



A geomorphometric model to determine topographic parameters controlling wildfires occurrence in tropical dry forests

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ABSTRACT

Tropical dry forests (TDF) are commonly affected by wildfires, especially during the dry season and drought periods. Many studies have identified ecological, pedological, and climatic variables that control fires ignition as well as other anthropogenic causes. Nonetheless, the intrinsic geomorphometric variables that shape the different TDF landscapes have been underestimated. Hence, we used a Generalized Linear Model (GLM) to study the occurrence of wildfires in a TDF on a TDF located in a protected area at northwest Costa Rica. The influences of nine topographic parameters (TP) were tested on the occurrence of wildfires during a period of 23-years (1997–2020). The statistical analysis demonstrate that Aspect (compass direction that a terrain surface faces) and Wind Exposition (areas degree exposed to wind) are the most influential TP to explain the wildfires occurrence in TDF. The results may be valuable for the understanding and assessment of geomorphometric variables controlling wildfires occurrence in TDF. Therefore, highlighting the importance of fire risk management in ecosystems comprising almost the half of the total of tropical forests proves relevant.

1. Introduction

Tropical dry forests (TDF) constitute almost half of the worldwide tropical forests (Murphy and Lugo, 1986; Dupin et al., 2018; Ocón et al., 2021). This kind of forests play a key role in the provision of ecosystem services sustaining human activities (Portillo-Quintero et al., 2015; Calvo-Rodríguez et al., 2017). The conversion into crops and pastures embody the most important threat to TDF, resulting from a spatiotemporal, long-scale human occupation attracted by flatlands, rich soils, and suitable climate for agriculture and livestock (Trejo and Dirzo, 2000; Miles et al., 2006). Increased deforestation and forest degradation constitute growing concerns worldwide with severe consequences at multiple scales (Sánchez-Romero et al., 2021).

On average, 39% of global forest loss was associated with fire (van Wees et al., 2021). Every year tropical forests record more fires than any other forest ecosystem on Earth (Cochrane, 2009). Wildfires occurrence is associated with regional climate changes and climatological modes such as El Niño Southern Oscillation (ENSO; Falk et al., 2011). These conditions generate droughts in many tropical areas such as Australia, Central America, Southeast Asia, and West Africa (Cochrane, 2009). Although in some places fire plays a key role in land management

(Schmerbeck and Fiener, 2015), fires in TDF have long-term consequences and effects in the vegetation structure and composition (Dillon et al., 2006), in landscape dynamics (Moreira et al., 2009), soil and nutrient loss (Venkatesh Preethi and Ramesh, 2020), as well as carbon storage and water quality (Harper et al., 2018).

Fire risk environments are dynamic in spatiotemporal dimensions and therefore complex to calculate (Chuvieco et al., 2010). Biotic and abiotic factors modulate fire risk (Fischer et al., 2015). Biotic conditions include the vegetation's morphology and physiology. Furthermore, meteorological and topographic variables are abiotic factors modulating fire risk (Miles et al., 2006; Adelabu et al., 2020). The variables explaining forest fires include, among others, the antecedent rainfall, forest composition, land use, and topography (Fernandes et al., 2016). Fire severity and behavior are defined by the combined influence of fuel, weather conditions, and topography (Sullivan, 2009; Adab et al., 2018). Topography variation can influence the local distribution of plant population types controlling wildfires (Falk et al., 2011). The spatial variation in burn severity is related to topography, which also influences the intensity and duration of fire (Dillon et al., 2006). For example, Aspect and Wind-Topography relationship has proved a predominant correlation in regards to the occurrence of wildfires (Barros and Pereira, 2014;

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Mansuy et al., 2014; Tehrany et al., 2019).

Normally, fire risk is determined through indexes. Some of these mathematical expressions are based on temporal scales occurrence or variables' sources (Adelabu et al., 2020). Both geographic information systems (GIS) and remote sensing have demonstrated their key function integrating dissimilar data to accomplish precise fire risk indexes. Mapping burnt areas is one of the most effective applications of satellite remote sensing at regional scales despite of its inherent limitations such as spatial resolution, the return rate, and atmospheric obstructions (Leblon et al., 2016; Cardil et al., 2021). Nonetheless at local scales, it is better to obtain information through ground-based cameras or drones (Sayad et al., 2019). The GIS application on wildfire processes and the creation of fire risk indexes have proved successful worldwide and will remain fundamental tools for decision makers in the future (Weber and Yadav, 2020; Santos et al., 2021).

We studied the TDF of the Guanacaste Conservation Area (GCA) at northern Costa Rica. The TDF of GCA comprises less than 1% of the TDF that once extended from Mexico to Panama, and the conservation process has taken decades to recover the actual ecosystem (Khatun et al., 2013; Corrales et al., 2015; Janzen and Hallwachs, 2016). In GCA, there is a variety of vegetation such as coastal, riparian and evergreen forests. Most of them have been transformed, destroyed, and homogenized because of the logging, burning, pasture sowing, and farming activities (Janzen, 1986). Despite the large number of studies in TDF at GCA, especially about their ecological (Sanchez-Azofeifa et al., 2014), land use (Gotlieb and Girón, 2020), climatological (Hidalgo et al., 2019; Quesada-Hernandez et al., 2019), and soil characteristics (Leiva et al., 2009), there is a clear absence of research relating the wildfires occurrence with their implicit topographic conditions. Using the most suitable available historical geospatial inventory of burned areas at GCA, we hypothesize that certain topographic parameters control the occurrence of wildfires in TDF. Our objective is to disentangle the land surface variables dominating the wildfires occurrence in northern Costa Rica using a Generalized Linear Model integrating nine topographic parameters. Moreover, we consider that a statistical model including several topographic parameters controlling areas where wildfires occur regularly is a useful approach to be implemented in the tropical forests affected by continuous wildfires, which represent a growing issue due to land use and global changes.

2. Methods

2.1. Geographical setting

The GCA is geologically settled in the Santa Rosa Ignimbrite Plateau, which is the product of the subduction of plates between Cocos and Caribe. Its subsequent volcanism of cones such as Rincón de la Vieja and Orosí have developed violent eruptions including pyroclastic flows with cemented lithological products such as ignimbrites as well as calmer eruptions with the deposition of lava or ash flows along the channels and plains that face the Pacific Ocean (Alvarado, 2021).

These landscapes are made up of mountain ranges and soils that are weathered with the existence of shallow profiles but with conspicuous horizons (Leiva et al., 2009). The variation between the Guanacaste Volcanic Mountain Range, with the presence of different volcanic cones of great volume such as the Rincón de la Vieja to the NE of Liberia and the Orosí located even further to the NE, represent a transition that extends into the volcanic foothills. Compounds of cemented pyroclastic materials and, in turn, highly weathered by the climatic influence of high temperatures and moderate rainfall do not allow the development of deep soil profiles but rather remain in the order of entisols and inceptisols given their recent evolution within the pedogenetic process. Besides the volcanic foothills of the volcanic complexes, a series of hills and low mountains of tectonic origin alternate as a result of the folding of the oldest geological structures in the country (140 Ma) as well as the valleys of several rivers and streams that flow into the ocean, various

coastal plains and beaches (Vargas-Sanabria and Quesada-Román, 2018).

The CGA presents an approximate annual precipitation between 900 and 2400 mm, the dry season extends from December to April with less than 20 mm monthly during this period, over 26 °C to 38 °C during the day and 16° and 23 °C at night (IMN, 2008; Calvo-Alvarado et al., 2018). The area has all the kinds of dry forest that can be found in Central America with a great variety of coastal vegetation, riverbanks, and evergreen forests; however, some habitats have been transformed and destroyed due to logging, burning, sowing pastures, and agricultural activities (Janzen and Hallwachs, 2016).

2.2. Wildfires database

We obtained the location and burned area caused by wildfires in GCA from 1997 to 2020 from the Fire Management Program (FMP) of the GCA. The database was generated through fieldwork after the fire was extinguished. The staff of FMP design a route to delimit the burned area using a GPS device. We transformed every delimited shapefile into raster format with a pixel value of 141 × 141 m. This size was chosen to depict the whole study area instead of using broad polygons. Subsequently, all raster inputs were summarized using the Cell Statistic Tool of ArcGIS 10.5. From the overlapping of areas, we obtained 14 categories of wildfires occurrence, which were divided in three categories and frequencies using a Jenks natural breaks classification method (Jenks, 1967): very low (1 fire), low (2–4 fires), and medium to high (5–14 fires). Using this mesh, we also estimated the centroid for each of the total 8120 pixels.

2.3. Geomorphometric indexes and statistical analysis

We used a digital elevation model (DEM) based on a Geographic Information System (ArcGIS 10.5) to calculate the morphometric indexes (topographic parameters) using 10-m contour lines supplied by CARTA (2005) with the analog camera RC-30. We used SAGA (Conrad et al., 2015) to determine and extract (using the aforementioned centroids) the mean value of nine topographic parameters (TP). From every centroid we extract Aspect (ASP), Flow Accumulation (FLO), L-S Factor (LSF), Slope (SLP), Terrain Ruggedness Index (TRI; (Riley et al., 1999)), Topographic Wetness Index (TWI), Wind Effect (WEF), Wind Exposition (WEP; (Boehner and Antonic, 2009)), and Analytical Hillshading (ANH; (Tarini et al., 2006)). Moreover, we employed a Pearson correlation equation (Vinod, 2017), and completed a generalized linear model (GLM) to statistically explain significant relationships among wildfires occurrence (N) with TP. Using an Akaike Information Criterion (AIC; (Anderson and Burnham, 2004)), we made a backward selection to compare the null hypothesis (i.e., $N \sim 1$), against the full ($\tilde{N}$ ASP + FLO + LSF + SLP + TRI + TWI + WEF + WEP + ANH) and the alternative model ($\tilde{N}$ ASP + WEP). All of the co-variables were standardized employing a z-score. The model parameters were used to assess the weight of each TP interaction describing the wildfires occurrence in GCA between 1997 and 2020.

3. Results

3.1. Wildfire's occurrence

The analysis of burned areas shows the spatial distribution of the wildfires' occurrence during 23 years (Fig. 2) (see Fig. 1). Overall, many areas have presented at least one fire located throughout the whole study area; most of them are located in higher altitudes (over 300–500 m a.s.l.) with limited road access whereas the areas with 2–4 fires (low frequency) are more common in flat terrains in the northern and western borders of the protected area. They are located next to main towns such as Quajiniquil, Soley, and Colonia Bolaños with road access among paths and the Interamerican Highway. The areas that are affected with 5–14

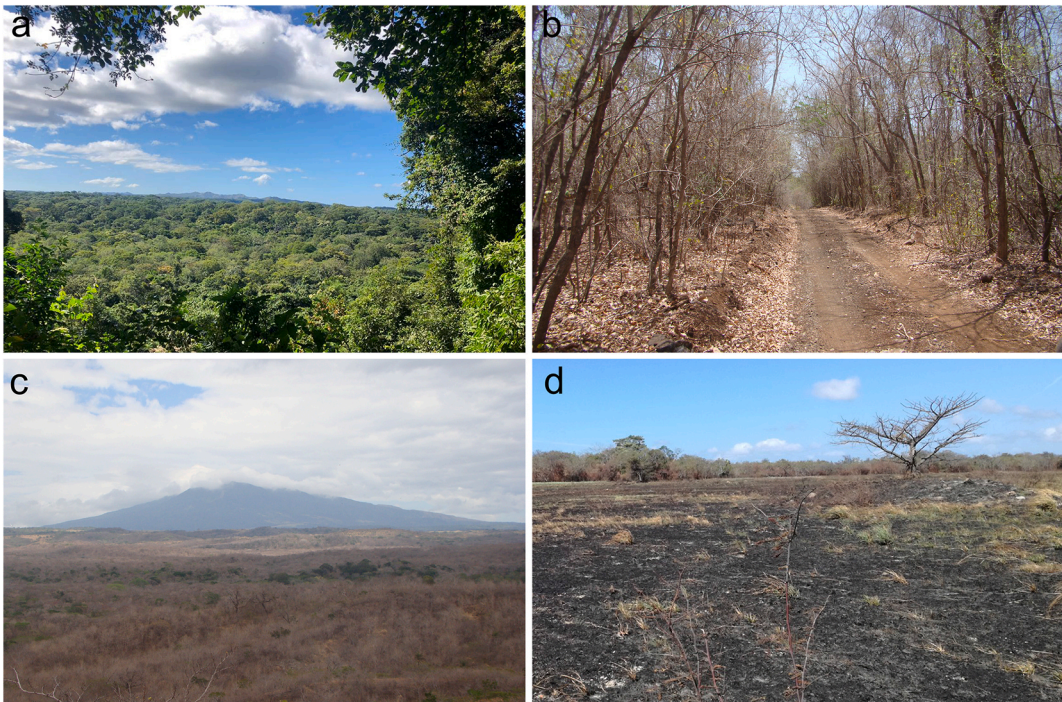


Fig. 1. (a) Dense TDF in Guanacaste during the rainy season (courtesy of Noelia Molina Montero). (b) Dense TDF in Guanacaste during dry season. (c) Orosí and Cacao volcanoes at the bottom, its piedmont, and the dense TDF coverage. (d) Wildfires inside the ACG during the dry season along flatlands.

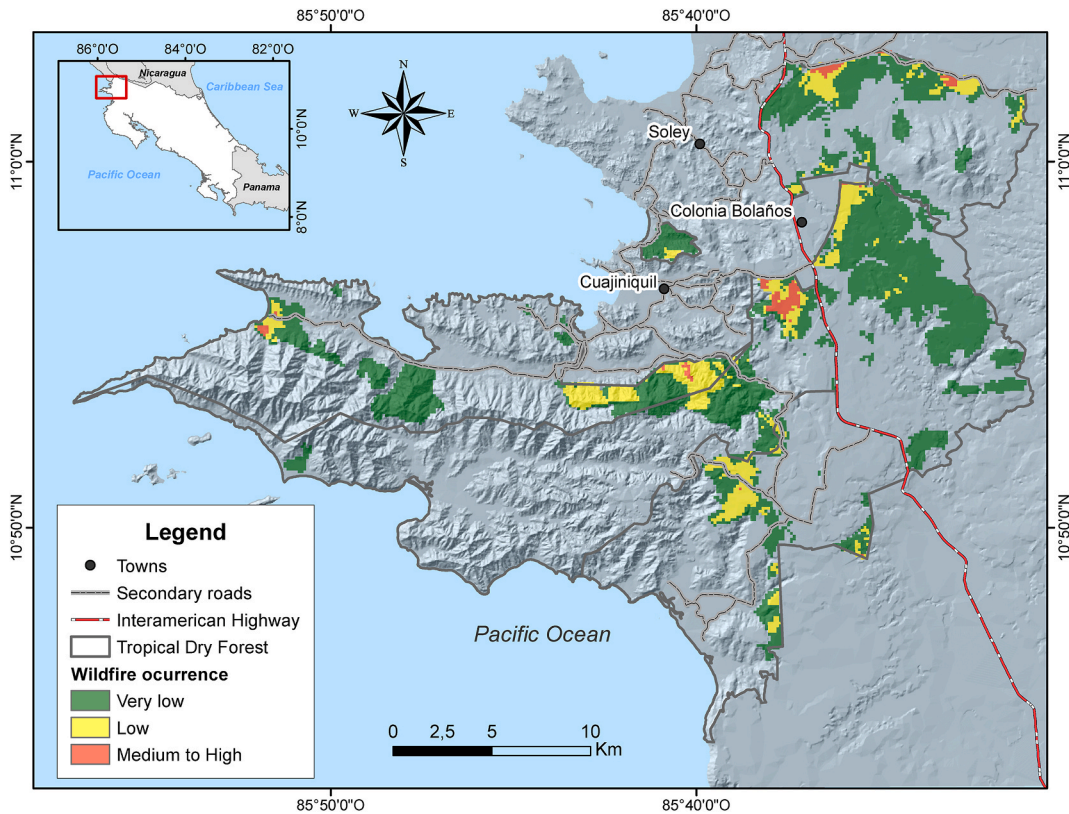


Fig. 2. Wildfires occurrence at GCA between 1997 and 2020.

fires (medium to high frequency), have access by public roads. They are more exposed to human intervention because of the low elevations (see [Table 1](#)).

3.2. Geomorphometric statistical analysis

The statistical analysis of the wildfires occurrence with TP centered on the AIC criterion validates the null model (AIC = 28,082.41) versus

the alternative model (AIC = 27,996.28). Moreover, the model indicates that the generalized linear model strengthens an interaction among Aspect and Wind Exposition ($\tilde{N} \text{ ASP} + \text{WEP}$). Table 2 indicates that the higher effect on onset likelihood of wildfires occurrence is given by Aspect and Wind Exposition as demonstrated by z-ratio tests of parameter estimations.

The predominant TP corresponding to the GLM that shows remarkable associations were Aspect and Wind Exposition. Main reported aspects were Flat areas (26.8%), in second order West (20.7%), and in third order North (17.9%), East (17.7%), and South (16.9%; Fig. 3a). Wind Exposition values vary as an index from 0.8 to 1.3, with a clear dominance between 0.95 and 1.15, and a mean of 1.035 (Fig. 3b). Once Aspect and Wind Exposition are correlated among them, interesting results emerge (Fig. 4). The density ridgeline plot demonstrates the distribution of a Wind Exposition Index for several Aspects. Distribution is represented using density plots aligned to the identical horizontal scale and shown with a slight overlap. Higher wind exposition densities (~ 1.1) are located in slopes heading to the east (where annual predominant wind directions come from), south, and flat terrains. Afterwards, north and west headings densities are oftentimes located in the peak of 1.05 wind exposition of index value.

4. Discussion

We discovered that Aspect and Wind Exposition were the topographic parameters that better explain the wildfires at GCA. These conditions are likely to be similar in other TDF environments where the application of this geomorphometric model can be implemented. Matching with our geomorphometric model, Vargas-Sanabria and Quesada-Román (2018) found that gentle slopes and flat surfaces relate more to a model of vulnerability to forest fires that included socioeconomic and ecological components. Moreover, Campos-Vargas and Vargas-Sanabria (2021) disclosed that fire occurrence at the GCA is mainly defined by the extent of early successional forest stages in flat or gentle slope terrains that are accessible to people through trails and roads. Similarly, the study showed that burned areas are positively related to the presence of early successional stages, accessibility, and

Table 1

Description of topographic parameters used as independent explanatory variables for modelling.

Topographic parameter	Description	Source
Aspect (ASP)	Compass direction in degrees or cardinal points	Conrad et al. (2015)
Flow Accumulation (FLO)	Accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster (units: 1–100)	Conrad et al. (2015)
L-S Factor (LSF)	Slope length (LS) factor based on slope and specific catchment area (units: 0–100)	Conrad et al. (2015)
Slope (SLP)	It is the angle of incline, expressed in degrees (0–90) or percentage	Conrad et al. (2015)
Terrain Ruggedness Index (TRI)	The amount of elevation difference between adjacent cells of a DEM (units: 0–1)	Riley et al. (1999)
Topographic Wetness Index (TWI)	It is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction (units: 0–1)	Boehner and Antonic (2009)
Wind Effect (WEF)	Values < 1 designates wind-shadowed areas, values > 1 indicates areas exposed to wind.	Conrad et al. (2015)
Wind Exposition (WEP)	Values < 1 indicates sheltered areas, while values > 1 designates areas exposed to wind.	Conrad et al. (2015)
Analytical Hillshading (ANH)	It simulates the effect of natural light on earth's surface (units: 0–90)	Tarini et al. (2006)

Table 2

Parameters used to model wildfires occurrence. Note: Null deviance is 15,095 on 8119° df, residual deviance is 14,929 on 8117° df, and the AIC is 27,996.28. 2 Fisher Scoring iterations. $\text{Pr}(> |z|)$ is the likelihood of obtaining the detected z-ratio in the normal distribution of z with a critical point of $|z|$. ***P = 0.

Model terms	Estimate	Std. Error	t value	$\text{Pr}(> t)$
(Intercept)	−0.096	0.208	−0.464	0.643
ASP	0.0367	0.008	4.196	2.74E-05 ***
WEP	1.737	0.194	8.938	<2e-16 ***

low landscape slope. Indeed, Falk et al. (2011) pointed out that fire frequency fluctuated with aspect at drier and lower but not at upper elevations.

In general, fires in Central America are related to human activities (Middleton et al., 1997) such as land clearing for agriculture, poaching, arson, and transition from forest to pastures (Koonce and González-Caban, 1992; Otterstrom et al., 2006; FAO, 2007). In addition, Gotlieb and Girón (2020) mentioned that those factors are driving the land cover changes in The Central American Dry Corridor (CADC). According to FAO (2007), global climate change and the local phenomena, El Niño, induce drought conditions that increase fire risk, and it affects sensitive ecosystems such as TDF. Otterstrom et al. (2006) found that fires in CADC are widely distributed with negative effects over the conservation of TDF.

Generally, the occurrence and behavior of fires are closely linked to the influence of vegetation type, fuel availability, and weather patterns (Moreira et al., 2009). However, topography is one of the main factors, which should be included in any fire analysis because of the way the elevation, aspect, and slope affect the behavior and geographic distribution of fire (Chuvieco and Congalton, 1989). Simental-Ávila and Pompa-García (2016) establish that topography exposition influences the vegetation due to the alteration and the effect of weather, solar radiation of the fuel and soils. Additionally, Wong and Villers (2007) suggested that slope aspect sometimes could generate changes in the amount of humidity of fuels and facilitate the spread of fires. Our results showed that flat terrains are more exposed to fire where fuels are related to pastures while forests at high elevations are not (Vargas-Sanabria and Campos-Vargas, 2020). In relation to this, Chuvieco and Congalton (1989) explained that aspect and exposure influence the fuel drying and spread of the fire, and the trend is to be less severe at higher elevations.

Falk et al. (2011) mentioned that the types of vegetation and the solar insolation are controlled by aspect and elevation as well as the fuel moisture levels and the phase when fuels are sufficiently dry to burn, which in our case responds to the dry season from December to May (Janzen and Hallwachs, 2016). Likewise, Pérez-Verdín et al. (2013) identified that topography plays a key role in fire distribution more related to the strategies of control and firefighting. The more affected areas are geographically located closer to roads and towns, and the attendance for an event should be faster than those farther areas without access.

Numerous research have pinpointed that topography control wildfires occurrence (e.g., aspect, elevation, and slope; Carmo et al., 2011; Lee et al., 2014; Martínez-Fernández et al., 2013; Oliveira et al., 2014; Satir et al., 2016; Viedma et al., 2009). Aspect demonstrated a positive correlation with the quantity of solar energy received as a forest fire conditioning factor and higher forest fire susceptibility in Vietnam (Tehrany et al., 2019). Moreover, drought effects were more severe on specific aspects and second-growth forests in Puerto Rico (Schwartz et al., 2019). Concomitantly to our results, very elongated (non-circular) fires normally tend to be bigger, indicating strong wind-topography connections rising wildfire sizes (Barros et al., 2012, 2013, 2014; Mansuy et al., 2014).

The study of topographic parameters which control wildfires on TDF are key to keep the edaphic, hydrological, climatic, and air quality controlling services that these ecosystems provide. Due to their benefits,

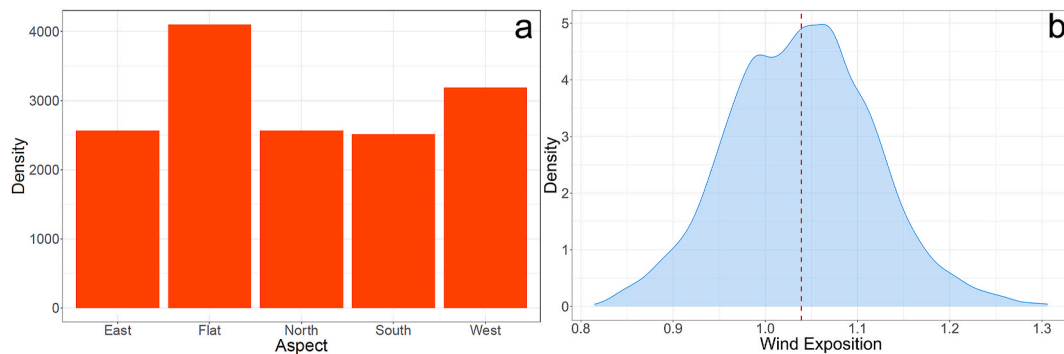


Fig. 3. (a) Density of the different preferential cardinal points (Aspect) and (b) Wind Exposition in the different pixels of wildfires at GCA.

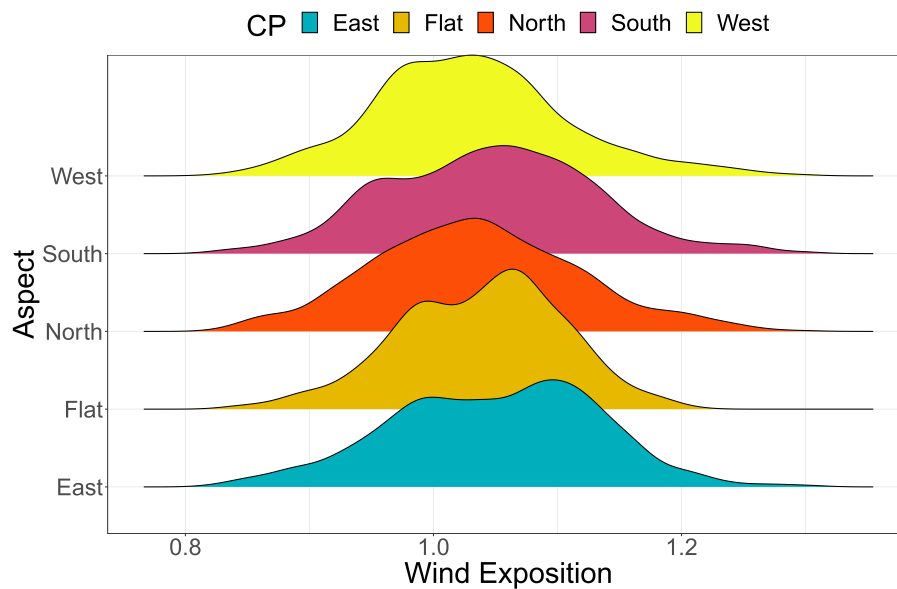


Fig. 4. Density ridgeline plot of the occurrence of wildfires according to the different main aspect orientations (CP – cardinal points) and wind exposition at GCA.

TDF must be preserved by governmental and non-governmental institutions along low latitudes (Portillo-Quintero et al., 2015). Further and accurate knowledge of worldwide TDF is vital to acknowledge forest cover dynamics, biodiversity perils, and the conservation condition of this endangered ecosystem. Recognizing the distribution, geomorphic dynamics, as well as the extent of TDF is key for forthcoming investigation on climate change impacts, land use change, and potential TDF conservation strategies (Ocón et al., 2021).

5. Conclusions

We performed a geomorphometric model to determine topographic parameters controlling wildfires occurrence in TDF in northern Costa Rica as a study case. We observed that Aspect and Wind Exposition were the most appropriate topographic parameters explaining the wildfires occurrence at GCA. These conditions are similar in other tropical and non-TDF environments where the application of this geomorphometric model can be implemented. Nonetheless, in other geomorphological and climatological contexts, other geomorphometric variables can have larger statistical relationships with wildfires' occurrence. Understanding these circumstances and their geomorphologically associated factors are key to design management and fire control strategies in dry environments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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