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Dear Dr. Peter Attiwill,

Please find annexed the manuscript entitled "Identifying geographical patterns of wildfire orientation in Portugal: a watershed-based approach", by Ana M.G. Barros, José M.C. Pereira and Ulric J. Lund, which we kindly request you to consider for publication in Forest Ecology and Management. We believe that our manuscript not only is under the scope of your journal, but would also be of interest to the general public of Forest Ecology and Management. We also reinforce that this manuscript has not been published or simultaneously submitted for publication elsewhere.

Yours sincerely,

Ana Margarida Barros

Identifying geographical patterns of wildfire orientation: a watershed-based analysis

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Abstract

This paper searches for geographical patterns in the orientation of wildfires, using watersheds as spatial support for the analysis. We used a 1975-2005 annual fire atlas of mainland Portugal and computed the orientation of fire perimeters and watersheds using principal component analysis. Circular statistics were employed to test for the existence of a preferred, as opposed to random, mean fire orientation in each watershed, and to search for evidence of orographic channelling of fire by comparing fire orientation and watershed orientation. We tested for differences in fire orientation patterns between the top 10 years and the bottom 10 years in terms of extent of area burned. Our findings show that in the 31 year period of the study, 84% of the overall burned area is accounted for by watersheds where fires display preferential orientation. Twelve of 102 watersheds display evidence of alignment between fire and watershed orientation and we found no distinction in fire orientation between low and high burned area years. The spatial arrangement of watersheds where fires present similar orientation suggests wind as a major driver of the broader patterns found in this study. Results from this analysis are appropriate to watershed-based, regional scale positioning of fuel break networks.

Keywords: Fire Orientation, Orographic Channelling, Watershed, Portugal, Circular Statistics

1. Introduction

During the 1980-2004 period, wildfires in Portugal burned the equivalent to 30% of the area of the country, an incidence about three times higher than

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that recorded for neighboring Spain and Italy (Pereira et al., 2006). Large fires, by the standards of temperate, developed countries, are a feature of the contemporary fire regime in Portugal. Over 40 fires larger than 1,000 hectares occurred in the summer of 1991, and more recently in 2003 and 2005, several fires exceeded 10,000 hectares. A 50,000+ hectares fire in central-eastern Portugal, which occurred under the extreme heat wave of 2003 (Trigo et al., 2006), was possibly the largest fire on record in southern Europe during the last 40 years.

Concerns with the social, economic and environmental consequences of large wildfires led to the development of a National Plan for Forest Protection Against Wildfires (AFN, 2006), which recommended a range of landscape and stand level, fuel management practices. These recommendations offer general guidelines for size, placement and maintenance of fuel treatments to be applied nationwide, but reinforce the need for site-specific analyses to be incorporated in regional implementation, sustaining the idea there is no such thing as a "one size fits all" in fuel treatment design (CNR, 2005; Reinhardt et al., 2008; Syphard et al., 2011).

Fuel treatments at landscape scale have the primary objective of reducing the risk of large, high intensity wildfires with devastating effects, while enhancing supression efforts (Weatherspoon and Skinner, 1996; Agee and Skinner, 2005; Reinhardt et al., 2008; Syphard et al., 2011). Moving from stand to landscape scale bears the underlying assumption that strategically placed treatment areas can modify fire behavior for the entire landscape (Collins et al., 2010).

Conceptual modeling shows that greatest reduction in fire spread and intensity occurs when fuel treatments intersect head fire spread(Finney, 2001, 2004; Finney et al., 2007; Schmidt et al., 2008), confirming the topological inefficiency of random pattern fuel treatments (Loehle, 2004; Finney et al., 2007; Schmidt et al., 2008). Finney et al. (2007) showed that long-term landscape treatment effects on fire growth and behavior in the western US are primarily dependent on the rate of application and spatial pattern of treatment units. Schmidt et al. (2008) showed the efficiency of dispersed, strategically arranged treatments in reducing fire spread and area burned, particularly in simulations of high intensity fire. Finney et al. (2007) also showed that placement of fuel treatments intersecting spread direction, would require half the area treated than random treatments, to produce same reduction in fire growth and behavior. The orientation of optimized treatment units in this study was determined using a fire growth simulation technique to identify major fire travel routes (Finney, 2001). Fire growth was simulated under specified weather conditions characterized by fuel moisture, wind speed and direction, obtained from historical records of climatology associated with severe fire events (Finney, 2001). Typically, this results in orientation of treatment units perpendicular to major fire spread movement, because heading fire behavior is more important to modify than flanking or backing portions (Finney, 2007). This suggests that research on the geographical orientation of fires is useful for fire management, assuming that the orientation of fire perimeters reveals the combined effects of wind and topography on fire spread patterns, and allows inference on heading fire movement. Systematic fire mapping over a time frame adequate for fire regime characterization can provide useful information for landscape-scale planning of fuel treatments, by establishing an historical pattern of spread orientation.

A few studies have addressed the issue of fire orientation in relation with weather patterns and topography. Parisien et al. (2006) found that the geographic orientation of fires was highly variable within and among Canadian ecozones, responding to the spatial variability of meteorological conditions. The main trends in fire direction across and within ecozones can be attributed not only to dominant weather patterns, but also to specific synoptic patterns associated with high fire danger. Throughout Canada, prevailing winds are generally from the west, and south-west winds dominate behind drying high pressure systems, often associated with increasing fire danger. As a consequence, nine out of the 10 ecozones had the highest fire bearing class frequency from west to east or southwest to northeast.

Bergeron et al. (2004) analyzed the main direction of fire spread in northwestern Quebec's black spruce forest, and showed that most of the distance covered by fires occurred in the northwest-southeast direction, although the frequency of occurrence of this direction is not high compared to the other directions. Also, those were larger fires, with a mean spread distance of 14.8 km (Bergeron et al., 2004).

Haydon et al. (2000) analyzed orientations of 196 fire "tongues", more commonly known as fire fingers, extracted from 224 grassland fires in the Great Victoria Desert, Australia, and found good correspondence between prevailing wind direction and "tongue" orientation.

The main objective of this study was to determine whether fires display a preferred, by opposed to random orientation, at landscape scale. Secondary objectives were to determine if preferred fire orientation, when present, varies as a function of fire season severity and search for evidence of orographic wind channelling on fire orientation. We used principal component analysis to compute the orientation of fires and watersheds perimeters following the methods developed by Luo (1998). A sequence of hypothesis tests for circular data were applied to establish preferential alignment of fire perimeter orientation in each watershed and for comparing fire orientation between years with area burned above and below the mean annual value for the study period (Fisher, 1993). Orographic channelling was evaluated according to three different criteria: 1) by comparing watershed orientation with the 95% confidence interval of the mean of fire perimeter orientations, 2) by comparing mean fire perimeter orientation with a interval within ±15°of watershed orientation and 3) by performing circular-circular correlation between watershed and mean fire perimeter orientation (Fisher, 1993).

2. Methods

2.1. Study Area

The study area is mainland Portugal, covering around 89,000 km^2, located in the Iberian Peninsula, southwestern Europe (Fig. 1).

The climate is typically Mediterranean with a wet and cool winter, followed by a dry and hot summer. The study area exhibits sharp topographic contrasts and can be roughly divided into two distinct regions, north and south of the Tagus river (Fig. 1). The region north of the Tagus river is dominated by a complex arrangement of mountains and highlands above 800 meters, interspersed by sharp valleys and pronounced depressions. South of the river Tagus valley is dominated by gentle rolling hills and plains and altitude is seldom higher than 600 meters, except for the mountains at the southwestern end (Ribeiro et al., 1987).

Forests of mostly evergreen species and woodlands cover nearly 60% of the study area (AFN, 2007). The natural vegetation is pyrophytic and resistant to drought. The most important tree species are maritime pine (*Pinus pinaster*), in the northern half of the country, and blue gum (*Eucalyptus globulus*) along the western half of the country, as well as in a few areas in the eastern central region of the country (Fig. 1).

Land cover in southern Portugal is dominated by evergreen oak woodlands, managed as agro-forestry systems. Agricultural areas occupy about half of the study area and, mostly dominate in the central coastal plain, along main river valleys, and in the southern half part of the country. In central

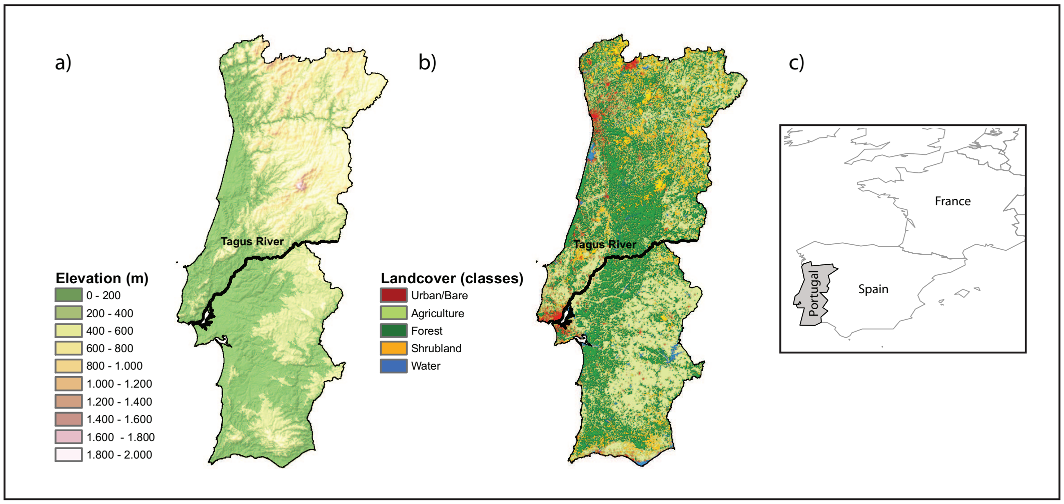

Figure 1: Map of the study area, mainland Portugal, elevation (a), land cover classification (b) and location in Iberian Peninsula, southwestern Europe (c).

and northern Portugal, land ownership is very fragmented, and the agricultural landscape is a fine-grained mosaic of small parcels of diverse crops, vineyards, and olive groves. The agricultural landscapes of southern Portugal are more extensive and homogeneous, dominated by dryland farming of cereal crops. Most shrublands are found in eastern Portugal, but also occur in other parts of the country, usually in mountainous and sparsely populated regions (Fig. 1).

Fire incidence is higher in the northern half of the country, where the typical Mediterranean summer coexists with high net primary productivity, leading to an abundance of available fuels. Most of the area burned in Portugal (80%) is due to fire events occurring during a small number (10%) of summer days, under a typical atmospheric circulation pattern dominated by a strong ridge located over the Iberian Peninsula (Pereira et al., 2005).

Fire history data were obtained from the Instituto Superior de Agronomia national fire atlas, based on late summer/fall Landsat imagery, covering the period from 1975 to 2005, on an annual basis. During the period used in this study, the fire atlas includes 34,345 fire perimeters, accounting for a total burned area of 3,670,000 hectares. The mean annual area burned is 118,000 hectares, with a minimum of 15,500 hectares in 1997, and a maximum of 440,400 hectares in 2003.

2.2. Watershed delineation

Watershed delineation was based on the 90-m digital terrain data from the Shuttle Radar Topography Mission (Farr et al., 2007) and, the number and size of watersheds was determined iteratively with two goals: to obtain a detailed topographically-based partitioning of the region, and to ensure that each watershed contained a minimum of 25 fires (Fisher, 1993).

Watersheds were delineated automatically in ArcMap 9.2 (ESRI, 2009), using a minimum area criterion. In the first iteration, minimum watershed area was set at 10,000 hectares, yielding a highly detailed map with around 700 watersheds. Most of these contained fewer than 25 fires consequently, the minimum area threshold was increased in 10,000 hectares increments, up to a value of 40,000 hectares. Along coastal areas, watersheds smaller than 40,000 hectares were included as long as they contained at least 25 fires. The final map was edited to exclude international watersheds, since we do not have the perimeters of fires occurring in the Spanish portion of these watersheds. This resulted in a total of 102 watersheds, with sizes varying from 10,400 hectares to 277,835 hectares. Each fire was considered as belonging to the watershed containing its centroid. The 102 watersheds correspond to 83% of the Portuguese mainland and contain 30,459 fire perimeters, accounting for 90% of the 1975-2005 overall burned area. The number of fires per watershed ranges from 25 to 2498, while the area burned varies from 500 hectares to 380,900 hectares (Fig. 2).

2.3. Orientation vs Direction

Circular data refers to all data measured on an angular scale, often in degrees or the corresponding interval in radians. A key distinction in circular data is between vectorial (direction) and axial (orientation) data. Vectorial data consists of a directed line where both the departure point and direction of movement are known, e.g. the vanishing directions of homing pigeons. Axial data consists of an axis or undirected line where either end of the line can be taken as direction of movement, such as a fracture in a rock exposure (Fisher, 1993).

The analysis of circular data requires definition of an origin, and a sense of rotation - clockwise or counterclockwise (Jammalamadaka and Sengupta, 2001). In this work we computed the orientation of each watersheds and fire event. These orientations correspond to axial data, since we lack information on ignition point and actual fire spread direction. We considered true North (N) as origin and measured orientations clockwise. Given that all orientations

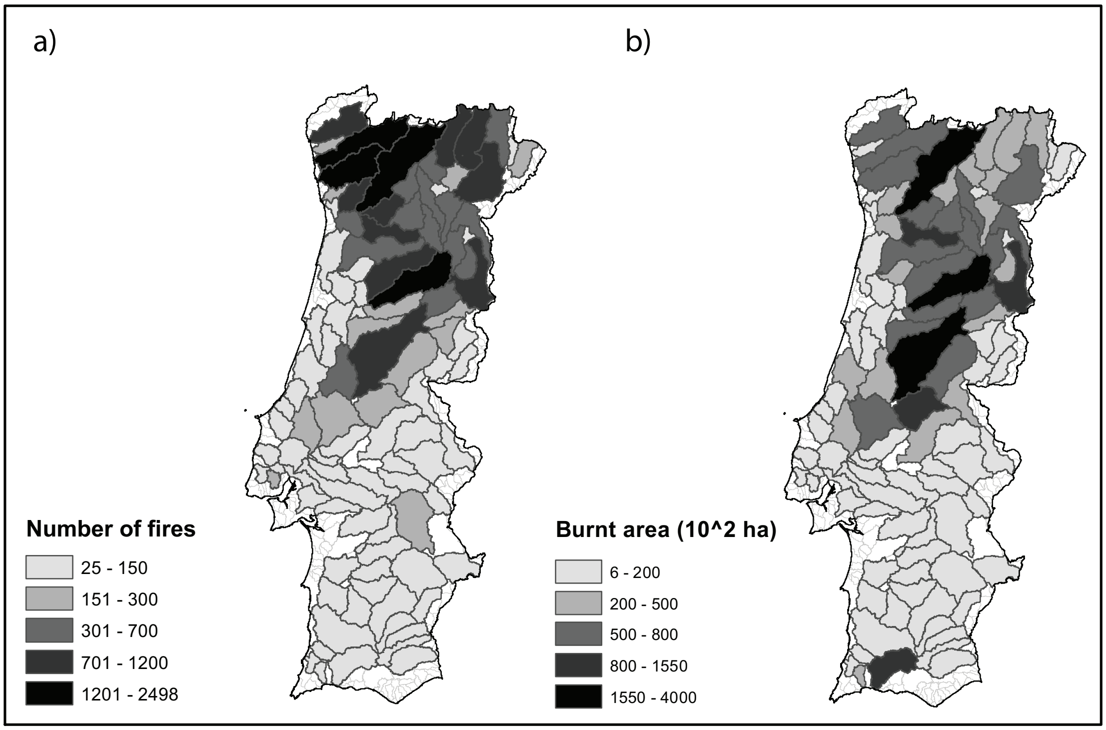

Figure 2: Number of fires (a) and burned area (b) per watershed. Each fire perimeter is associated with the watershed that contains its centroid. Automatic delineation of watersheds, based on setting the minimum size threshold and delineating all watersheds above it, resulted in a partition of the study area into 102 watersheds with minimum of 25 fire observations in each. International watersheds and watersheds with less than 25 fires were excluded. Burned area reported to an watershed is the sum of the area of all fire perimeters associated with that watershed.

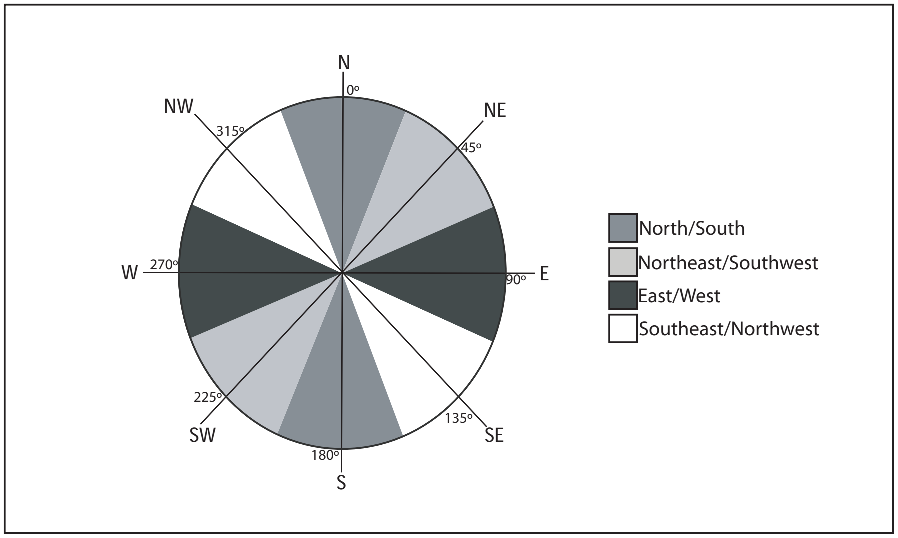

Figure 3: Classification of axial data in compass orientation. For each fire and watershed perimeter an orientation value, θ_{or} is calculated. Orientation values range between 0°and 180°and were classified into compass classification is a function of θ_{or} as follows: N/S $\Leftrightarrow \theta_{or} \in [0; 22.5] \wedge \theta_{or} \in]157.5; 180]$; $NE/SW \Leftrightarrow \theta_{or} \in]22.5; 67.5]$; E/W $\Leftrightarrow \theta_{or} \in]67.5; 112.5]$; SE/NW $\Leftrightarrow \theta_{or} \in]112.5; 157.5]$. Different shades of grey distinguish the range of the intervals described above.

are axial, it follows that 0°(North, N) is equivalent to 180°(South, S) (Fig. 3). For the sake of simplicity, we shall refer to axial measurements in the compass classifications: N/S, NE/SW, E/W, and SE/NW, which can be regarded as equivalent to the orientations S/N, SW/NE, W/E and NW/SE, respectively.

2.4. Fires and watershed perimeter orientations

We used principal component analysis (PCA) (Jolliffe, 2002) to determine the orientation of fire and watershed perimeters, following the approach proposed by Luo (1998). Each object (fire or watershed) boundary vertex corresponds to a point in a bi-dimensional space defined by its (X,Y) geographical coordinates. The first principal component (PC1) corresponds to an axis in this bidimensional space that passes through the object's center of mass and onto which all points are projected. The orientation of this axis maximizes the variance of projected boundary points, reflecting the length of the object's longest diagonal, and is taken as the object orientation (Fig. 4).

Object orientation by PCA is less sensitive to boundary details, including inaccuracies, than alternative methods for orientation analysis (Luo, 1998). This is advantageous in our case, since fire boundaries have different levels of detail depending on whether they result from automatic image classification, or from post-classification manual boundary editing. For a detailed description of a four step algorithm to compute orientation by principal component analysis see Luo (1998), pp. 131 to 136. For the purpose of the present work, this algorithm was implemented in Matlab using the built-in *princomp* function (The MathWorks, 2008).

2.5. Circular statistics analysis

We conducted a sequence of hypothesis tests - Kuiper's, Watson's and Rayleigh's - that infer the form of the population of fire perimeter orientations in each watershed (Fig. 5).

The objective is to determine whether each population fits one of three circular distributions: circular uniform, von Mises and unimodal. The circular uniform distribution plays a central role in circular statistics because it represents the absence of a preferred direction, i.e., all directions are equally probable.

The von Mises distribution, is the circular analog to the Normal distribution of linear statistics (Davis, 1986). It has two parameters, the first of which defines the location of the reference direction of the distribution (mean direction), while the second parameter defines the scatter about that location and is called concentration (k). The von Mises distribution is symmetric around the mean and increasing k corresponds to increasing concentration around the mean direction. As k approaches zero the von Mises distribution tends toward the circular uniform distribution (Fisher, 1993).

If the data fit neither a von Mises, nor a uniform distribution, it may still contain a single mode, thus following a unimodal distribution (Fisher, 1993). In this case, although it is not possible to identify the actual distribution, the presence of a mode not only indicates a preferred orientation in the sample, but also enables the use of non-parametric methods to compute a mean direction and confidence interval.

Figure 5 represents the sequence of hypothesis tests performed in this analysis. The Kuiper test is an *omnibus* test, meaning it tests the hypothesis of the sample following a uniform distribution, against any alternative distribution. If the null hypothesis is rejected, then there is evidence against uniformity and the possibility that the data fit the von Mises distribution is

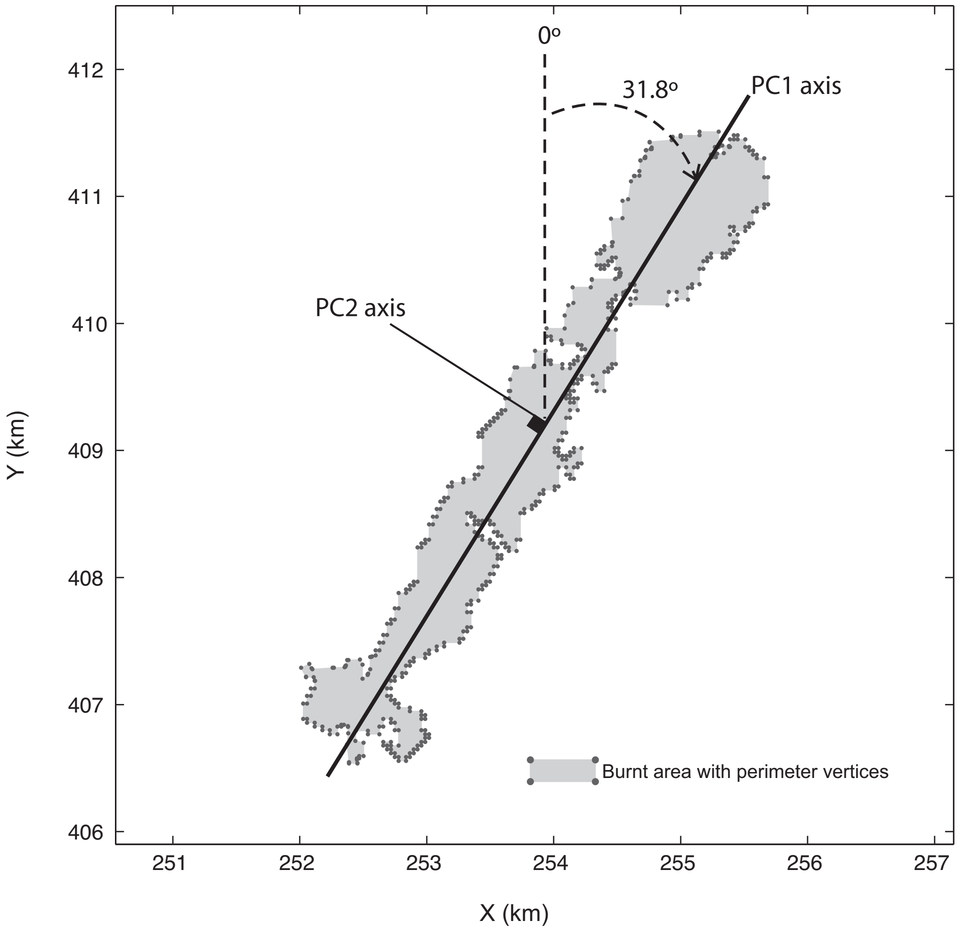

Figure 4: Fire perimeter vertices are represented by its X and Y coordinates, in a bidimensional space. From all possible axis passing through the object center of mass, the first principal component axis (PC1 axis), corresponds to the axis that maximizes the variance among projection of all points that constitute the object boundary and also reflects the longest diagonal of the object. The second principal component axis (PC2) is orthogonal to the PC1. In this example principal component analysis of the vertices resulted in a PC1 axis with NE/SW (31.8°) orientation. This orientation is measured considering True North as 0°and rotating clockwise.

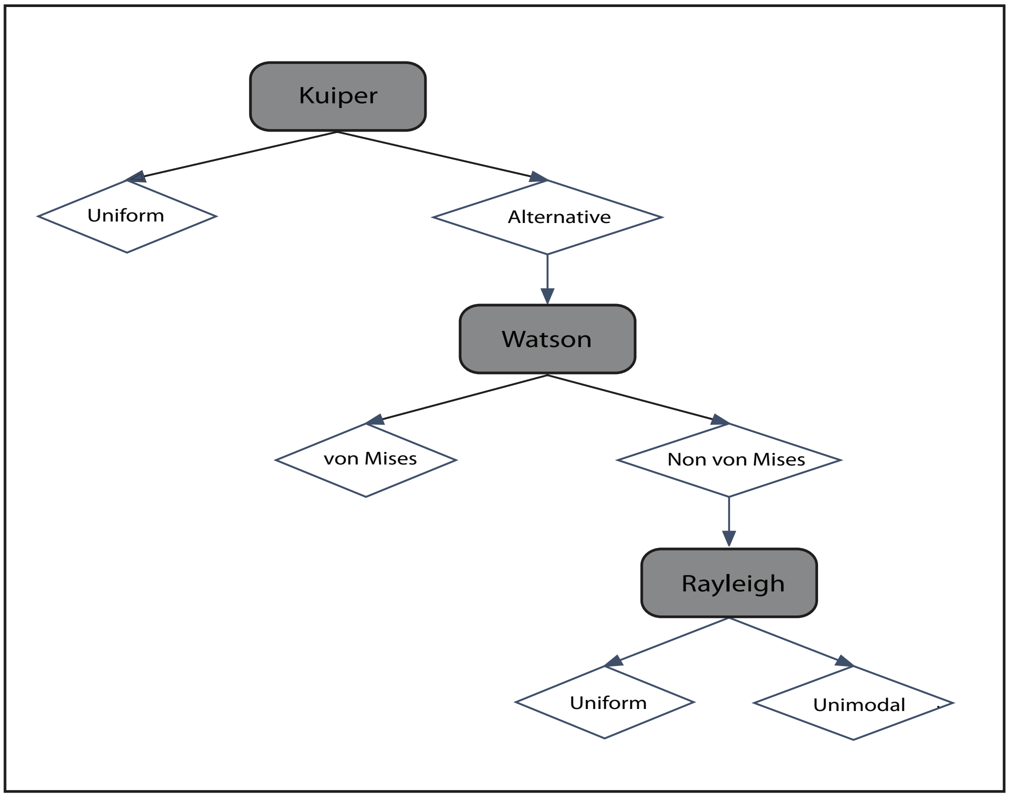

Figure 5: Flowchart representing the sequence of hypothesis tests based on circular distributions. Round rectangles represent tests and splits to the left and right represent acceptance and rejection of the null hypothesis, respectively. White diamonds represent the decisions regarding the fit to circular distributions (Uniform, von Mises, Unimodal) at a significance level of 5%.

tested. The goodness of fit of the von Mises model can be formally assessed using Watson's test (Fisher, 1993). The null hypothesis in this test is that the data are drawn from a von Mises distribution, against the alternative that they are not drawn from a von Mises distribution. Rejection of the null hypothesis in the Watson's test, leads to rejecting the hypothesis that the data fits a von Mises model. The next step is to determine whether the data presents a single modal direction, using Rayleigh's test, which is considered more powerful than Kuiper's, when the alternative hypothesis is unimodality (Fisher, 1993).

For each watershed in which a preferred fire perimeters orientation was detected (von Mises or unimodal) we calculated the circular mean (Fisher, 1993; Otieno and Anderson-Cook, 2006), its confidence interval, and circular variance. The circular mean, denoted by $\overline{\theta}$, is defined as:

$$cos\overline{\theta} = \frac{C}{R}, \qquad sin\overline{\theta} = \frac{S}{R} \tag{1}$$

where,

$$C = \sum_{i=1}^{n} \cos\theta_i, \qquad S = \sum_{i=1}^{n} \sin\theta_i, \tag{2}$$

$$R^2 = C^2 + S^2 (R \geq 0) \tag{3}$$

The circular variance varies between zero and one and its interpretation is similar to variance in linear data, the smaller the value of circular variance, the more concentrated is the distribution. Circular variance is defined as:

$$V = 1 - \overline{R} \tag{4}$$

where, $\overline{R}$ is the mean resultant length associated with the mean orientation $\overline{\theta}$, and is defined by:

$$\overline{R} = \frac{R}{n} \tag{5}$$

where, n is the number of observations and R is defined by Eq.3.

Confidence intervals for the circular mean fire orientation were computed in two ways, depending on whether the goodness of fit tests indicated a von Mises distribution or a unimodal distribution for the fire orientations within the watershed. A parametric approach was used if the fire orientations had a von Mises distribution, and a non-parametric approach was used if only a unimodal distribution was suggested by the goodness of fit tests (Fisher, 1993).

The 95% confidence intervals for the mean fire orientation in each watershed were used to formally assess alignment between mean fire orientation in a watershed and the orientation of the watershed itself. Alignment is considered to occur when the watershed orientation is contained in the mean fire orientation confidence interval (Rothermel, 2004). This definition of alignment is sensitive to the number of observations in each watershed, therefore, as an alternative measure of similarity between fire and watershed orientation, we identified watersheds where mean fire orientation was within ±15°of watershed orientation. To evaluate the influence of major watershed orientation on fire perimeter mean orientation we calculated the circular correlation between watershed orientation and mean fire orientation (Fisher, 1993). Airflow is guided by topographic features, such as mountains or valleys, establishing local wind direction (Schroeder and Buck, 1970). Alignment between fire orientation and the watershed orientation may be indicative of watersheds where topography determines directional orographic alignment of winds and consequently, wildfires (Schroeder and Buck, 1970; Pyne et al., 1996).

We hypothesized that fire orientation patterns may differ between severe and mild fire years, assuming they occur under distinct synoptic weather conditions (Trigo et al., 2006; Pereira et al., 2005). Using annual burned area as a proxy for fire weather severity (Nunes et al., 2005; Syphard et al., 2011), we compared the 10 years with higher burned area with the 10 years with lower burned area, under the assumption that the two samples are drawn from distinct populations. This analysis was performed considering watersheds with at least 25 fire observations in both time periods, which corresponds to 36 of the 102 watersheds in the study area. The statistical comparison between the high and low burned area datasets was done using the Watson-Wheeler test, that compares two populations to determine if their distributions are identical (Fisher, 1993). This is a non-parametric test, with the null hypothesis that the two populations are drawn from identical distributions (Fisher, 1993).

All statistical analysis was performed with Oriana (Kovach, 2003) with the exception of non-parametric confidence intervals, that were computed in Matlab (The MathWorks, 2008), following Fisher (1993). All formal hypothesis tests were conducted using a 5% significance level.

3. Results

Analysis of fire perimeters over the 31-year dataset showed that, of the 102 watersheds in the study area, 53 watersheds displayed a preferred fire orientation, out of which 41 watersheds fit a von Mises distribution, whilst 12 watersheds follow a unimodal distribution (Fig. 6). Forty-eight watersheds followed a uniform distribution. For one watershed no conclusive results were attained regarding its fire orientation distribution, but we tested the fit to a limited number of circular distributions (Uniform, von Mises and unimodal). This watershed accounts for less than 0.5% of the study area and of the overall burned area.

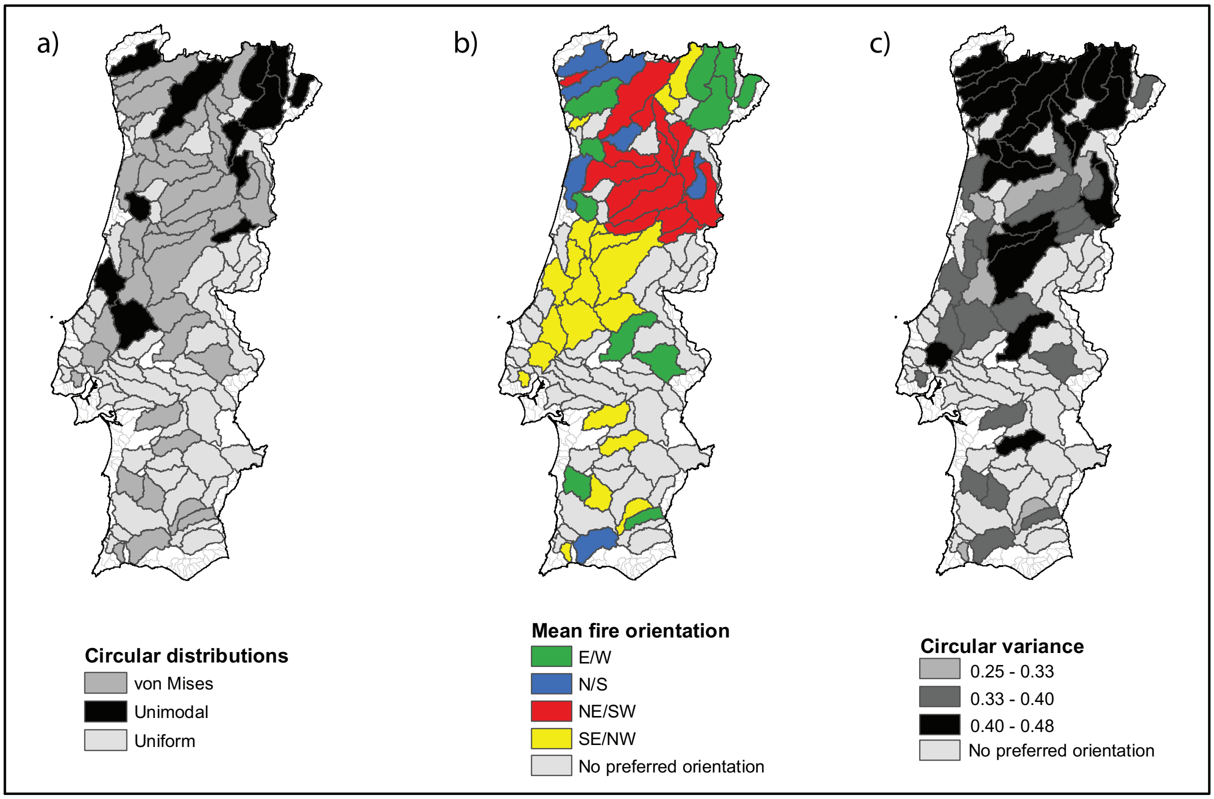

Figure 6: Circular distributions fitted to fire perimeter populations (a), mean fire perimeter orientation (b) and its circular variance (c), in each watershed. Both von Mises and unimodal distributions indicate the presence of a preferential orientation in the data, while watersheds where fire perimeters follow a circular uniform distribution show no indication of preferential orientation, at a 95% confidence level (a). Watersheds where fires display a preferential orientation are represented in a color coded scheme according to the compass classification of its mean fire perimeter orientation - green, blue, red and yellow, for mean fire orientation in the E/W, N/S, NE/SW and SE/NW orientations, respectively (b). Light grey represents watersheds with no preferred orientation (Uniform distribution). Circular variance of the mean ranges from 0 to 1, with higher values for higher variance around the mean direction, (c).

Watersheds where fires display a uniform distribution of fire orientation, mostly found along the southern half of the country, represent 38% of the study area, and account for 16% of overall burned area. Watersheds with von Mises and unimodal fire orientation distributions are mostly located in northern and central Portugal and represent 86% of the overall burned area, while covering 61% of the study area. Variance of the mean fire orientation ranges from 0.25 to 0.48, and watersheds in the northern part of the country present higher dispersion around the mean fire orientation (Fig. 6).

The circular mean orientation was computed for watersheds where fires display preferential orientation. Compass classification of mean fire orientation shows two distinct clusters in central Portugal, with NE/SW and NW/SE orientations (Fig. 6). These two clusters account for around 65% of total area burned in the 31-year dataset (Fig. 7). All watersheds aligned NE/SW occur in the northern half of the study area, while the remaining orientations are associated with watersheds, either clustered or isolated, but distributed throughout the entire study area. There is also a group of watersheds with E/W orientation in NE Portugal.

Major topographic orientation of each watershed varies throughout the study area, with clusters of NE/SW and SE/NW orientation in the center and northwest regions, N/S clusters along the coast and northeastern border with Spain, and E/W clusters throughout the entire study area (Fig. 8). Comparison between fire and watershed orientation shows that while fire orientation shows two important clusters, with NE/SW and SE/NW orientations (Fig. 6), watershed orientation is more variable (Fig. 8).

From a total of 53 watersheds evidencing preferential fire orientation, only eight display a watershed orientation that is contained within the mean fire orientation confidence interval, revealing strong alignment between watershed orientation and fire orientation in these watersheds. Following the alternative criterion for topographic alignment resulted in four more watersheds with evidence of mean fire-watershed alignment. Circular-circular correlation coefficient between watershed orientation and mean fire orientation per watershed has a value of 0.208, suggesting a weak relationship between major watershed orientation and corresponding fires.

The Watson-Wheeler test did not indicate that fires occurring in the 10 years with highest burned area and fires occurring in the 10 years with the lowest burned area had differing distributions of fire perimeters orientation. For only one of the 36 watersheds analyzed, was there a significant difference (α=0.05). This suggests that during severe fire weather years, although total

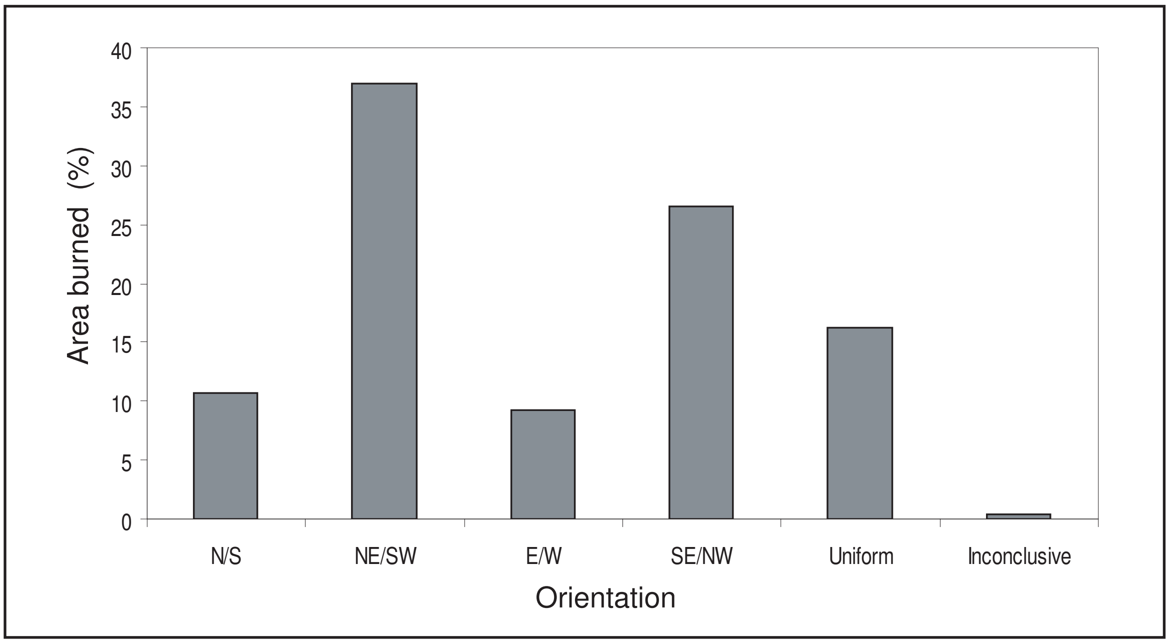

Figure 7: Burned area per orientation class. Two major clusters, in the NE/SW and SE/NW account for around 65% of the total area burned in the 1975-2005 time period. Watersheds where fire perimeter orientation is circular uniform, i.e., with no preferential orientation of fires, represent roughly 16% of the overall burned area and are mostly located in the southern portion of the study area.

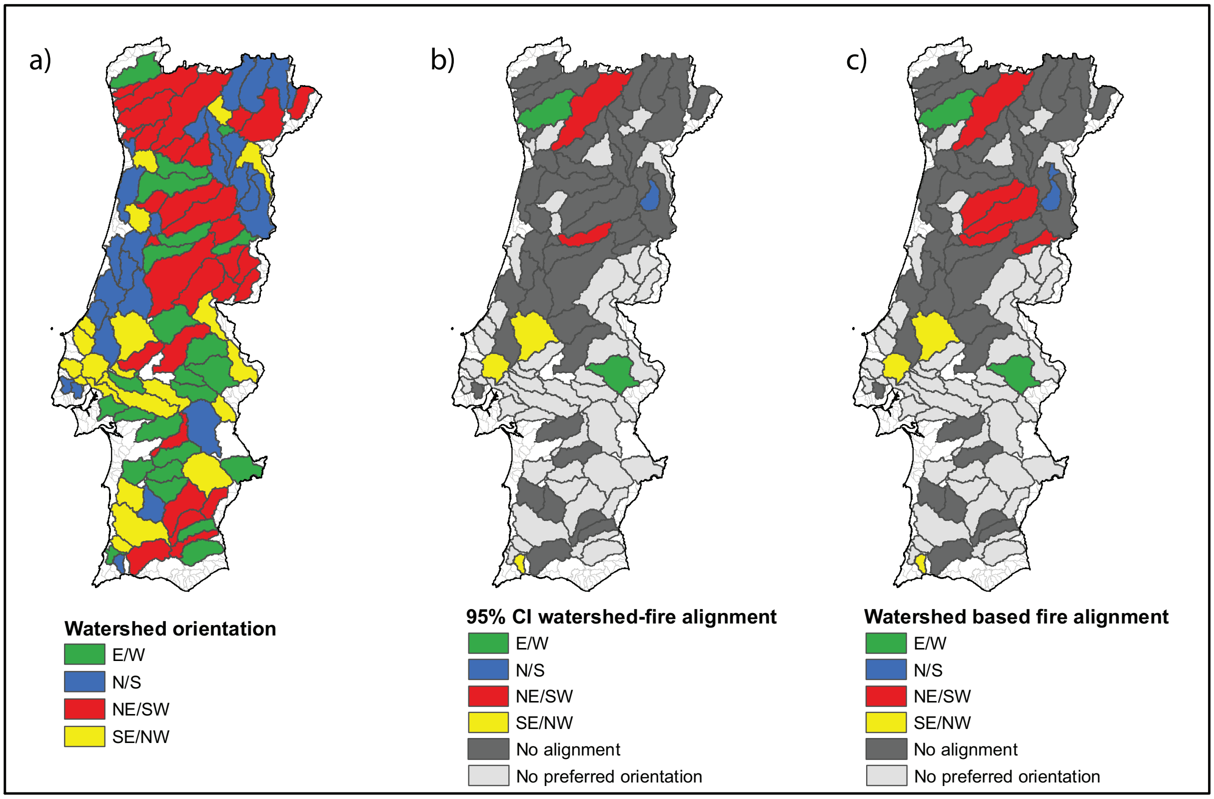

Figure 8: Watershed orientation (a), watershed-fire alignment following the 95% confidence interval (b) and alignment according to watershed orientation (c). In (b) fires were considered aligned with watershed when watershed orientation is contained in the 95% confidence interval for fire mean direction. An alternative measure of alignment (c) is to consider that fires are aligned with watershed if mean fire orientation is within the angular interval centered at the watershed orientation $\pm 15°$. The analysis of potential topographic alignment is performed only for watersheds where fires display evidence of preferential orientation, i.e., watersheds where fire orientation fits the circular uniform distribution were excluded.

area burned increases, the orientation of fire perimeters remain consistent with that observed during moderate and mild fire seasons.

4. Discussion and Conclusions

The primary objective of this work was to determine whether fires display geographical orientation patterns, at the watershed scale. A secondary objective was to analyze the relationship between the orientation of fires in a watershed and the orientation of the watershed itself. We also investigated the hypothesis that fire orientation patterns would vary between mild (low burned area) and severe (high burned area) fire seasons.

Circular statistics analysis showed that 84% of the area burned between 1975 and 2005 is located in watersheds where fires display preferential orientation. This is a remarkable result, considering the heterogeneity of land cover, topography and infrastructure networks across these watersheds, and the role of fire suppression activities. In southern Portugal only a few watersheds display non-uniform fire orientation, but this region corresponds to a small fraction of the total number of fires and area burned. Gently rolling terrain, without very prominent topographic features, relatively homogeneous land cover, and a prevalence of agricultural land management fires, typically set under mild weather conditions, may account for the lack of preferred orientation of fire perimeters.

Two large clusters of watersheds with preferentially-oriented fires are found in central Portugal. Fire orientation is NE/SW in the northernmost cluster (red), and SE/NW in the southernmost cluster (yellow). Together, these two clusters represent 65% of overall burned area and contain many of the largest fires recorded during the study period. The location and geographical extent of these clusters is suggestive of a broader scale, climatic determinant, rather than finer scale topographic control. This is particularly true, considering that Pereira et al. (2005) identified synoptic patterns of severe fire weather which, although relatively rare, are responsible for most of the area burned in Portugal. The wind field composite for the 10% highest burned area days over the period 1980-2000 clearly shows north-easterly component that may influence fire orientation in the northernmost (red) watershed cluster. However, that spatial resolution of the analysis is too coarse to elucidate finer scale wind flow patterns.

Hoinka et al. (2009) analyzed relationships between regional scale weather patterns and wildfires in central Portugal, namely the role of the Iberian thermal low (Hoinka and Castro, 2003; Hoinka et al., 2007). They showed that previously to days with extensive area burned, the atmospheric flow above Portugal is from the north, turning to easterly at the severe fire day, and from to south-easterly afterwards. Analysis of the relationship between the Iberian thermal low and burned area showed that peak fire incidence was observed up to three days after the appearance of a thermal low. Hoinka et al. (2009) interpret this observation as indicating that during a few days preceding a large area burned episode, heated air is transported westward from central Iberia towards Portugal. They also show that during severe fire days and at 10m above sea level, wind flow is from the northeast in the northern half of Portugal and from east-southeast in the southern half of Portugal, in agreement with the fire orientation patterns detected in this study. Further clarification of regional fire spread directions will be gathered from analysis of smoke plumes and time series of active fire, observed with satellite imagery.

Alignment of watershed orientation and mean fire orientation occurs in a small number of watersheds scattered throughout the study area. Directional wind channeling by topography may contribute towards coincidence of main valley, wind, and fire orientation. It occurs when a large drainage diverts some of the incoming wind flow sending it in a direction parallel to the drainage (Pyne et al., 1996). Nevertheless, topographic wind channeling cannot be ruled out where coincident orientation of fire perimeters and the main drainage is absent, because this alignment may occur within second order basins, which was not tested in this work.

While we did not formally assess differences in fire orientation in relation with land cover, we believe that land cover is unlikely to be responsible for the patterns of fire perimeter orientation found in this study. Our results show that fire perimeter orientation remains consistent across watersheds with widely variable proportions of major land cover types. It is also reasonable to assume that fire suppression does not alter fire perimeter orientation within or among watersheds. Historically, fire suppression in Portugal has focused on the vicinity of human settlements and infrastructures and therefore emphasizes protecting these areas from fire, with considerable less amount of suppression effort applied directly to containing the flame front while it spreads through wildland fuels (Beighley and Quesinberry, 2004; AFN, 2006).

The geographical pattern of clustering detected in fire perimeter orientation and the heterogeneous relationship between mean fire orientation and watershed orientation highlight the need to regionalize the design of fuel break networks and include site-specific information to optimize their effectiveness. Locating fuel breaks along the main ridge or main riparian area of a watershed may not be the best option. On a more local scale, the identification of potential orographic channelling has direct implications in terms of fire risk and management, because of it creates conditions for potentially high intensity fires.

The fact that more than half of the overall burned area displays non-random orientation, which remains consistent between mild and severe fire seasons, indicates that the spatial patterns identified are indeed useful to support regional-scale planning of fuel break networks. Of course, much more remains to be done concerning the complex, finer-scale interactions between wind and topography and their effects on fire behavior (Sharples, 2008; Linn et al., 2007). Further clarification of regional fire spread directions will be gathered from analysis of smoke plumes and time series of active fire, observed with satellite imagery. Future work should focus on analysis of multi-annual MM5 weather data coupled with topographic exposure/deflection indexes to investigate which variables and interactions contribute to the patterns found in this study. This will highlight the relative influence of meteorology and topography in regional fire patterns, in support of fire management and suppression decisions.

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*Highlights

>We computed wildfire orientation for all fires in Portugal from 1975 to 2005.

>At watershed level, we assessed the existence of a preferred fire orientation.

>We found that 84% of the burned area shows preferential geographical orientation.

> Spatial pattern of preferred orientation suggests synoptic wind as key driver.