastern Deserts (SD) are characterized by isolated mountain ranges with steep slopes surrounded by broad basins. The bioregion is arid, due to the rain shadows of the Sierra Nevada, Transverse and Peninsular ranges. Some years, high rainfall produces fine fuels, often from invasive species, that promote fire spread where fuels are otherwise sparse [47].

Most of California falls into a Mediterranean type climate, alternating wet winters with dry summers [48]. As the marine influence decreases, regions east of the Cascades, Peninsular Range, Sierra Nevada and deserts experience dry climates [39]. Fire season runs from from mid-May through October in northern California and from late March through November in southern California [20]. During the dry season, synoptic weather conditions are dominated by dry air masses; therefore, most of the state experiences fire weather conditions virtually every day of the season, until the onset of the first winter rains, normally by October-November in northern California and November-December in southern California. Along the coast, the dominance of the marine layer can ameliorate average fire weather conditions, lessening fire danger in these regions until extreme fire weather events occur [17].

2.2. Fire and Watershed Data

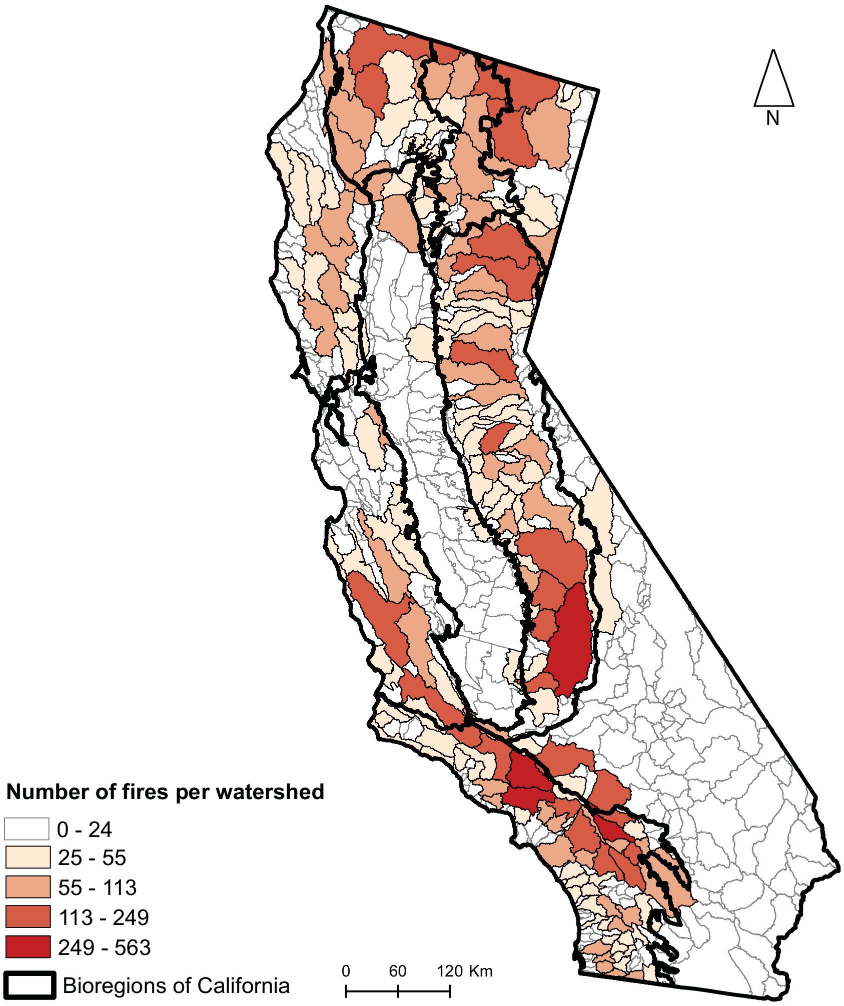
The CalFire fire database includes fire perimeters from public and private lands throughout California [49]. This results from the compilation of fire data from several federal, state and local agencies and begins in 1878, representing the most complete digital record of fire perimeters in California. Nevertheless, the CalFire database is incomplete, since fire records as far back as 1910 typically only occur for US Forest Service lands, and contributions from other land ownerships have shorter records [49]. Also, the quality and accuracy of mapped perimeters in the database degrades in the early part of the record. Our analysis included all fire perimeters larger than 5 ha dated between 1910 and 2010. From these, we excluded 739 perimeters (2.5% of overall burnt area) associated with prescribed burning and perimeters entered as simple circles. This was done to eliminate fire records where the size and location of reported fires were available, but the fire perimeter was represented by an artificial shape.

We analyzed fire perimeter orientation at the watershed level using the sub-unit level of the California Interagency Watershed Map of 1999 (CalWater 2.2.1) [50]. Each fire perimeter was allocated to the watershed containing its centroid, with the same criterion applying to cases where a fire perimeter spans multiple watersheds. This analysis included only watersheds with 25 or more fires [51], resulting in a total of 171 usable watersheds from the original 582 watersheds at the sub-unit level of the CalWater map (Figure 2). Watershed sizes range from 847 km^2 to 4,775 km^2, with an average watershed size of 1,012 km^2. The sub-unit level corresponds to the best compromise between an appropriate spatial scale for management purposes (while maintaining a minimum of 25 observations) and analyzing the majority of fire perimeters (90%) and burnt area (80%) in the 1910–2010 CalFire database. The majority of watersheds in Central Valley and Southeastern Deserts were excluded, due to the lack of sufficient fire observations (Figure 2). In the Central Valley, the long history of occupation and intensive agricultural use have led to a landscape devoid of natural vegetation, where, due to fuel types and their fragmented spatial arrangement, few fires extend beyond 4 ha [46]. In the Southeastern Deserts, the arid climate with high interannual variation in rainfall limits fuel load and continuity, which accounts for the low fire frequency in this bioregion [47].

2.3. Circular Statistics Analysis

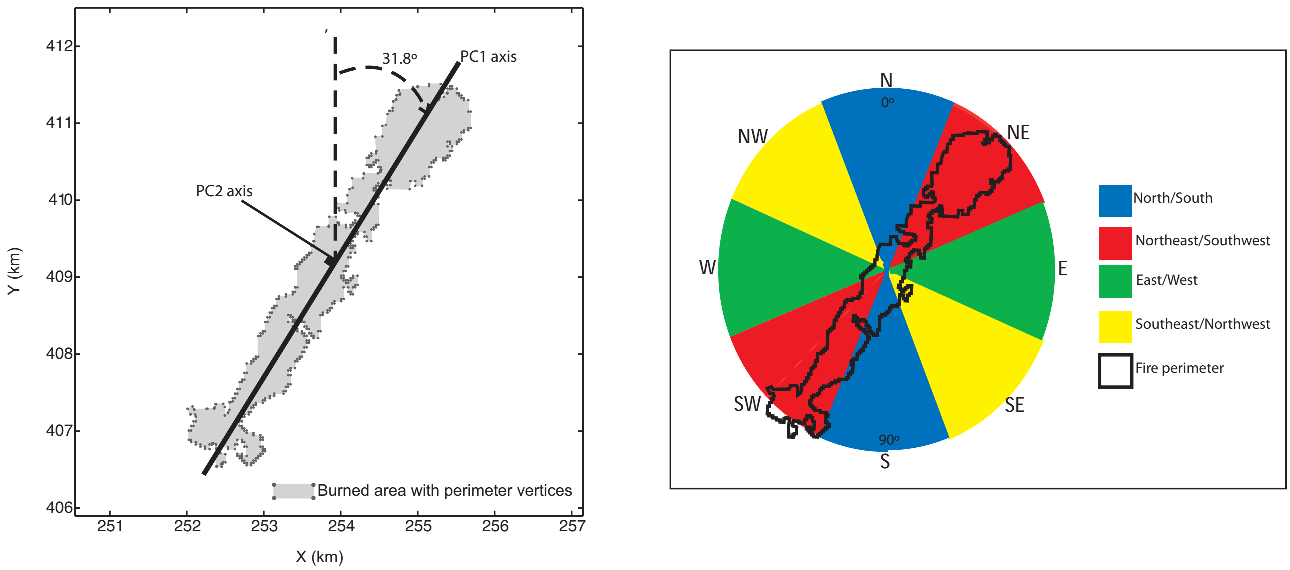
A distinction should be made between the orientation and direction of an object: direction assumes the definition of a starting point (e.g., flying directions of bees leaving the hive), while orientation makes no such distinction (e.g., seismic faults on a landscape). Therefore, directions correspond to vectorial data, ranging from 0–360°, while orientations correspond to axial data, ranging from 0–180°. Here, we computed the orientation of each fire and watershed perimeter, considering 0° as true north and rotation as clockwise. Fire perimeter and watershed orientations are classified into one of four categories, ranging from 0–180° and each category spanning 45°, namely N/S, NE/SW, E/W and SE/NW (Figure 3).

Figure 2. Partition of California into hydrologic sub-units (watersheds) according to the CalWater map and number of fires per unit. Each fire was associated with the watershed containing its centroid. Watersheds with less than 25 observations were not included in this analysis (represented in white).



In this study, both fire and watershed perimeters are considered as objects. We computed the orientation of each object using principal component analysis applied to the coordinates of its vertices (Figure 3) [34,52]. The first principal component of a bi-dimensional object corresponds to an axis that passes through the object center of mass and maximizes the variance in the object's shape [52]. Elongated objects will have higher variance, explained by the first principal component and, therefore, a higher degree of confidence in the orientation that is calculated. The example in Figure 3 corresponds to a fire with a first principal component axis oriented along 31.8° (NE/SW), which has a percent of variance explained of 91%. To assess the average elongation of fire perimeters, we computed and mapped the mean variance explained by the first principal component for all fires in each watershed. Watersheds with high mean variance explained exhibit fire perimeters that are (on average) more elongated and, therefore, have a well defined orientation.

Figure 3. On the the left, fire perimeter vertices are represented by its X and Y coordinates, in a bi-dimensional space. The first principal component axis (PC1 axis) corresponds to the axis that maximizes the variance among the projection of all points that constitute the object boundary and also reflects the object's orientation. On the right, classification of axial data is in the compass orientation. Fires and watersheds have orientations, rather then directions; therefore, their orientation values range from 0–180°. Compass classification is a function of the orientation value, θ_{or}, as follows: N/S $\Leftrightarrow$ $\theta_{or} \in [0; 22.5] \wedge \theta_{or} \in]157.5; 180]$; NE/SW $\Leftrightarrow$ $\theta_{or} \in]22.5; 67.5]$; E/W $\Leftrightarrow$ $\theta_{or} \in]67.5; 112.5]$; SE/NW $\Leftrightarrow$ $\theta_{or} \in]112.5; 157.5]$



Next, we determined whether the fire perimeter orientations in each watershed are isotropic or display a preferential orientation. This is done following a sequence of hypothesis tests that determine if the fire population in each watershed follows one of three statistical distributions: circular uniform, von Mises or unimodal. The uniform distribution corresponds to an assumption of randomness among orientations, *i.e.*, for a particular watershed, all fire perimeter orientations are equally probable [51]. It is worth mentioning that a watershed may have high mean variance explained and random distribution of fire orientation, which would suggest that while having elongated fire perimeters, such perimeters occur with similar frequency along all possible orientations. The von Mises and unimodal distributions are characterized by the presence of a preferential orientation. The von Mises, which is analogous to the Normal distribution for linear data, is centered on the mean direction, while in the unimodal case there is a single modal direction [51]. In either case, one can establish the presence of a preferential orientation (mean orientation) and calculate metrics of dispersion around this central tendency—circular variance and confidence interval for the mean. For each watershed, we tested the goodness of fit of fire perimeter orientations for circular uniform, von Mises and unimodal distributions, using a Kuiper's, Watson's and Rayleigh's test, respectively. Both null and alternative hypothesis are presented in Table 1, and mathematical demonstrations can be found in Fisher [51] and Mardia and Jupp [53]. All distribution tests and confidence interval calculations were performed with Oriana [54] at the 5% significance level.

Table 1. Hypothesis for goodness of fit tests based on circular distributions. All tests were performed at the 5% significance level.

Test	Hypothesis	Circular distributions
Kuiper	H0	Uniform
	H1	Not uniform
Watson	H0	von Mises
	H1	Not von Mises
Rayleigh	H0	Uniform
	H1	Unimodal

For all watersheds, we mapped the mean fire elongation and compass classification of watershed orientation. A simple linear regression model was tested at the 5% significance level, with watershed elongation as the explanatory variable and mean fire elongation as the dependent variable. For each watershed in which a preferential fire orientation was determined, we mapped its mean fire orientation as a color-coded compass classification (N/S, NE/SW, E/W and SE/NW). Mean fire orientation in each watershed was also compared with the orientation of the watershed itself, to search for evidence of orographic conditioning on fire spread. This was done by mapping watersheds where (1) watershed orientation is contained within the mean fire orientation 95% confidence interval and (2) mean fire orientation and watershed orientation are aligned in the same compass class. The latter provides a less formal assessment of orographic alignment between fires and watershed, although independent from the number of fire observations in each watershed.

The determination of a preferential *vs.* random orientation of fires is based on the frequency distribution of fire perimeter orientations around the circle, so it is based on the number of fires in each angular class, disregarding fire size. Given the highly skewed nature of fire size distributions [55], it is possible to find watersheds where a significant number of fire orientations are aligned along some preferential axis, but where those perimeters account for a small proportion of overall burnt area in the watershed. To provide an estimate of the burnt area from fires aligned with mean fire orientation, we mapped for each watershed the proportion of burnt area from perimeters aligned with the mean fire orientation $\pm 15°$.

Our analysis uses fire perimeter shapes, and therefore, the quality of its results depends on the quality of fire perimeter mapping, which varies greatly according to the source, region, year and, in some cases, with each fire event. However, given that orientation obtained by PCA is less sensitive to boundary details, including inaccuracies, than alternative methods for orientation analysis [52], we believe that these limitations will not affect our results. Additionally, results can be sensitive to the spatial partitioning of the study area. We used watersheds as analysis units, because they provide a topographical context to interpret the results. This is particularly true considering potential interactions between meteorology and complex terrain, which may be clear at a regional scale, but missed at larger scales [20]. Nevertheless, watershed systems are by nature hierarchical, and different levels of spatial partitioning can generate different outcomes. This stems from the well-known modifiable areal unit problem: any geographical study area can be divided into multiple non-overlapping areal units for the purpose of spatial analysis [56,57]. Analysis of fire preferential orientation using other distinct analysis units (e.g., higher or lower level watersheds, bioregions or administrative units, such as counties) could thus generate distinct patterns of fire perimeter orientation different from those presented in this study.

3. Results

Mean variance explained by the first principal component of fire perimeter coordinates ranges between 68% and 81% (Figure 4). The linear regression model between fire elongation and watershed elongation was not significant. Watersheds where fires are less elongated (variance within 68%–72%) are clustered on the southern end of the Sierra Nevada and along the North and Central Coast. Watersheds where fires are more elongated (percent of variance explained greater than 74%) are mostly located in the northern Sierra Nevada, Northeastern Plateau and also in the South Coast transition to the Southeastern Deserts bioregion.

The map of watershed orientation for California shows that watersheds occur in all compass classes (Figure 5a). Along the North and Central Coast, watersheds are mostly aligned N/S and SE/NW, while in the South Coast, E/W watersheds are more common. A few watersheds, aligned NE/SW, occur mostly in the Sierra Nevada, Klamath and South Coast (Figure 5a).

In total, 86 out of 171 watersheds display a non-random orientation, corresponding to watersheds that account for 49% of the overall burnt area and 53% of all fire perimeters used in this analysis (Figure 5b). From these, approximately 25% and 18% of the overall burnt area is associated with watersheds where mean fire orientation is oriented NE/SW (40 watersheds, represented in red) and E/W (30 watersheds represented in green), respectively. Watersheds where fires are predominantly aligned NE/SW and E/W include 44% of all fire perimeters and are predominantly located in the northern Sierra Nevada, Northern Plateau, Cascades and South Coast (Figure 5b). Mean fire orientation N/S (blue) and SE/NW (yellow) is less common and occurs in only six and ten watersheds, respectively. These watersheds are scattered throughout the study area (Figure 5b). Together, watersheds where fires display mean fire orientation aligned N/S and SE/NW account for only 6% of the overall burnt area and 11% of fire perimeter observations. In 85 out of 171 watersheds, fire perimeter orientation is random, accounting for 51% of the overall burnt area and 47% of the fire observations. These are located mostly along the North and Central Coast and interspersed with watersheds where fires display preferential orientation along the South Coast, Sierra Nevada and Cascades (Figure 5b). Variance around mean fire orientation ranges from 0.16 to 0.49 without any apparent spatial pattern within the study area (Figure 6).

Figure 4. Mean fire elongation in each watershed. This metric is computed as the mean variance explained by the first principal component of all fires in the watershed.

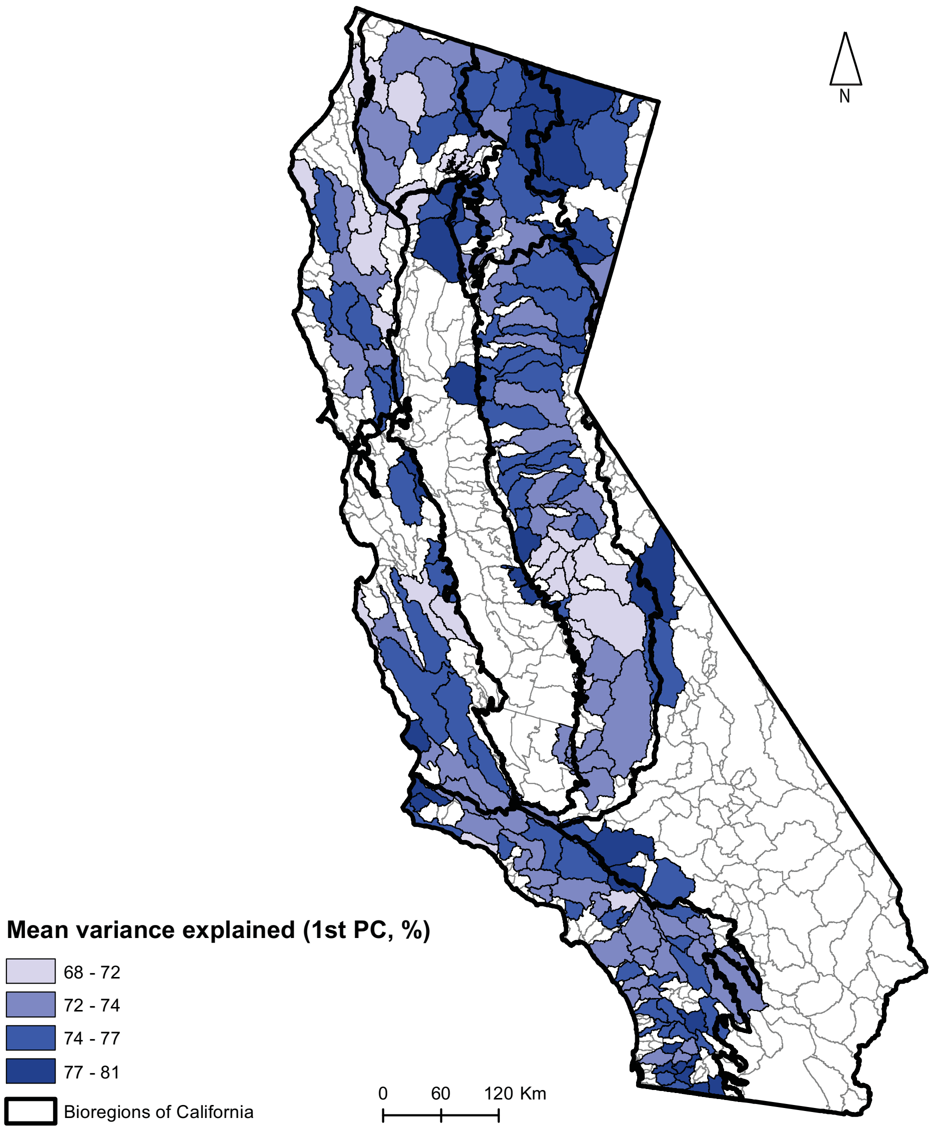


Figure 5. The left map (**a**) represents watershed orientation using the sub-unit level of the CalWater watershed map. The center map (**b**) presents results of fire perimeter orientation analysis for each watershed. Watersheds with preferential fire orientation are color-coded according to the compass classification of mean fire orientation, and watersheds where fire orientations are random are shown in gray. The right map (**c**) presents watersheds with evidence of orographic channeling of fires. Watersheds represented in black-striped pattern have their orientation contained within the 95% confidence interval of mean fire orientation. Alternatively, watersheds that share the same compass orientation as fires are color-coded accordingly. Watersheds that are both color-coded and black-striped depict evidence of orographic channeling of fires according to both criteria. Watersheds mapped as dark gray show no alignment between mean fire and watershed orientation.

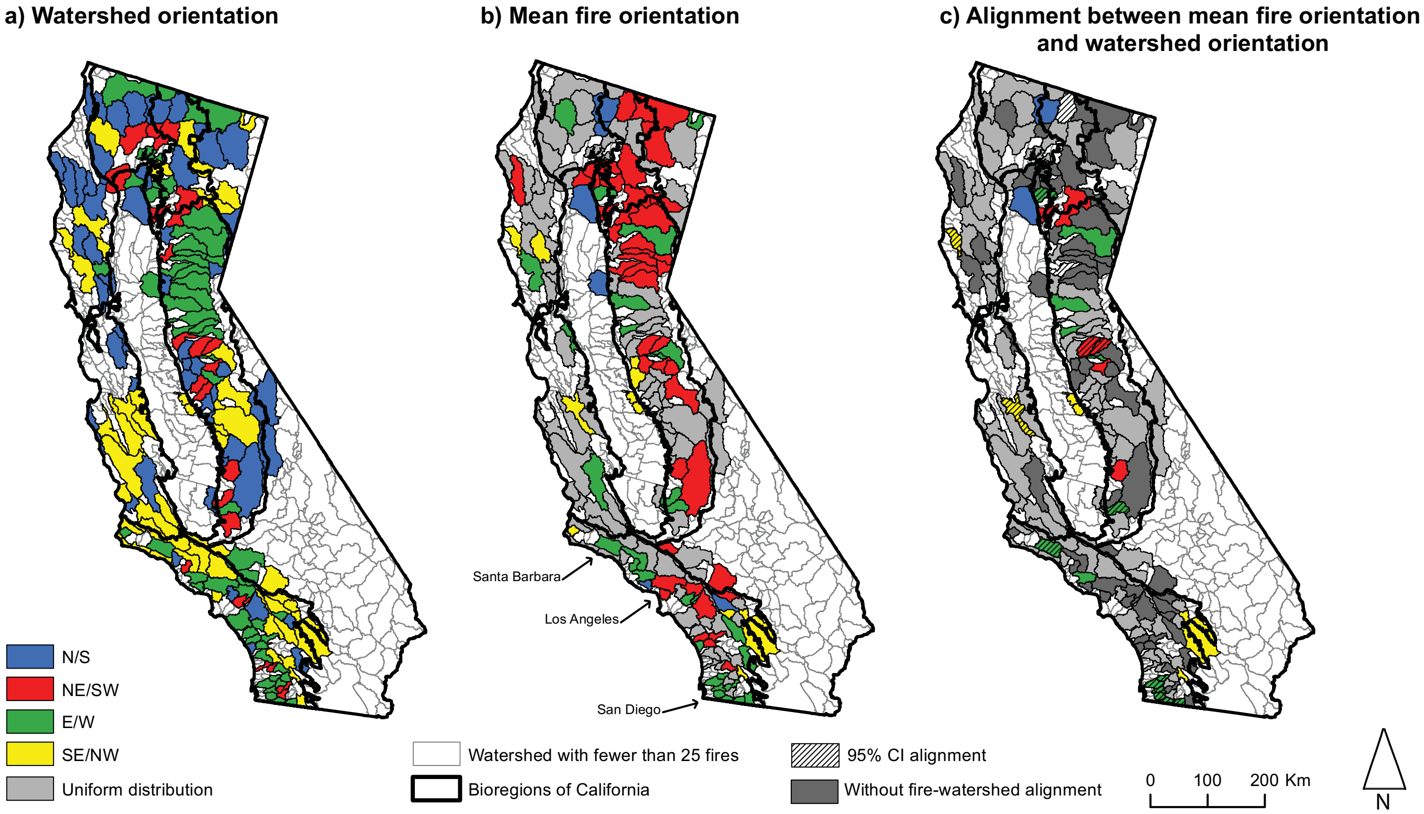
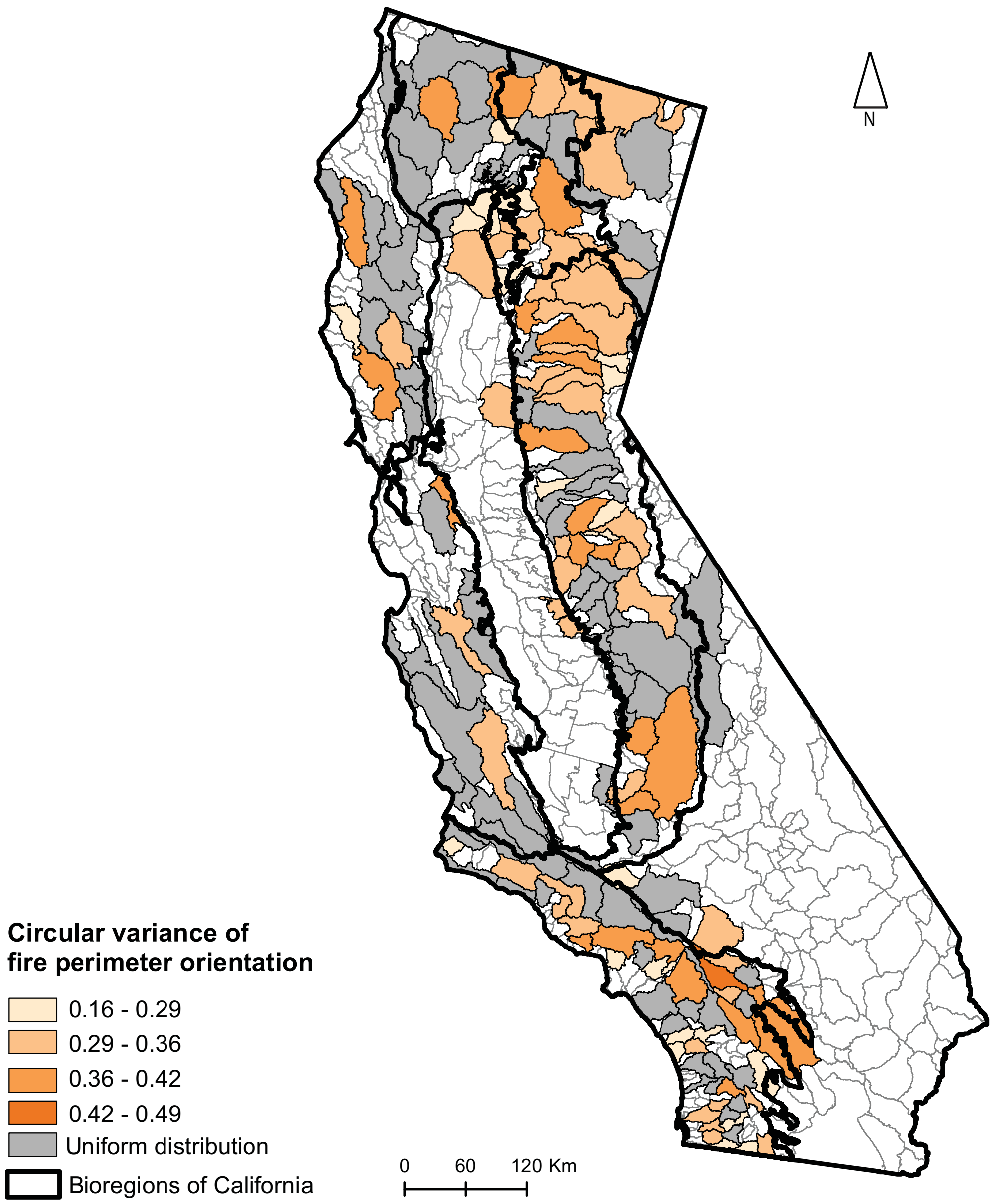


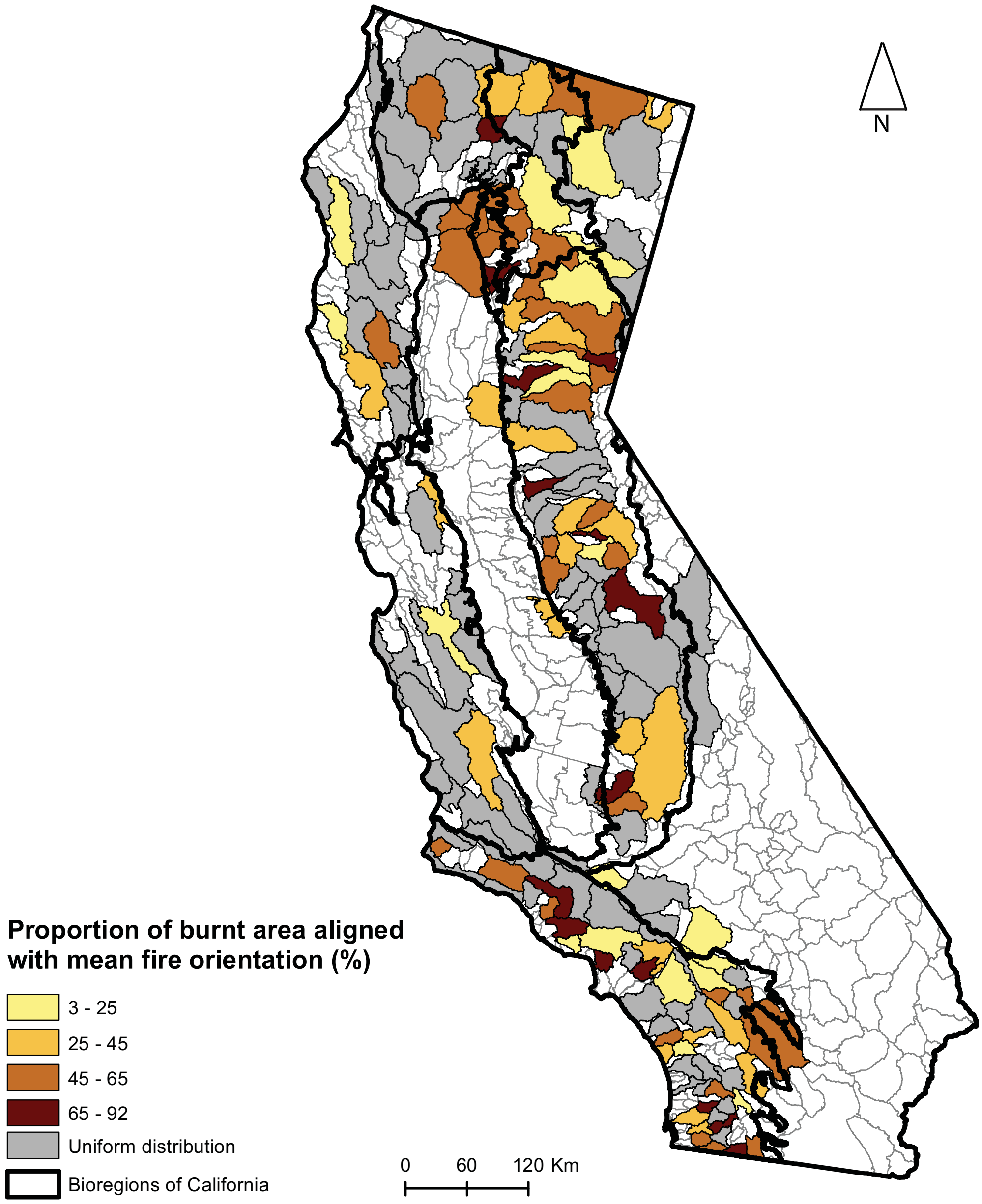
Figure 6. Circular variance for the mean fire orientation in watersheds where fires display preferential alignment (Figure 5b).



Fifteen watersheds display evidence of alignment between the watershed's main axis and its fires. This occurs in three watersheds in the Sierra Nevada and in the cluster of six watersheds in the San Diego region (South Coast) (Figure 5c). Comparing the compass classification of watershed and fire orientation suggests orographic alignment in 12 additional watersheds. Watersheds with fires predominantly aligned with their main axis occur in the northern Sierra Nevada, South Coast and Cascades (Figure 5c).

The proportion of burnt area from fire perimeters aligned with mean fire orientation ranges from 3% to 92% (Figure 7). Watersheds where a small fraction of the burnt area is aligned with mean fire orientation occur in all bioregions. In 19 out of 33 watersheds with preferential alignment in the South Coast, 45% to 92% of the burnt area comes from fire perimeters aligned with mean fire orientation. In the Sierra Nevada, this occurs in 15 out of 27 watersheds with preferential fire alignment.

Figure 7. Proportion of burnt area associated with fire perimeters aligned with the mean fire orientation (Figure 5b). In each watershed, a perimeter is considered aligned when its individual orientation is aligned with the mean fire orientation ± 15°.



4. Discussion

Analysis of fire orientation at the watershed level in California suggests the existence of preferential fire alignment patterns in the Sierra Nevada and Southern California bioregions. It was also found that in half of the watersheds analyzed, fire perimeters present random orientation. These results are in agreement with a similar study in Portugal, using a 31-year fire atlas, where 54 out of 102 watersheds tested showed preferential fire perimeter orientation [34].

Watershed orientation in the Northeastern Plateau and Southern Cascades occurs in all compass classes. and mean fire elongation ranges between 74 and 81%, with fire alignment occurring mostly NE/SW. In these bioregions. only two watersheds, in the Southern Cascades, showed correspondence between fire and watershed orientation. We hypothesize that the orientations found in northern California bioregions are influenced by synoptical weather patterns that occur during the fire season. The most common critical fire weather type in northern California occurs when surface high pressure builds into the Pacific Northwest, resulting in large pressure gradients across northern California. This leads to strong dry winds blowing from the north and northeast as air masses move from Oregon southward to the Sacramento Valley. Local topography, upper level windflow and the strength of the pressure gradient determine surface wind speed, which can exceed 65 km/h in these areas [20,58]. When the center of the surface pressure is over Utah and Nevada, these north and northeastern winds can change into strong easterlies, known as Mono Winds [20]. These conditions can account for the dominance of NE/SW oriented fires in the Southern Cascades and Northeastern Plateau.

In the Sierra Nevada watersheds where a preferential orientation was found, there is a dominant pattern of NE/SW and E/W fire orientation. The Sierra Nevada is also affected by the Mono winds; however, due to the orientation of its watersheds, it is very likely that dominant winds also interact with topography and, therefore, may be enhanced by the funneling across the east-west valleys and canyons that constitute the Sierras. We found alignment between fire perimeter and watershed orientation in 10 watersheds of the Sierra Nevada bioregion. In these watersheds, orographic channeling may explain the pattern found in fire orientation. Moreover, the fire orientation pattern found in northern California may also indicate the dominance of thermally driven winds, blowing along the axis of the valley, as opposed to slope winds, that blow parallel to the incline of the valley sidewalls. Valley winds, associated with stronger velocities and horizontal extent, result from the onset of horizontal pressure gradients, due to temperature differences between the valley and the adjacent plain [59,60]. The strength of this thermally-driven circulation is a function of valley geometry, aspect, time of day and time of year [61]. Under the assumption that the patterns found in this region correspond mostly to wind-aided fire spread, one can infer that the dominant NE/SW and E/W orientation in fact corresponds to a direction spread from the northeast, *i.e.*, in these watersheds, fires have spread more often from the northeast. However, in the Sierra, 20 out of 49 watersheds analyzed showed random fire orientations, which suggests that other factors (e.g., unexplored wind-topography interactions, fuel conditions or fire suppression) are influencing fire spread. Inspection of local land cover and landforms could provide additional insight as to why fires in those watersheds lack preferential orientation.

Southern California shows a general pattern of E/W and NE/SW orientation of fire perimeters. In Southern California, most burning (on an area weighted basis) coincides with offshore Santa Ana winds [62–64]. The NE/SW pattern in the Los Angeles region is in agreement with the work of Xu *et al.* [65] and is most likely due to the occurrence of the Santa Ana winds. These are strong north to northeast winds that reach Los Angeles County through passes in the local topography of the Transverse Ranges [64,66–68]. In the San Diego region, there is a cluster of several small watersheds where fire orientation displays a clear E/W component. These results are in agreement with the occurrence of Santa Ana winds, which present a strictly easterly component in the San Diego region, due to the Peninsular range's north-south orientation [69,70]. Additionally, watersheds in this region show fires with a high proportion of variance explained by the first principal component, thus suggesting highly elongated fire perimeters and evidence of orographic alignment according to both of our criteria-confidence interval and compass classification. The Santa Barbara region is somewhat sheltered from the effect of severe Santa Ana's, but nevertheless has its own critical fire weather, where sundowner winds play a major role in severe fire behavior [64,71]. The sundowner is a mesoscale phenomenon, which develops due to a ridgetop north to south low pressure gradient across Santa Barbara County. Early in the day, downslope air movements on the south side of the Santa Ynez mountains are blocked by the relatively cool marine inversion at the Santa Barbara coast. The weakening of the Santa Barbara marine inversion during the day removes the resistance to downslope wind movement, and warm gradient winds begin their extrusion onto the coast, funneling through major topographic passes in the Santa Ynez Mountains [71]. Sundowners reach Santa Barbara County as north or northwest winds, possibly due to surface deflection of their flow caused by marine air intrusion at the beaches and/or interaction with outflow stream canyons [71]. While speculative, the fact that the many passes and canyons in the Santa Ynez mountains channel sundowners into the coastal plain, where interaction again occurs with marine intrusions, may explain why the coastal basin displays a random fire orientation pattern [71]. Another possible explanation is that these random orientations may be due to the hours/days of strong directional winds alternating with less severe fire weather, characterized by moderate winds that interact with the topography. At this point, the original flaming front is driven in new and random directions, losing its original orographic signature. On the other hand, on the northern slope of Santa Ynez, fires show preferential SE/NW alignment. It is likely that this pattern occurs due to offshore winds, generated under the gradient pressures between the basin and coastal Santa Barbara, similar to those associated with the occurrence of sundowners. We found little evidence of orographic alignment in the northern parts of the Southern California bioregion.

In watersheds where correspondence was found between fire and watershed orientation, orographic channeling is a possible explanation. However, additional information and analyses would be required to test this hypothesis. Describing fire spread in relation to position in the watershed (e.g., valley, up-slope or ridge) and comparison with wind direction and speed during fire events could provide additional insights. Moreover, since we only tested orientation along each watershed main axis, this does not preclude the possibility of orographic alignment that may occur at finer spatial scales, *i.e.*, considering nested watersheds within the sub-unit level.

The proportion of burnt area that is aligned with the mean fire orientation of the perimeters is highly variable, ranging from 3% to 92%. This highlights one of the caveats of the fire perimeter distribution analysis, which is ignoring fire size and treating all observations equally, which can hinder interpretation of these results. In watersheds where only a small proportion of the burnt area is aligned with the mean fire orientation, it is likely that an area-weighted analysis of fire perimeter orientation would yield different results. However, with such an approach, a few very large fires could potentially become highly influential on the result of statistical tests and resultant mean fire orientation. This could also lead to potentially misleading conclusions, since very large fires usually burn during several days, under different wind directions and spanning multiple watershed divides [72,73]. In such cases, the resulting fire perimeter is less prone to represent phenomena, such as orographic conditioning of fire spread and channeling between local winds, topography and fire [60], thus increasing the uncertainty associated with fire perimeter analysis. Since our analysis of fire orientation is independent of size and under the assumption that the analysis of fire orientation patterns reflects the historical paths of fire, use of these results should be taken cautiously, because they describe the orientation of fire events and not burnt areas. Consideration of the amount of burnt area that is actually oriented along the mean orientation and how elongated fires are (here, described by the percent of variance explained by the first principal component) will be required when fully applying our findings in practice. The proportion of the area burnt in each watershed that corresponds to fires aligned with the mean fire orientation provides the extent to which managers can use these results to anticipate fire paths. This is particularly important considering that fire size distributions are usually highly skewed and that for several regions, a large percentage of the burnt area comes from a very small number of events [55]. Confidence about the most likely direction of spread will be greatest in watersheds where fires are elongated and a large proportion of the burnt area is aligned according to the mean fire orientation. These areas would be good candidates for strategically placed landscape area treatments (SPLAT's), which need to be oriented orthogonally to the main direction of fire spread [24,74].

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