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Modeling daily natural-caused ignition probability in the Iberian Peninsula

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Abstract

In the European Mediterranean region natural-caused wildfires are a small fraction of total ignitions. Lightning strikes are the most common source of non-human fires, being strongly tied to specific synoptic conditions and patterns associated with atmospheric instability, such as dry thunderstorms. Likewise, lightning-related ignitions often associate with dry fuels and dense vegetation layers. In the case of Iberian Peninsula, the confluence of these factors favors recurrent lightning fires in the eastern Mediterranean mountain ranges, the western region of "El Bierzo" and central Portugal. However, under appropriate conditions lightning fires can start elsewhere, holding the potential to propagate over vast distances.

In this work, we assessed the likelihood of ignition leveraging a large dataset of lightning strikes and historical fires available in Spain. We trained and tested a machine learning model to evaluate the probability of ignition provided that a lightning strikes the ground. Our model was calibrated in the period 2009-2015 using data for mainland Spain plus the Balearic Islands. To build the binary response variable we classified lightning strikes between that triggered a fire event. For each lightning strike we extracted a set of covariates relating fuel moisture conditions, the presence and density of the vegetation layer and the shape of the relief.

The final model was subsequently applied to forecast daily probabilities at 1x1 km resolution for the entire Iberian Peninsula. Although the model was originally calibrated in Spain, we extended the predictions to the entire Iberian Peninsula. By doing so we were able to validate in the future our outputs against the Portuguese dataset of recent natural-caused fires (bigger than 1 ha) from 2001 to 2021. Overall, the model attained a great predictive performance with a median AUC of 0.82. Natural-caused ignitions triggered mainly in low dead (dFMC <8%) and moderate alive (DC > 250) fuel moisture conditions. Lightning strikes with negative polarity seem to trigger fires more frequently when the mean density of discharger was greater than 5. Finally, natural wildfires usually started at higher elevations (above 500 m.a.s.l.).

1. Introduction

In Europe, natural-caused fires represent a small percentage of the total number of fires. In contrast to anthropogenic fires, which are arranged in a spatial pattern close to the human footprint, the spatial location of natural fires is often clustered in specific hot spots of intense lightning occurrence and fuel availability. Recent studies warn of the likely increase in fire frequency and size linked to climate warming and global change. Most climate predictions envisage a decrease in fuel moisture content while fuel accumulation due to land abandonment is creating the perfect conditions for larger and more extreme fires. Although further research is needed, there is already evidence of an increase in the occurrence of natural fires related to the increased frequency of dry storms and heat waves (Li et al. 2020; Coogan et al. 2020). Lightning fires start more frequently in distant and remote regions, which pose an additional layer of difficulty to suppression, potentially growing into large fire events when fuel and relief conditions facilitate fire spread.

The Iberian Peninsula is one of the main hotspots of forest fire activity in Europe and the western Mediterranean basin. Numerous studies have focused on addressing the probability of fires caused by lightning, by man or by both. Understanding the linkages and feedbacks between environmental and atmospheric conditions that ultimately relate to lightning-caused fires is relevant. Most studies dealing with natural fires are based on historical compilations of natural fires coupled to environmental and climatic variables (Rodríguez-Pérez et al. 2020) or on meteorological data to determine the atmospheric conditions conducive to lightning fires (Soler et al. 2021; Pérez-Invernón et al. 2021; Pineda et al. 2022). Other works, like the one by Couto et al. (2020), investigated the interactions between atmospheric models and the rate of spread of wildfires. However, there is still a lack of homogeneity in the methods, variables, and protocols to predict, and therefore anticipate, the occurrence of natural wildfires. We advocate an approach that decouples the conditions that favor lightning strikes from the environments that favor ignition.

The present work is developed within the framework of the H2020 project FireEUrisk, aimed at understanding, modeling, and predicting fire risk conditions by addressing the main risk components (hazard, exposure, and vulnerability) and mitigation steps (prevention, planning and adaptation) at the European scale. The main objective of this work is to predict the probability of ignition of natural forest fires using lightning records in the period 2009-2015. For this purpose, we analyzed a large lightning strike dataset (more than 17 million) to ascertain the conditions under which a lightning strike will trigger an ignition, i.e., the probability of ignition conditional on the occurrence of the lightning strike itself. The model was initially trained and validated using data covering all peninsular Spain plus the Balearic Islands, subsequently investigating its ability to predict ignitions in Portugal. Several variables related to fuel moisture content and vegetation structure, topography, as well as some factors related to polarity, intensity and density of impacts were used. The methodology is based on Random Forest modeling and other related techniques to assess the accuracy of the probability obtained. In this way, a daily and high-resolution lightning ignition prediction for the whole Iberian Peninsula has been elaborated.

2. Material and methods

The study area encompasses the whole Iberian Peninsula, i.e., mainland Spain and Portugal plus the Balearic Islands, covering a surface circa 588,000 km2 (Figure 1).

Figure 1- Digital elevation model and rivers network of mainland Spain plus Balearic Islands and Portugal.

2.1. Dependent variable: lightning strikes and fire ignitions

The core of our approach leverages a large and comprehensive dataset of cloud-to-ground lightning strikes recorded in the period 2009-2015. The dataset was provided by Meteogrid S.L.. It consists of more than 17 mill records reporting the intensity (and polarity) and density of flashes. Information about fire ignitions (location, date, cause, and size) was retrieved from the Spanish (EGIF) and Portuguese (DECIF) databases. The Spanish dataset was used to identify those lightning strikes that started a fire while the Portuguese records were retained to evaluate the applicability of the model to the specific conditions of Portugal.

The response variable was extracted from ignitions in Spain consisted in 11,000 fires. Approximately 2,500 fires were matched to a lightnings strike (i.e., occurring within 1,000 meters and no more than 3 days holdover period respect to the ignition date). Upon this information we built a binary response variable combining lightnings that triggered a fire (1 or presence) with lightning not related to a fire (0 or absence). We implemented a stratified sampling procedure to prevent undesired effects from the largely unbalanced response (more 0 than 1) and minimize spatial autocorrelation.

2.2. Independent variables

To predict the probability of fires, we employed 7 factors related to vegetation state, topography and others directly linked to sparks' discharges (Figure 2). Firstly, we retrieved both the daily dead fuel (FM; calculated as described in Resco de Dios et al. (2015) and live fuel moisture content (using the Drought Code -DC- as proxy) at 11 km of spatial resolution. Secondly, elevation (*elev*) and relief curvature (*curvG*) were selected to depict the influence exerted by the terrain in the ignition of natural-cause fires. In turn, we included the vegetation height (hveg) as a proxy of the vegetation structure. The model also accounts for lightning-related features, such as strike intensity (mxi) and density (nse). To perform model predictions the latter two were set as constant figures equal to their average value over the study area (-10 of intensity and 5 discharges, respectively). All variables (aside FM and DC) were retrieved at 30x30 meters of resolution and later resampled at 1x1 km.

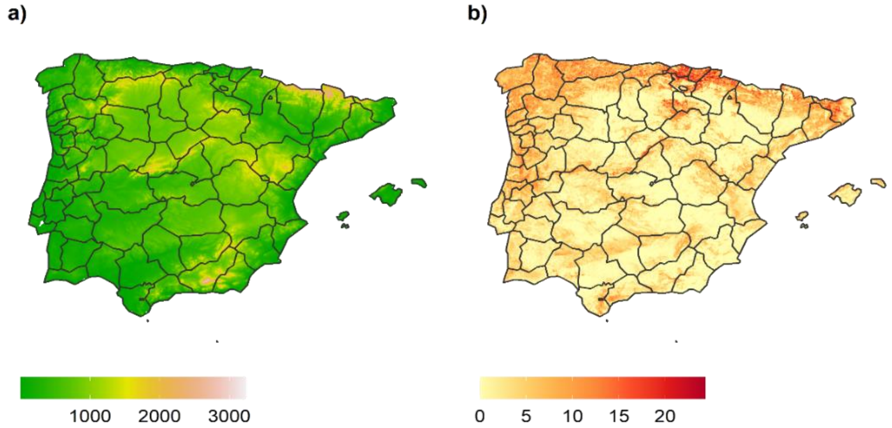

Figure 2- A) Digital elevation model (meters) and, B) height of vegetation (meters) in mainland Spain plus Balearic Islands and Portugal.

2.3. Model calibration with random forest

The model was trained using the random forest algorithm (Breiman 2001). We trained a total of 100 models exploring different realizations of the response variable. For each realization we extracted a balanced sample of 1-presence (flashes igniting a fire) and 0-absence (lightnings non-conducive to fire). The process was stratified using a 100x100 km grid so that at each grid cell we extracted an even sample of 1-presence and 0-absence. In turn, the absence observation pool included the same number of records in days experiencing fires and days not experiencing a fire. It must be noted that we only analyzed the April-to-October period, since natural fires seldom occur outside that season.

Model calibration was conducted using the caret package (Kuhn 2008) in the R environment for statistical computing (R Core Team, 2021). For each model realization we implemented a 5-fold repeated (3 repetitions) cross-validation, optimizing model parameters: number of trees (ntree) and number of variables to use at each split (mtry). We evaluated the importance of each co-variate using the Mean Decrease in the Gini index and the overall performance of each model via AUC. Out of the set of 100 models we selected the one attaining the average prediction performance (AUC=0.828) as candidate model to forecast and map the daily evolution of lightning-related ignition probability. The model was subsequently evaluated calculating the AUC from the Portuguese fire data, which consisted in 105 lightning fires (>1ha) in the period 2009-2015.

3. Results

In general terms, the Random Forest models attained a high AUC value (average AUC=0.828; Figure 3). The most relevant factor was fuel moisture content (DC and FM), followed by elevation, density of strikes, relief curvature, intensity/polarity and vegetation height. The response to fuel moisture content was the most remarkable linkage found (Figure 4). In the case of DC (i.e., live fuel moisture content), the response curve showed an increase in ignition likelihood peaking around the 300 mark, remaining constant afterwards. In turn, dead fuel moisture content (FM) related to higher ignition likelihood below 10% moisture content. Likewise, probability peaked at above 20 of strikes density up yo 1,500 m.a.s.l. According to the spatial distribution of daily natural-caused probability, the highest values were often in the inner mountain ranges of the Iberian Peninsula, especially in the south-eastern half (see Figure 5). Locally, the likelihood of lightning fires is more common in the forested areas of medium elevations, thus usually excluding the lowest and altitudes but also the agricultural areas.

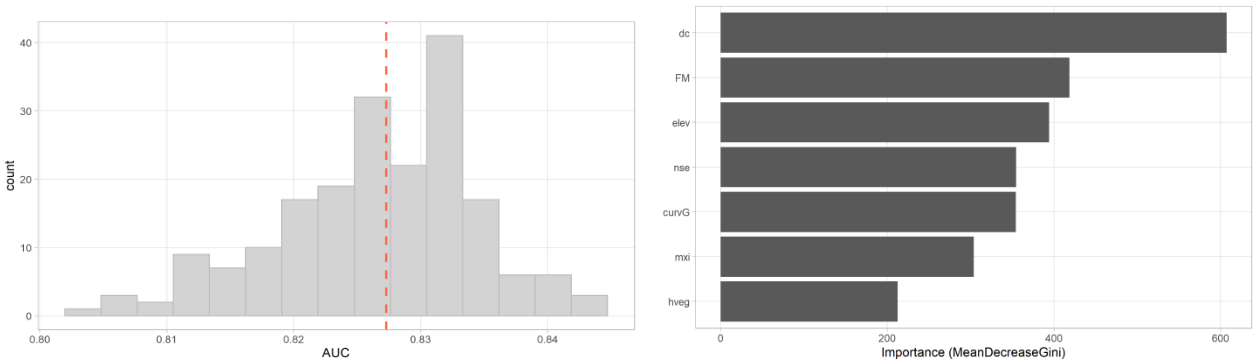

Figure 3- Model accuracy according to Area Under the Curve (left) and Random Forest variable importance (right).

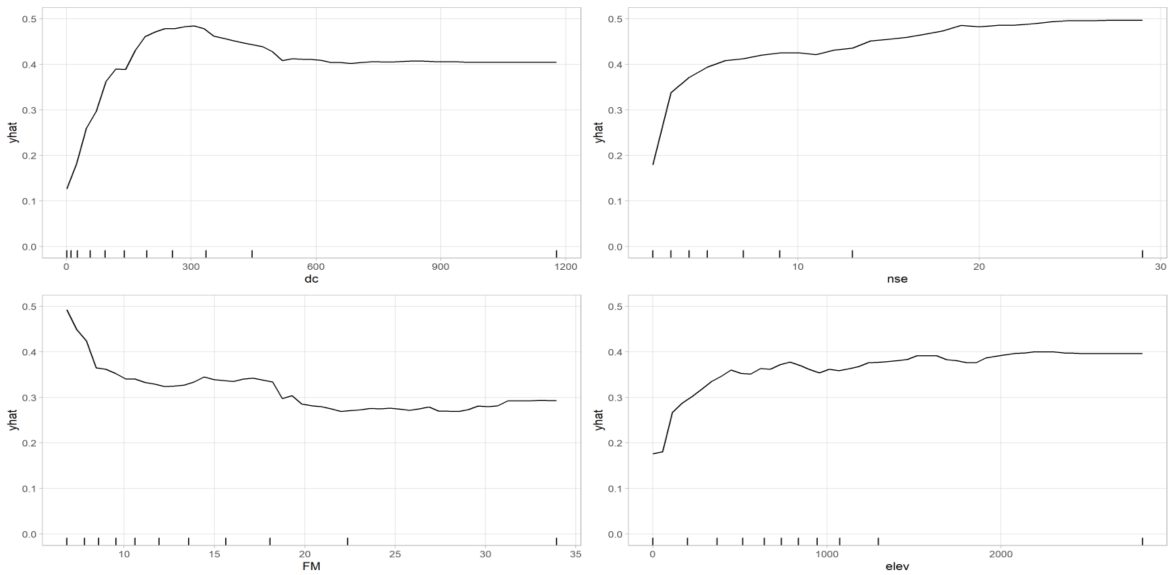

Figure 4- Partial effects plots for the most important variables included in the Random Forest model built to predict the natural-caused probability.

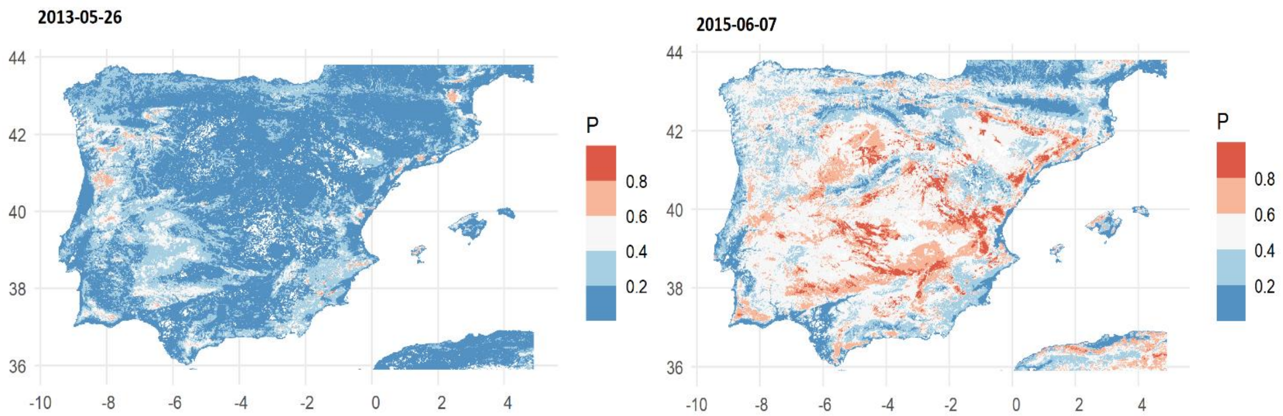

Figure 5- Daily lightning wildfire predictions examples for four specific days in the Iberian Peninsula and Balearic Islands.

4. Discussion

In this work we produced a daily forecast of natural-caused wildfire ignition probability over the whole Iberian Peninsula plus the Balearic Islands. We followed a novel method based mainly on lightning strikes, opposite to fire-based approaches. The model holds a good predictive accuracy (around 0.82 AUC), which is noteworthy given the rare nature of thunderstorm-driven fires (Fernandes et al., 2021). In turn, the future calibration of our fitted model in Portugal shows the feasibility of extending the model to regions like Spain. The observed relationships between ignition drivers and predicted likelihood are in line with the expected behavior, i.e., fuel moisture as the most influential factor modulating ignition followed by topography. The important role of the moisture of the live/dead fuels causing the ignition and propagation of new fire events have been documented in many works previously (Baranovskiy & Kirienko, 2022; Resco de Dios et al., 2021, 2022; Rodrigues et al., 2021). However, our findings were non-conclusive in terms of the role of the characteristics of the fire-prone flash. We did not find a strong signal in terms of intensity nor polarity, though an increased density of strikes did increase the chance of ignition.

In terms of risk assessment, we believe that the strategy of breaking down ignition likelihood and the probability of lightning occurrence offers several advantages. Decoupling both phenomena allow us to better understand their relative importance while enabling embedding different models for lightning or thunderstorm forecast, or even real observations of lightning flashes. That is particularly important for short-term predictions. In turn, long-term modeling would also benefit for such approach. Our ignition forecast requires few weather-related factors (the same necessary for the calculation of the FWI), thus their prediction under climate scenarios (SSP or RCP) is already feasible. In the same line, several models are available to forecast lightning strikes (Woodard et al., 2014), hence, being possible to combine them with the ignition component. Our next steps include extending the temporal span of calibration and, more important, modeling the phenomena in other locations, preferably in northern latitudes. Furthermore, we need to investigate the performance of the model outside the calibration time frame, both forward and backward in time.

5. Conclusions

In this work we produced a daily forecast of the probability of natural wildfires in the Iberian Peninsula and the Balearic Islands. We combined lightning and wildfire data with environmental variables to train and test a binary Random Forest model. Our results revealed the major role played by fuel moisture content, the most sensitive factor to climate warming in the coming decades. This highlights the need for further research and consideration of natural ignitions in hazard mitigation plans, even though their contribution to fire activity is currently moderate.

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