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Drivers and Trends in the Size and Severity of Forest Fires Endangering WUI Areas: A Regional Case Study

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Abstract: This study explored, for the first time, the drivers shaping large fire size and high severity of forest fires classified as level-2 in Spain, which pose a great danger to the wildland–urban interface. Specifically, we examined how bottom-up (fuel type and topography) and top-down (fire weather) controls shaped level-2 fire behavior through a Random Forest classifier at the regional scale in Galicia (NW Spain). We selected for this purpose 93 level-2 forest fires. The accuracy of the RF fire size and severity classifications was remarkably high (>80%). Fire weather overwhelmed bottom-up controls in controlling the fire size of level-2 forest fires. The likelihood of large level-2 forest fires increased sharply with the fire weather index, but plateaued at values above 40. Fire size strongly responded to minimum relative humidity at values below 30%. The most important variables explaining fire severity in level-2 forest fires were the same as in the fire size, as well as the pre-fire shrubland fraction. The high-fire-severity likelihood of level-2 forest fires increased exponentially for shrubland fractions in the landscape above 50%. Our results suggest that level-2 forest fires will pose an increasing danger to people and their property under predicted scenarios of extreme weather conditions.

Keywords: fire severity; fire weather; level-2 forest fires; Spain

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1. Introduction

In the 21st century, extreme forest fire events have become a major global concern because of their significant ecological and socioeconomic impacts [1–3]. Fire-prone forest ecosystems in the western Mediterranean Basin have shown a high resilience to fire under natural fire disturbance regimes [4]. However, changes in land use in recent years [5,6] involving the abandonment of rural agricultural lands [7] because of countryside depopulation [8], mainly in mountainous areas [9], have caused fuel to accumulate and form seamless stands in areas with former lower fuel loads [10]. These dynamics increased fire hazards and thus ignition probability and resistance to fire control, particularly near the wildland–urban interface (WUI) [11–14].

Increasingly extreme weather conditions as a consequence of anthropic climate change, involving prolonged heat waves and droughts [15], dries the large fuel accumulations ensuing from land use changes, thus favoring extreme fire behavior and severe ecological impacts [16,17]. Many of these extreme forest fires occur in areas under some environmental protection status [18–20], in which the lack of fuel management exacerbates the problem. These disturbances not only entail serious consequences to ecosystems, including severe vegetation and soil damage [21,22] and water system disturbance [23,24], but also to human life and assets [25–27]. In the Mediterranean Basin, where the WUI area has increased [28], extreme forest fires, such as those that occurred in Portugal in 2017, in Greece in 2018 or in Spain in 2021 and 2022, have seriously endangered inhabitants and caused unusual fatalities [29–31].

Although in some European regions there is a high incidence of lightning-caused forest fires [32,33], ignitions in Spain (western Europe) mainly depend on anthropic causes, either due to accidents, negligence or arson [34,35]. Both the number of forest fires and the burned area have decreased in Spain in recent decades [36]. However, the Autonomous Community of Galicia, located in northwestern Spain, accounts for most of the forest fires in the country in recent decades [37]. Indeed, Galicia, together with Portugal, is the most fire-prone region in Europe [38].

Fire size and severity are two essential attributes for land managers because of their connection to ecosystem responses in the context of extreme forest fire events [39–41]. The interaction between bottom-up (fuel and topography) and top-down (fire weather) variables can exert strong control over the attributes of the fire regime [42–44], but these interactions may be highly variable between different biophysical contexts [39,45]. Topography configuration can determine not only the spread rate and severity of the fire [46–48], but also the dominant vegetation types over the landscape and the vegetation condition [49,50]. Both the fuel type and load can constrain or promote fire size [51,52], and, jointly with fuel moisture, fireline intensity and thus fire severity [51,53]. Fire weather variables that are highly variable over time, such as relative air humidity, wind, temperature and precipitation, are of great importance in determining fuel moisture content and fuel availability to burn [54–57], and thus in shaping fire spread and intensity [53,58]. Remarkably, increasingly long drought periods in the context of climate change de-seasonalize and lengthen periods of increased fire risk [59,60]. Although the drivers of fire behavior and fire regime attributes are generally well-investigated, the understanding of fire behavior drivers that endanger populations is limited at present in southern Europe, particularly so in Galicia, the case-study territory of this paper. Therefore, new frameworks must be developed to better understand fire behavior in the WUIs of this fire-prone region.

Fire disturbance promotes high fuel connectedness and landscape homogeneity in the productive environments of the western Mediterranean Basin, with rapid post-fire build-up [10,61], as in Galicia, which in turn favors fire spread and intensity of subsequent forest fires [62–64]. In this context, reduced landscape heterogeneity as a consequence of the discontinuation in extensive agricultural practices and the use of forest ecosystems as a resource near rural settlements have promoted, in recent decades, an elevated forest fire incidence in WUI areas [65,66]. This is particularly relevant in Galicia, where 8% of the surface is occupied by the WUI [67], and accounts for up to 50% of Spain's total small villages, according to the national statistics institute (INE, https://www.ine.es/nomen2/index.do (accessed on 25 September 2023)). In the western Mediterranean Basin, another factor driving forest fire vulnerability in WUI areas is the increased urban sprawl in the wildland environment [68,69]. Altogether, the understanding of the factors driving extreme fire behavior in the context of forest fires that seriously endanger human settlements is of utmost importance to design adequate management plans and strategies aimed at reducing forest fire hazard [70,71]. In Spain, including Galicia, forest fires are classified according to their risk to populations. Accordingly, forest fires are classified as level-2 when they seriously endanger human settlements and properties [72,73].

Accordingly, this study explored for the first time the drivers shaping extreme fire behavior in level-2 forest fires in Galicia. Specifically, we examined the temporal trends in fire regime attributes of level-2 forest fires, and how fuel type, topography and fire weather shaped individual level-2 fire size and severity. We selected for this purpose level-2 forest fires that occurred in Galicia during the period 2015–2022.

2. Material and Methods

2.1. Study Area

The Autonomous Community of Galicia is located in the northwestern region of the Iberian Peninsula, bordering the north of Portugal (Figure 1). It has an extension of 29,575 km^2 and a population of 2,690,464 inhabitants in 2022, being the fifth largest Autonomous Community in population and the seventh largest in terms of size. The climate is mostly temperate oceanic in north and west Galicia regions, whereas the dominant climate in the east and southeast is Mediterranean [74]. The mean annual precipitation and annual temperature range from 600 to 2600 mm and 6 to 15 °C, respectively [75]. In the last 10 years, the mean temperature in Galicia has always been above the average value for the period 1981–2010, whereas the precipitation has been below the average value in six of the last ten years [76]. Elevation ranges from sea level in the western and northern coast of the region to about 2100 m in the mountain range located in the easternmost region. Topography is rugged, particularly in the north and east areas. Galicia has up to 15% of its surface protected within the Natura 2000 Network, with a total of six natural parks and six Biosphere Reserves as outstanding figures of nature protection [77]. The forested area exceeds 2 million ha, representing 69% of the land surface, and is dominated by forests and plantations of *Pinus pinaster* Ait. and *Eucalyptus globulus* Labill. [78]. Other less extensive forest areas include broadleaf forests dominated by *Quercus robur* L. and *Quercus pyrenaica* Willd. Shrublands dominated by *Cytisus scoparius* (L.) Link, *Erica australis* L., and *Ulex europaeus* L. are also abundant. Only 23.7% of the forested area of Galicia is managed [77].

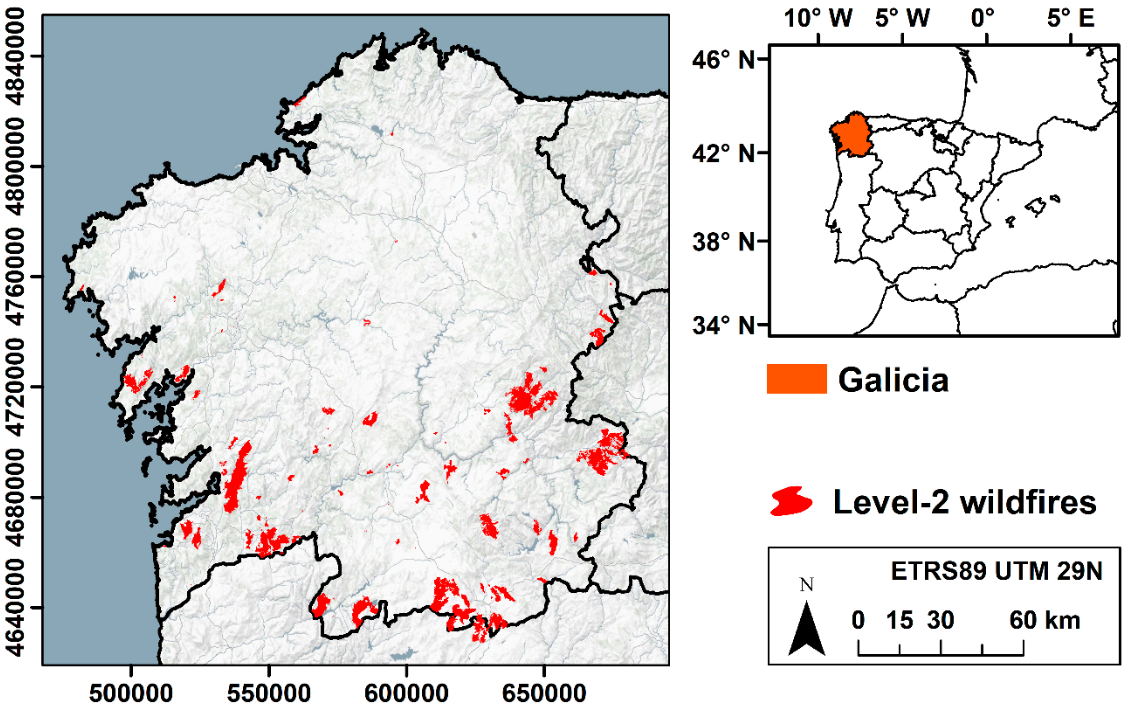

Figure 1. Location of the study area and perimeters of level-2 forest fires that occurred in Galicia during the period 2015–2022.

2.2. Datasets

Fire attributes (fire size and fire severity) of level-2 forest fires across Galicia were retrieved from the official fire database provided by the Basic Autonomous Plan (PBA) of Galicia, the Prevention and Defense Plan against Forest Fires in Galicia (PLADIGA), and Landsat multispectral data at a spatial resolution of 30 m (Table 1). Bottom-up and top-down environmental controls of fire size and severity (topography, pre-fire fuel type and fire weather) were retrieved from the Spanish National Center of Geographic Information

(CNIG), the United States Geological Survey (USGS), the CORINE Land Cover (CLC) project (2012 and 2015 inventories) embedded into the Copernicus program of the European Commission (CLC, 2012, 2018), the United States Geological Survey (USGS), and the Galicia Meteorological Observation and Prediction Unit (MeteoGalicia) (Table 1).

Table 1. Fire attributes of level-2 forest fires and environmental controls of fire behavior considered in this study.

Group	Source	Variable	Unit
Fire attributes	BAP Galicia	fire size	ha
	Landsat data	[a] fire severity	-
Topography	PNOA DTM	[a] slope	%
		[a] slope aspect cosine	-
		[a] altitude	m
Fire weather	MeteoGalicia	[a,c] wind gust speed	m/s
		[a,c] wind speed	m/s
		[a,c] relative humidity (RH)	%
		[a,b] temperature	°C
		[a,c] Initial Spread Index (ISI)	-
		[a,c] Buildup Index (BUI)	-
		[a,c] Fire Weather Index (FWI)	-
Pre-fire fuel type	CLC 2012, CLC 2018	[a] cropland fraction	%
		[a] grassland fraction	%
		[a] shrubland fraction	%
		[a] broadleaf forest fraction	%
		[a] conifer forest fraction	%
		[a] mixed forest fraction	%

[a] Mean value; [b] Minimum value; [c] Maximum value. BAP: Basic Autonomous Plan (PBA); PNOA DTM: digital terrain model of the Spanish National Plan for Aerial Orthophotography; CLC: Corine Land Cover.

The PAB forest fire database of Galicia was used to identify and retrieve the perimeters of all forest fires that occurred in Galicia over the period 2015–2022 (available at https://mapas.xunta.gal/visores/pba/ (accessed on 29 September 2023)). The identifying code, municipality where fire ignition was located, start and extinction dates, and the corresponding fire size (ha) were extracted for each forest fire. The PLADIGA database (available at https://mediorural.xunta.gal/es/temas/defensa-monte (accessed on 29 September 2023)) was used to identify the number of level-2 forest fires for each year over the study period. The institutional profile from the Regional Government of Galicia (@incendios085) in the social network X was used to identify level-2 forest fires by searching hashtag date and municipality, and crossing report information with those forest fires retrieved from the PAB database. We verified that the total number of level-2 forest fires identified each year matched with the PLADIGA database. The size of level-2 forest fires was classified as small (<500 ha) and large (≥500 ha) [79].

Fire severity for the selected level-2 forest fires was retrieved using Landsat-8 Operational Land Imager (OLI) Level 2 (Collection 2, Tier 1) surface reflectance products at a spatial resolution of 30 m from Google Earth Engine (GEE) [80] data catalog. The difference Normalized Burn Ratio (dNBR) [81] spectral index was used to estimate the magnitude of ecological effects on the burned areas (aboveground biomass consumption) [82] with respect to the pre-fire scenario [83]. We used the pre- and post-fire Landsat-8 cloud-free scenes closest to the ignition and extinction dates of the level-2 forest fires, respectively, to calculate the dNBR index for each forest fire in GEE. Mean severity at forest fire level of level-2 event was classified according to the United States Geological Survey thresholds (USGS) [83] widely used not only in previous research [84,85], but also in the European Forest Fire Information System (EFFIS) to assess fire severity in Europe [86]. Level-2 forest fires with a mean dNBR higher than 0.42 are classified as high severity; otherwise, they are classified as low severity.

The mean slope (%), slope aspect cosine and altitude (m) of the terrain within each forest fire were computed as topographic drivers of fire behavior from the digital elevation model (DEM) acquired from CNIG (available at https://centrodedescargas.cnig.es/ (accessed on 29 September 2023)) with 25 m grid size. The DEM was produced from low-density LiDAR point clouds of the Spanish National Plan for Aerial Orthophotography (PNOA).

Individual weather variables were retrieved from MeteoGalicia weather stations. For each level-2 forest fire, we selected the nearest weather station, at a distance of less than 10 km in all cases. The mean and maximum or minimum values during fire spread were computed for each level-2 forest fire from 10 min data. The variables considered were wind gust speed (m/s), wind speed (m/s), relative humidity (%), and temperature (°C). Wind variables were collected at 10 m above the ground. Moreover, integrated fire danger conditions were described through the Canadian Fire Weather Index System [87]. The fuel moisture codes, including Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC), as well as fire behavior descriptors, namely Initial Spread Index (ISI), Buildup Index (BUI) and Fire Weather Index (FWI) within the Canadian Fire Weather Index System relied on noon observations acquired from MeteoGalicia weather stations. We considered ISI, BUI and FWI mean and maximum values during fire spread.

The pre-fire fuel type fraction for each forest fire was retrieved through CLC 2012 for the level-2 forest fires of the period 2015–2017, and the CLC 2018 for the fires from this year onwards in order to work with the most up-to-date land cover information available. CLC features a minimum mapping unit of 25 ha and is procured from photo-interpreted remote sensing data at a high spatial resolution. The overall accuracy of the classification is higher than 85% (CLC 2012 and 2018). The CLC datasets were acquired from the Copernicus Land Monitoring Service (https://land.copernicus.eu/ (accessed on 2 October 2023)). We retained from the three-level hierarchical CLC system the cropland, grassland, shrubland, broadleaf forest, conifer forest and mixed forest fractions.

2.3. Data Analysis

The non-parametric Mann–Kendall test (M-K) [88] was used to test for the presence of significant increasing or decreasing monotonic trends in the duration, fire size, fire severity and number of level-2 forest fires, as well as in fire weather, over the period 2015–2022 in Galicia. If a significant trend was identified (p-value < 0.05), its magnitude was calculated using the Theil–Sen slope estimator (T-S) [89]. M-K and T-S tests were implemented with the *mk.test* and *sens.slope* functions using the *trend* package [90] in R 4.0.5 [91].

A prior data exploratory analysis to detect potential collinearity issues among pre-fire fuel type, topography and fire weather drivers (Table 1) was conducted through the computation of Pearson's correlation coefficient (R). First, we identified strongly correlated ($R > |0.7|$) groups of variables [92,93]. Subsequently, we only preserved within each group the variable with the highest ecological relevance for the following analyses.

We unraveled the relationship between the uncorrelated drivers of fire behavior (predictors) and categorized fire regime attributes (fire size and fire severity; dependent variables) of level-2 forest fires through a Random Forest (RF) classification algorithm [94]. Therefore, we fitted two separate models, one for each dependent variable. RF models were calibrated with the randomForest function using the RandomForest package [95]. This algorithm is an ensemble classifier that produces multiple decision trees, using a randomly selected subset of training samples and variables, and was chosen due to its robust performance to uncover complex interactions among predictors and non-linear relationships with the dependent variables, while effectively handling overfitting [93,96,97]. The Boruta feature selection method [98], designed as a wrapper algorithm around RF, computes permutation tests relying on RF variable importance measures to determine important and non-redundant features within the candidate predictors. The Boruta algorithm was implemented with the *Boruta* function and package [98], prior to RF classification, to reduce the dimensionality of the uncorrelated predictors and improve the RF model's robustness and predictive performance [99]. Subsequently, the RF classification algorithm was calibrated from the selected Boruta features. The *ntree* RF model hyperparameter was set to 2000 to promote RF prediction stability [100]. The appropriate *mtry* hyperparameter value was found by 10-fold cross-validation tuning experiments using the *train* function within the *caret* package [101]. We assessed the performance of RF classification using 10-fold cross validation repeated 10 times. The average confusion matrix across resamples was computed, followed by the Kappa index, overall accuracy (OA; %), and user's (UA; %) and producer's (PA; %) accuracy for each dependent variable class. Partial dependence plots depicting the probability of large fire size and high fire severity in a centered logit scale were computed for each predictor in the RF model using the *partial* function within the *pdp* package [102].

3. Results

From 2015 to 2022, there were 93 level-2 forest fires in Galicia, burning close to 100,000 ha. The fire size varied from 4.4 ha to more than 11,000 ha, the largest forest fire ever recorded in Galicia [103]. Most of the level-2 forest fires (72%) occurred between June and September. For the study period, 21 of the remaining level-2 forest fires occurred in October 2017. There is no significant annual trend (Mann–Kendall p-value > 0.05) for the period 2015–2022 in the number, duration, area burned and fire severity of level-2 forest fires, as well as in the fire weather for such a period (Figure 2). The maximum number of level-2 forest fires occurred in 2016, 2017 and 2022, with the largest mean area burned registered for the latter two years. The highest annual mean fire severity of level-2 forest fires occurred in 2018, the year with the lowest burned area. The mean annual FWI registered during the occurrence of level-2 forest fires followed a consistent pattern over the study period.

The Boruta feature selection algorithm identified the maximum FWI as the most important variable in predicting the fire size of level-2 forest fires in Galicia, followed by minimum relative humidity and altitude (Figure 3). Therefore, extreme values (minimum and maximum) of fire weather-related variables explained the variation of level-2 fire size better than their mean values over the fire duration. Using the predictors selected by the Boruta algorithm, the accuracy of the RF fire size classification was remarkably high (OA = 81.11% and Kappa index = 0.62). The producer's and user's accuracy of the RF model classes were balanced. The confusion between level-2 fire size classes was minimal, especially the commission error in the case of large fire size, which is particularly relevant for management purposes (Table 2). The relationships between Boruta-selected predictors were strongly non-linear, with the presence of potential thresholds (Figure 4). The likelihood of large level-2 forest fires increased sharply with FWI and altitude, but plateaued at values above 40 and 900 m, respectively. Fire size strongly responded to minimum relative humidity at values below 30%.

The Boruta algorithm also identified as relevant, for the fire severity of level-2 forest fires, the same variables as in the case of level-2 fire size (maximum FWI, minimum relative humidity and altitude), with the pre-fire shrubland fraction in addition (Figure 5). Maximum FWI was also the most important predictor. The overall accuracy procured by the selected drivers of fire behavior in the RF classification of fire severity (OA = 80.00% and Kappa index = 0.61), as well as the producer's and user's accuracy (Table 3), followed the same pattern as in the case of the level-2 fire size model. The commission error was smaller in the high-fire-severity class than in the low-severity class. The high-severity likelihood of level-2 forest fires increased exponentially from shrubland fractions in the landscape above 50%. The relationship for the remaining variables was similar to that for the likelihood of large level-2 forest fires (Figure 6).

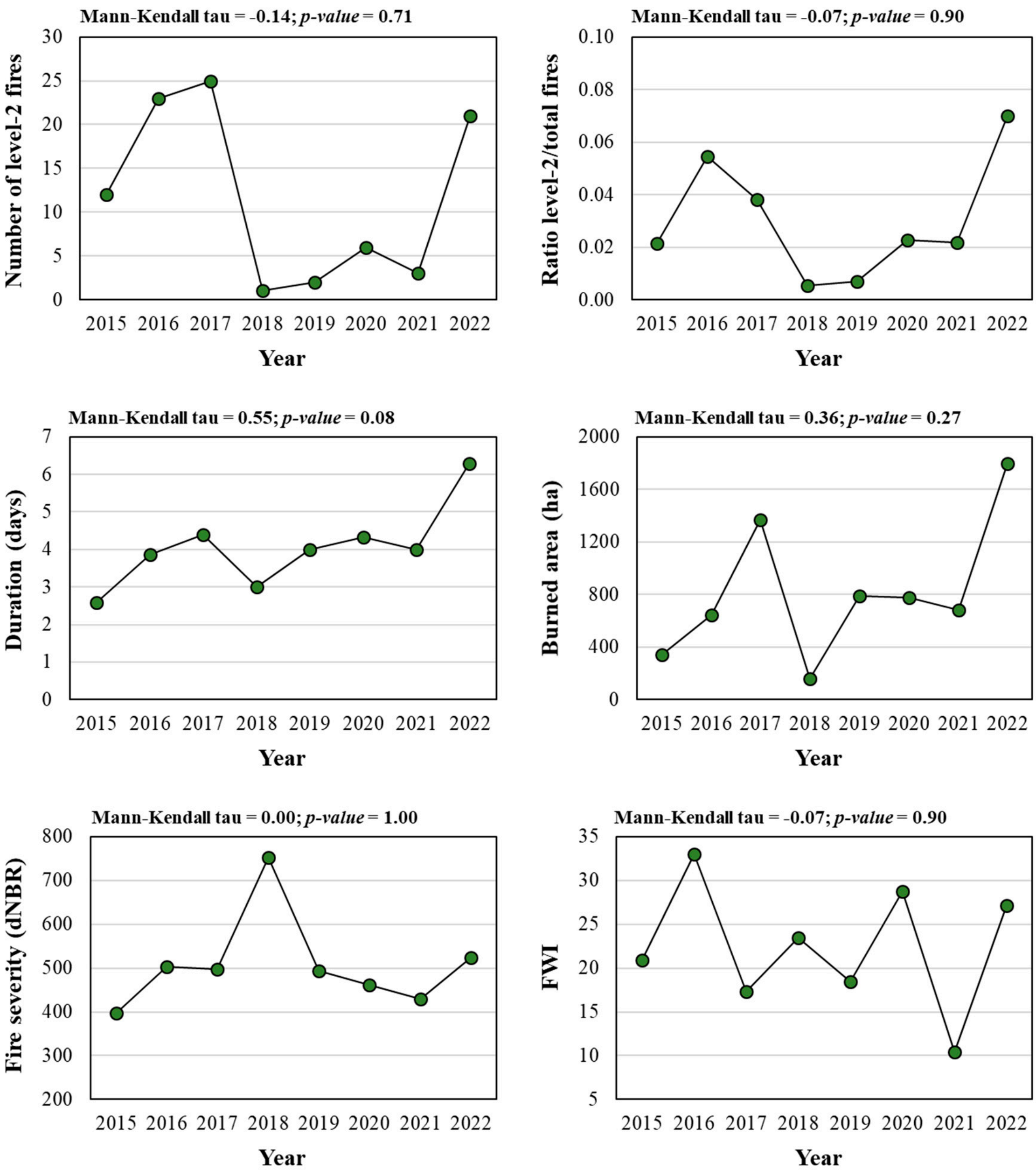

Figure 2. Annual number of level-2 forest fires over the period 2015–2022 in Galicia, and their ratio of level-2 forest fires with respect to the total number of forest fires. We also show the mean annual duration, fire size, and fire severity of level-2 forest fires, as well as the mean annual fire weather index (FWI) for such forest fires. The result of the Mann–Kendall trend test is presented for each variable.

Table 2. Random Forest (RF) classification performance of fire size in level-2 forest fires.

Fire Size		**Ground Truth**	
		Small	**Large**
Predicted	Small	41	6
	Large	11	32
	PA (%)	78.85	84.21
	UA (%)	87.23	74.42
	OA (%)	Kappa	
	81.11	0.62	

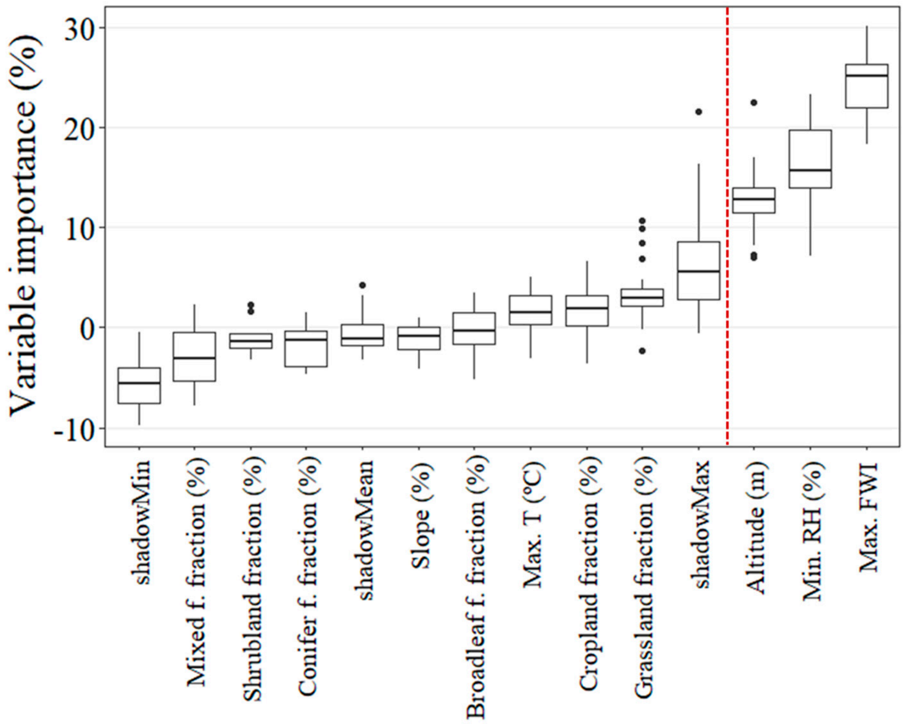

Figure 3. Variable importance of uncorrelated bottom-up and top-down drivers of fire behavior in explaining fire size of level-2 forest fires as determined by the Boruta algorithm. Altitude, minimum relative humidity (min. RH) and maximum Fire Weather Index (max. FWI) were deemed as important (variable importance higher than the "*shadowMax*" internal variable).

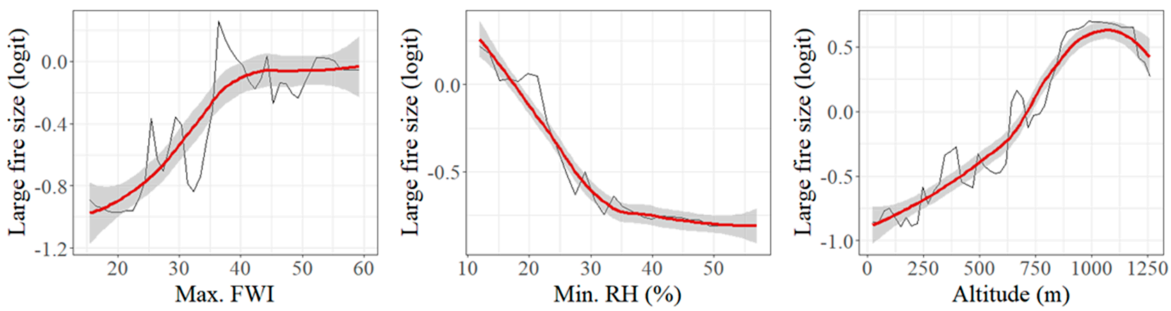

Figure 4. Partial dependence plots depicting the relationship between the large fire size likelihood of level-2 forest fires and the variability of bottom-up and top-down drivers of fire behavior in the Random Forests (RF) classification algorithm. The red line is a LOESS smooth curve.

Table 3. Random Forest (RF) classification performance of fire severity in level-2 forest fires.

Fire Severity		**Ground Truth**	
		Low	**High**
Predicted	Low	37	8
	High	10	35
	PA (%)	81.39	78.72
	UA (%)	77.78	82.22
	OA (%)	Kappa	
	80.00	0.61	

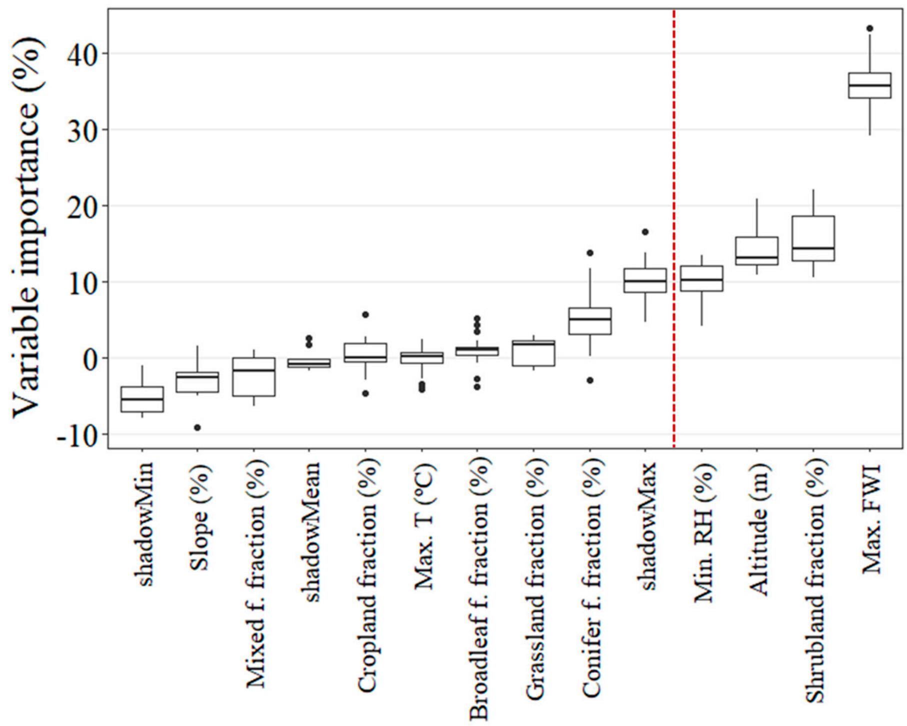

Figure 5. Variable importance of uncorrelated bottom-up and top-down drivers of fire behavior in explaining fire severity of level-2 forest fires as determined by the Boruta algorithm. Minimum relative humidity, altitude, shrubland fraction and maximum FWI were deemed as important (variable importance higher than the "*shadowMax*" internal variable).

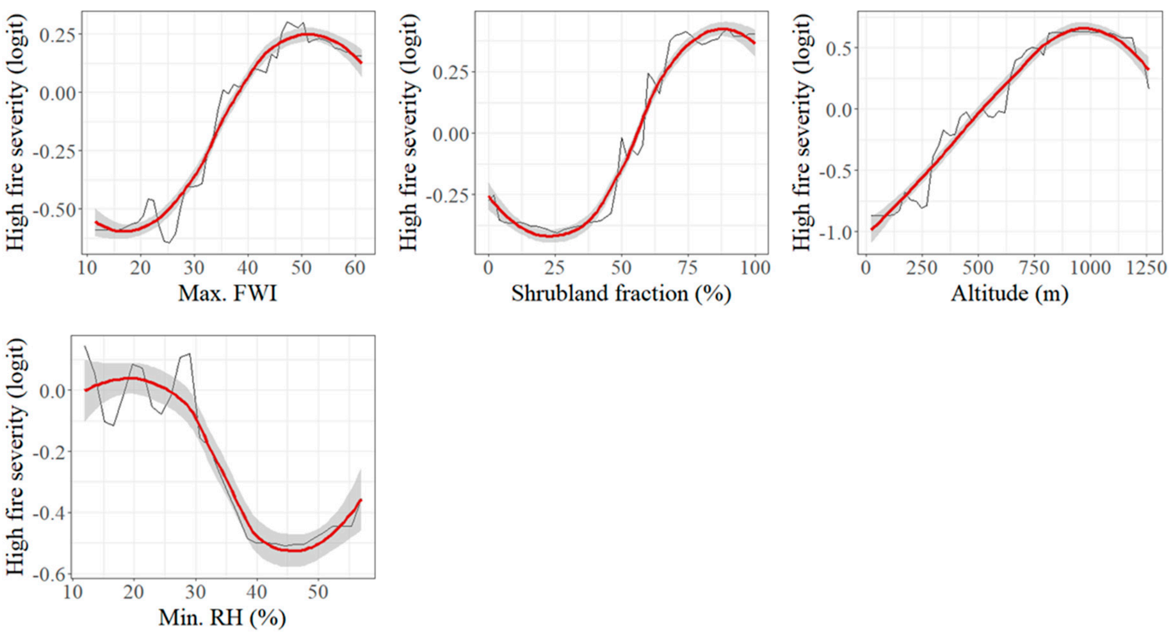

Figure 6. Partial dependence plots depicting the relationship between the high-fire-severity likelihood of level-2 forest fires and the variability of bottom-up and top-down drivers of fire behavior in the Random Forests (RF) classification algorithm. The red line is a LOESS smooth curve.

4. Discussion

In the Mediterranean countries of southern Europe, WUI areas are commonly affected by large forest fires [104] with strong socioeconomic impacts [29], including those related to the defense of population settlements. Importantly, the prevalent forest fire causes in this region are mainly arson, exceeding 50% [105], although many forest fires are also unintentional or due to negligence [106]. Specifically in the study region, only 5% of the fires are caused naturally by lightning [32,107]. Regardless of the fire causes, fire weather-related variables overwhelmed bottom-up controls in controlling the fire size of level-2 forest fires in Galicia, which is consistent with previous research worldwide in wildland areas [108–111]. In fact, fire weather has been reported to be the triggering factor between small and large forest fires [111,112]. Furthermore, the suppression effectiveness of level-2 forest fires may be limited under extreme fire behavior conditions [113,114], supporting the relationship between extreme weather conditions and the size of large fires. The lack of sensitivity of large fire likelihood to FWI > 40 is consistent with previous research [39], namely in the neighboring regions of Portugal [115], as well as to relative humidity below 30% [116,117]. The close relationship between fire weather and fire behavior evidenced here may also account for the absence of significant temporal trends in the level-2 fire attributes (mean burned area, severity, number of fires and duration) because of the high temperature and precipitation intra- and inter-annual variability in the western Mediterranean Basin, despite the significant drought-increasing trends in this region [118,119]. The interannual variability in fire weather conditions may also be responsible for the lack of correlation between the temporal trend of FWI and burned area, e.g., the burned area of a forest fire under extreme FWI conditions may exceed the burned area of the remaining forest fires in the same year occurring under relatively low FWI conditions. Nonetheless, future research should not only consider longer time series, but also the temporal evolution of fire regime attributes at finer spatial scales since WUI vulnerability to fire is expected to vary spatially among major WUI types (e.g., scattered or clustered) [120].

The dominant vegetation types in Galicia, namely *Pinus pinaster* and *Eucalyptus globulus* stands and shrublands, are highly prone to fast-spreading forest fires and, therefore, with greater variability within than between vegetation types [112], particularly when extreme fire weather supports large fire development [121]. This may be related to the non-sensitivity of fire size to generic pre-fire fuel types. The same behavior was reported by Fernandes et al. [52] in mainland Portugal. Moreover, high accumulations of homogeneous fuels in the landscape due to land use changes in southern European countries [10] switched fire regimes from fuel-limited to drought-driven [122], thus increasing the response of fire activity to fire weather [123]. The strong relationship between altitude and fire size is a direct outcome of steeper terrain on fire spread, but may also be related with access difficulties for firefighters in mountainous areas, which has been previously reported in Portugal [124].

The same type of relationships evidenced from fire weather variables and altitude with size and severity of level-2 fires may be related to the fact that conditions conducive to rapid fire spread are also prone to increased high-severity patch size [58,125] and the aggregation of high-severity patches on the landscape [126]. For example, Keane et al. [40] reported that large forest fires in the northern Rocky Mountains tend to show larger burned areas at high severity than small forest fires. In central Portugal, Fernández-Guisuraga et al. [39] found that extremely large forest fires were characterized by large and homogeneous fire severity patterns at the forest fire scale as determined by fire weather feedbacks, which is consistent with the results reported here for forest fires that may endanger human settlements. Although fire weather was the strongest fire severity driver, as evidenced by Zald and Dunn [127] in the Klamath Mountains Ecoregion, United States, pre-fire fuel conditions may have a strong influence on fire severity–weather feedbacks [128], which may explain the relevance of pre-fire generic fuel-type variables in explaining fire severity in level-2 forest fires.

Shrublands were prone to high-severity fire, agreeing with the expectation that temperate shrubland supports high fire intensities, even under not too severe fire weather, thus posing a serious threat to human settlements [129]. This may be attributed to the high flammability of most shrub fuel types in Galicia, such as *Erica australis* or *Ulex eu-*

ropaeus [130], and their high fuel build-up and high continuity over the landscape, particularly in productive environments [131]. Indeed, Beltrán-Marcos et al. [132] reported that the WUI typology most prone to high fire severity in southern Europe corresponds to isolated buildings amongst high shrub cover, which is coincident with the main WUI type in Galicia.

Altogether, extreme fire weather conditions may seriously endanger WUI areas because of large fire development and high fire intensity. These results may be extrapolated to other southern European regions with oceanic climates, although some deviations in the relative weight of environmental controls may be expected. Current fire management strategies in southern Europe are highly targeted at reducing large burned area [133]. Fuel treatments in the vicinity of WUI are advised, and are often adopted, and could increasingly include vegetation-type conversion to deciduous woodland forming green fuel breaks [134]. However, our results support that management efforts should also be focused on reducing fuel loads of flammable vegetation types in the landscape, namely shrublands, diminishing fuel connectivity and enhancing landscape fragmentation to minimize high-fire-severity likelihood in WUI areas. This may also expand fire weather scenarios under which forest fire suppression is feasible and delay fire spread before a WUI or intermix is threatened [135]. Therefore, minimization of large fire spread and severity will not only reduce the risk to populations, but could also allow to focus firefighting efforts on wildland areas by reducing fire hazard in WUI areas [136]. Also, it is necessary to raise awareness not only in the promotion of self-protection in WUI areas, but also by considering fire hazards in land use planning [133], particularly in the context of changing climates and future scenarios of increasingly extreme weather conditions, and adapt fire management accordingly [137].

Future research should consider using longer time series to confirm the links between fire behavior and area burned/severity of forest fires that endanger human settlements. Moreover, the consistency of these relationships should be tested in other temperate oceanic and Mediterranean climate regions worldwide. Moreover, the use of relativized fire severity metrics could be more appropriate at regional scales to capture varying pre-fire fuel load conditions as bottom-up drivers of fire behavior [39]. Although the results at the forest fire scale in this study support conclusions from studies conducted at the pixel or patch level, our analysis scale may weaken relationships between attributes of extreme fire behavior and their driving mechanisms [125]. In addition, future research should examine fire behavior patterns at fine spatial scales considering fuel typologies inside WUI areas with distinct edification patterns [132].

5. Conclusions

The results of this study shed light for the first time on the environmental controls driving level-2 forest fires that endanger human life and property in WUI areas. Our results evidenced that (i) there is no clear annual trend in the number, duration, area burned and fire severity of level-2 forest fires in Galicia, (ii) top-down controls, namely maximum FWI and relative humidity, overwhelmed bottom-up controls in controlling the fire size of level-2 fires, (iii) fire weather conditions conducive to rapid fire spread were also conducive to increased high severity of level-2 forest fires, and (iv) the danger of level-2 forest fires in relation to extreme fire weather conditions may be amplified with high shrubland continuity over the landscape, which may be attributable to the high flammability of the dominant shrub fuel types in Galicia. In this context, prolonged droughts and heat waves in response to current and predicted climate scenarios may seriously endanger WUI areas because of the expected faster-spreading and severe fires.

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References

1. Bento-Gonçalves, A.; Vieira, A. Forest fires in the wildland-urban interface: Key concepts and evaluation methodologies. *Sci. Total Environ.* **2020**, *707*, 135592. [CrossRef]
2. Fernandez-Anez, N.; Krasovskiy, A.; Müller, M.; Vacik, H.; Baetens, J.; Hukić, E.; Kapovic Solomun, M.; Atanassova, I.; Glushkova, M.; Bogunović, I.; et al. Current Wildland Fire Patterns and Challenges in Europe: A Synthesis of National Perspectives. *Air Soil Water Res.* **2021**, *14*, 11786221211028184. [CrossRef]
3. Yadav, K.; Escobedo, F.J.; Thomas, A.S.; Johnson, N.G. Increasing forest fires and changing sociodemographics in communities across California, USA. *Int. J. Disaster Risk Reduct.* **2023**, *98*, 104065. [CrossRef]
4. Harrison, S.P.; Prentice, I.C.; Bloomfield, K.J.; Dong, N.; Forkel, M.; Forrest, M.; Ningthoujam, R.K.; Pellegrini, A.; Shen, Y.; Baudena, M. Understanding and modelling forest fire regimes: An ecological perspective. *Environ. Res. Lett.* **2021**, *16*, 125008. [CrossRef]
5. Ascoli, D.; Moris, J.V.; Marco, M.; Lorenzo, S. Land use change towards forests and wooded land correlates with large and frequent forest fires in Italy. *Ann. Silvic. Res.* **2021**, *46*, 177–188.
6. Vilar, L.; Herrera, S.; Tafur-García, E.; Yebra, M.; Martínez-Vega, J.; Echavarría, P.; Martín, M.P. Modelling forest fire occurrence at regional scale from land use/cover and climate change scenarios. *Environ. Model. Softw.* **2021**, *145*, 105200. [CrossRef]
7. Montiel-Molina, C.; Vilar, L.; Romão-Sequeira, C.; Karlsson, O.; Galiana-Martín, L.; Madrazo-García de Lomana, G.; Palacios-Estremera, M.T. Have historical land use/land cover changes triggered a fire regime shift in central Spain? *Fire* **2019**, *2*, 44. [CrossRef]
8. de Diego, J.; Fernández, M.; Rúa, A.; Kline, J.D. Spatializing and temporalizing socioeconomic determinants of forest fires in Galicia (Spain). **2022**. *preprint*.
9. MacDonald, D.; Crabtree, J.R.; Wiesinger, G.; Dax, T.; Stamou, N.; Fleury, P.; Lazpita, J.G.; Gibon, A. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *J. Environ. Manag.* **2000**, *59*, 47–69. [CrossRef]
10. Moreira, F.; Viedma, O.; Arianoutsou, M.; Curt, T.; Koutsias, N.; Rigolot, E.; Barbati, A.; Corona, P.; Vaz, P.; Xanthopoulos, G. Landscape–forest fire interactions in southern Europe: Implications for landscape management. *J. Environ. Manag.* **2011**, *92*, 2389–2402. [CrossRef]
11. Balmes, J.R. The changing nature of forest fires: Impacts on the health of the public. *Clin. Chest Med.* **2020**, *41*, 771–776. [CrossRef]
12. Borchers Arriagada, N.; Bowman, D.M.J.S.; Palmer, A.J.; Johnston, F.H. Climate change, forest fires, heatwaves and health impacts in Australia. In *Extreme Weather Events and Human Health: International Case Studies*; Springer: Cham, Switzerland, 2020; pp. 99–116.
13. Nunes, A.N.; Figueiredo, A.; Pinto, C.; Lourenço, L. Assessing Wildfire Hazard in the Wildland–Urban Interfaces (WUIs) of Central Portugal. *Forests* **2023**, *14*, 1106. [CrossRef]
14. Palaiologou, P.; Ager, A.A.; Nielsen-Pincus, M.; Evers, C.R.; Day, M.A. Social vulnerability to large forest fires in the western USA. *Landsc. Urban Plan.* **2019**, *189*, 99–116. [CrossRef]
15. Giorgi, F.; Lionello, P. Climate change projections for the Mediterranean region. *Glob. Planet. Change* **2008**, *63*, 90–104. [CrossRef]
16. Jones, M.W.; Smith, A.; Betts, R.; Canadell, J.G.; Prentice, I.C.; Le Quéré, C. Climate change increases the risk of forest fires. *Sci. Rev.* **2020**, *116*, 117.
17. Rodrigues, M.; Camprubí, À.C.; Balaguer-Romano, R.; Megía, C.J.C.; Castañares, F.; Ruffault, J.; Fernandes, P.M.; de Dios, V.R. Drivers and implications of the extreme 2022 forest fire season in Southwest Europe. *Sci. Total Environ.* **2023**, *859*, 160320. [CrossRef] [PubMed]
18. Da Ponte, E.; Alcasena, F.; Bhagwat, T.; Hu, Z.; Eufemia, L.; Dias Turetta, A.P.; Bonatti, M.; Sieber, S.; Barr, P.-L. Assessing wildfire activity and forest loss in protected areas of the Amazon basin. *Appl. Geogr.* **2023**, *157*, 102970. [CrossRef]

19. San-Miguel-Ayanz, J.; Durrant, T.; Boca, R.; Camia, A. *Forest Fire Damage in Natura 2000 Sites 2000–2012*; JRC Scientific and Policy Reports; Publisher European Commission, Joint Research Centre: Luxembourg, 2012.
20. Zaimes, G.N.; Tsioras, P.A.; Kiosses, C.; Tufekcioglu, M.; Zibtsev, S.; Trombitsky, I.; Uratu, R.; Gevorgyan, L. Perspectives on protected area and wildfire management in the Black Sea region. *J. For. Res.* **2020**, *31*, 257–268. [CrossRef]
21. Santín, C.; Knicker, H.; Fernández, S.; Menéndez-Duarte, R.; Álvarez, M.Á. Forest fires influence on soil organic matter in an Atlantic mountainous region (NW of Spain). *Catena* **2008**, *74*, 286–295. [CrossRef]
22. Zavala, L.M.M.; de Celis Silvia, R.; López, A.J. How forest fires affect soil properties. A brief review. *Cuad. Investig. Geográfica* **2014**, *40*, 311–331. [CrossRef]
23. Hohner, A.K.; Rhoades, C.C.; Wilkerson, P.; Rosario-Ortiz, F.L. Forest fires alter forest watersheds and threaten drinking water quality. *Acc. Chem. Res.* **2019**, *52*, 1234–1244. [CrossRef]
24. Pacheco, F.A.L.; Fernandes, L.F.S. Hydrology and stream water quality of fire-prone watersheds. *Curr. Opin. Environ. Sci. Health* **2021**, *21*, 100243. [CrossRef]
25. Caamano-Isorna, F.; Figueiras, A.; Sastre, I.; Montes-Martínez, A.; Taracido, M.; Piñeiro-Lamas, M. Respiratory and mental health effects of forest fires: An ecological study in Galician municipalities (north-west Spain). *Environ. Health* **2011**, *10*, 48. [CrossRef] [PubMed]
26. Filonchyk, M.; Peterson, M.P.; Sun, D. Deterioration of air quality associated with the 2020 US forest fires. *Sci. Total Environ.* **2022**, *826*, 154103. [CrossRef] [PubMed]
27. Knorr, W.; Dentener, F.; Lamarque, J.-F.; Jiang, L.; Arneth, A. Forest fire air pollution hazard during the 21st century. *Atmos. Chem. Phys.* **2017**, *17*, 9223–9236. [CrossRef]
28. Navarro-Carrión, J.T.; León-Cadena, P.; Ramon-Morte, A. Open data repositories and Geo Small Data for mapping the forest fire risk exposure in wildland urban interface (WUI) in Spain: A case study in the Valencian Region. *Remote Sens. Appl. Soc. Environ.* **2021**, *22*, 100500.
29. Chas-Amil, M.-L.; García-Martínez, E.; Touza, J. Iberian Peninsula October 2017 forest fires: Burned area and population exposure in Galicia (NW of Spain). *Int. J. Disaster Risk Reduct.* **2020**, *48*, 101623. [CrossRef]
30. Meier, S.; Strobl, E.; Elliott, R.J.R.; Kettridge, N. Cross-country risk quantification of extreme forest fires in Mediterranean Europe. *Risk Anal.* **2022**, *43*, 1745–1762. [CrossRef]
31. Vaiciulyte, S.; Hulse, L.M.; Veeraswamy, A.; Galea, E.R. Cross-cultural comparison of behavioural itinerary actions and times in forest fire evacuations. *Saf. Sci.* **2021**, *135*, 105122. [CrossRef]
32. Pérez-Invernón, F.J.; Huntrieser, H.; Soler, S.; Gordillo-Vázquez, F.J.; Pineda, N.; Navarro-González, J.; Reglero, V.; Montanyà, J.; van der Velde, O.; Koutsias, N. Lightning-ignited forest fires and long continuing current lightning in the Mediterranean Basin: Preferential meteorological conditions. *Atmos. Chem. Phys.* **2021**, *21*, 17529–17557. [CrossRef]
33. Rodríguez-Pérez, J.R.; Ordóñez, C.; Roca-Pardiñas, J.; Vecín-Arias, D.; Castedo-Dorado, F. Evaluating lightning-caused fire occurrence using spatial generalized additive models: A case study in central Spain. *Risk Anal.* **2020**, *40*, 1418–1437. [CrossRef]
34. Martínez, J.; Chuvieco, E.; Martín, P.; Gonzalez-Caban, A. Estimation of risk factors of human ignition of fires in Spain by means of logistic regression. In *Proceedings of the Second International Symposium on Fire Economics, Planning, and Policy: A Global View*; US Forest Service: Albany, CA, USA, 2008; pp. 265–278.
35. Romero-Calcerrada, R.; Barrio-Parra, F.; Millington, J.D.A.; Novillo, C.J. Spatial modelling of socioeconomic data to understand patterns of human-caused forest fire ignition risk in the SW of Madrid (central Spain). *Ecol. Modell.* **2010**, *221*, 34–45. [CrossRef]
36. Urbieta, I.R.; Franquesa, M.; Viedma, O.; Moreno, J.M. Fire activity and burned forest lands decreased during the last three decades in Spain. *Ann. For. Sci.* **2019**, *76*, 90. [CrossRef]
37. de Diego, J.; Rúa, A.; Fernández, M. Vulnerability variables and their effect on forest fires in Galicia (Spain). A panel data analysis. *Land* **2021**, *10*, 1004. [CrossRef]
38. Damianidis, C.; Santiago-Freijanes, J.J.; den Herder, M.; Burgess, P.; Mosquera-Losada, M.R.; Graves, A.; Papadopoulos, A.; Pisanelli, A.; Camilli, F.; Rois-Díaz, M. Agroforestry as a sustainable land use option to reduce forest fires risk in European Mediterranean areas. *Agrofor. Syst.* **2021**, *95*, 919–929. [CrossRef]
39. Fernández-Guisuraga, J.M.; Martins, S.; Fernandes, P.M. Characterization of biophysical contexts leading to severe forest fires in Portugal and their environmental controls. *Sci. Total Environ.* **2023**, *875*, 162575. [CrossRef]
40. Keane, R.E.; Agee, J.K.; Fule, P.; Keeley, J.E.; Key, C.; Kitchen, S.G.; Miller, R.; Schulte, L.A. Ecological effects of large fires on US landscapes: Benefit or catastrophe? *Int. J. Wildl. Fire* **2008**, *17*, 696–712. [CrossRef]
41. Lutz, J.A.; Key, C.H.; Kolden, C.A.; Kane, J.T.; Van Wagtendonk, J.W. Fire frequency, area burned, and severity: A quantitative approach to defining a normal fire year. *Fire Ecol.* **2011**, *7*, 51–65. [CrossRef]
42. Parks, S.A.; Holsinger, L.M.; Panunto, M.H.; Jolly, W.M.; Dobrowski, S.Z.; Dillon, G.K. High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environ. Res. Lett.* **2018**, *13*, 44037. [CrossRef]
43. Prichard, S.J.; Povak, N.A.; Kennedy, M.C.; Peterson, D.W. Fuel treatment effectiveness in the context of landform, vegetation, and large, wind-driven forest fires. *Ecol. Appl.* **2020**, *30*, e02104. [CrossRef]
44. Viedma, O.; Quesada, J.; Torres, I.; De Santis, A.; Moreno, J.M. Fire severity in a large fire in a Pinus pinaster forest is highly predictable from burning conditions, stand structure, and topography. *Ecosystems* **2015**, *18*, 237–250. [CrossRef]
45. Falk, D.A.; Miller, C.; McKenzie, D.; Black, A.E. Cross-scale analysis of fire regimes. *Ecosystems* **2007**, *10*, 809–823. [CrossRef]

46. Estes, B.L.; Knapp, E.E.; Skinner, C.N.; Miller, J.D.; Preisler, H.K. Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA. *Ecosphere* **2017**, *8*, e01794. [CrossRef]
47. Hong, H.; Jaafari, A.; Zenner, E.K. Predicting spatial patterns of forest fire susceptibility in the Huichang County, China: An integrated model to analysis of landscape indicators. *Ecol. Indic.* **2019**, *101*, 878–891. [CrossRef]
48. Sullivan, A.L. Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *Int. J. Wildl. Fire* **2009**, *18*, 369–386. [CrossRef]
49. Istanbulluoglu, E.; Bras, R.L. Vegetation-modulated landscape evolution: Effects of vegetation on landscape processes, drainage density, and topography. *J. Geophys. Res. Earth Surf.* **2005**, *110*, F02012. [CrossRef]
50. Lydersen, J.; North, M. Topographic variation in structure of mixed-conifer forests under an active-fire regime. *Ecosystems* **2012**, *15*, 1134–1146. [CrossRef]
51. Davies, G.M.; Domènech, R.; Gray, A.; Johnson, P.C.D. Vegetation structure and fire weather influence variation in burn severity and fuel consumption during peatland forest fires. *Biogeosciences* **2016**, *13*, 389–398. [CrossRef]
52. Fernandes, P.M.; Barros, A.M.G.; Pinto, A.; Santos, J.A. Characteristics and controls of extremely large forest fires in the western Mediterranean Basin. *J. Geophys. Res. Biogeosciences* **2016**, *121*, 2141–2157. [CrossRef]
53. Collins, B.M.; Kelly, M.; Van Wagtendonk, J.W.; Stephens, S.L. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. *Landsc. Ecol.* **2007**, *22*, 545–557. [CrossRef]
54. de Dios, V.R.; Hedo, J.; Camprubí, À.C.; Thapa, P.; Del Castillo, E.M.; de Aragón, J.M.; Bonet, J.A.; Balaguer-Romano, R.; Díaz-Sierra, R.; Yebra, M. Climate change induced declines in fuel moisture may turn currently fire-free Pyrenean mountain forests into fire-prone ecosystems. *Sci. Total Environ.* **2021**, *797*, 149104. [CrossRef] [PubMed]
55. Gutierrez, A.A.; Hantson, S.; Langenbrunner, B.; Chen, B.; Jin, Y.; Goulden, M.L.; Randerson, J.T. Forest fire response to changing daily temperature extremes in California's Sierra Nevada. *Sci. Adv.* **2021**, *7*, eabe6417. [CrossRef] [PubMed]
56. Holden, Z.A.; Swanson, A.; Luce, C.H.; Jolly, W.M.; Maneta, M.; Oyler, J.W.; Warren, D.A.; Parsons, R.; Affleck, D. Decreasing fire season precipitation increased recent western US forest forest fire activity. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, E8349–E8357. [CrossRef] [PubMed]
57. Sharples, J.J.; McRae, R.H.D.; Wilkes, S.R. Wind–terrain effects on the propagation of forest fires in rugged terrain: Fire channelling. *Int. J. Wildl. Fire* **2012**, *21*, 282–296. [CrossRef]
58. Dillon, G.K.; Holden, Z.A.; Morgan, P.; Crimmins, M.A.; Heyerdahl, E.K.; Luce, C.H. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. *Ecosphere* **2011**, *2*, 1–33. [CrossRef]
59. Gudmundsson, L.; Rego, F.C.; Rocha, M.; Seneviratne, S.I. Predicting above normal forest fire activity in southern Europe as a function of meteorological drought. *Environ. Res. Lett.* **2014**, *9*, 84008. [CrossRef]
60. Pausas, J.G.; Keeley, J.E. Forest fires and global change. *Front. Ecol. Environ.* **2021**, *19*, 387–395. [CrossRef]
61. Baeza, M.J.; Vallejo, V.R. Vegetation recovery after fuel management in Mediterranean shrublands. *Appl. Veg. Sci.* **2008**, *11*, 151–158. [CrossRef]
62. Faivre, N.; Roche, P.; Boer, M.M.; McCaw, L.; Grierson, P.F. Characterization of landscape pyrodiversity in Mediterranean environments: Contrasts and similarities between south-western Australia and south-eastern France. *Landsc. Ecol.* **2011**, *26*, 557–571. [CrossRef]
63. Loepfe, L.; Martinez-Vilalta, J.; Oliveres, J.; Piñol, J.; Lloret, F. Feedbacks between fuel reduction and landscape homogenisation determine fire regimes in three Mediterranean areas. *For. Ecol. Manag.* **2010**, *259*, 2366–2374. [CrossRef]
64. McKenzie, D.; Miller, C.; Falk, D.A. Toward a theory of landscape fire. In *The Landscape Ecology of Fire*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 3–25.
65. Barreiro, J.B.; Hermosilla, T. Socio-geographic analysis of the causes of the 2006's forest fires in Galicia (Spain). *For. Syst.* **2013**, *22*, 497–509.
66. Regos, A.; Pais, S.; Campos, J.C.; Lecina-Diaz, J. Nature-based solutions to forest fires in rural landscapes of Southern Europe: Let's be fire-smart! Int. *J. Wildl. Fire* **2023**, *32*, 942–950.
67. Chas-Amil, M.L.; Touza, J.; García-Martínez, E. Forest fires in the wildland–urban interface: A spatial analysis of forest fragmentation and human impacts. *Appl. Geogr.* **2013**, *43*, 127–137. [CrossRef]
68. Galiana-Martin, L. Spatial planning experiences for vulnerability reduction in the wildland-urban interface in Mediterranean European countries. *Eur. Countrys.* **2017**, *9*, 577–593. [CrossRef]
69. Galiana-Martin, L.; Herrero, G.; Solana, J. A wildland–urban interface typology for forest fire risk management in Mediterranean areas. *Landsc. Res.* **2011**, *36*, 151–171. [CrossRef]
70. Ager, A.A.; Vaillant, N.M.; Finney, M.A. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. *J. Combust.* **2011**, *2011*, 572452. [CrossRef]
71. Schoennagel, T.; Nelson, C.R.; Theobald, D.M.; Carnwath, G.C.; Chapman, T.B. Implementation of National Fire Plan treatments near the wildland–urban interface in the western United States. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 10706–10711. [CrossRef]
72. BOE. Real Decreto 893/2013, de 15 de noviembre, por el que se aprueba la Directriz básica de planificación de protección civil de emergencia por incendios forestales. *Boletín Of. del Estado* **2013**, 97616–97638. Available online: https://www.boe.es/buscar/doc.php?id=BOE-A-2013-12823 (accessed on 16 October 2023).
73. DOG. DOG Numero 88. *D. Of. Galicia* **2022**, *88*, 1580–1614.

74. Paz-Ferreiro, J.; Trasar-Cepeda, C.; Leirós, M.C.; Seoane, S.; Gil-Sotres, F. Effect of management and climate on biochemical properties of grassland soils from Galicia (NW Spain). *Eur. J. Soil Biol.* **2010**, *46*, 136–143. [CrossRef]
75. Ninyerola, M.; Pons, X.Y.; Roure, J.M. *Atlas Climático Digital de la Península Ibérica: Metodología y Aplicaciones en Bioclimatología y Geobotánica*; Universitat Autònoma de Barcelona: Bellaterra, Sapin, 2005.
76. Meteogalicia. Informe Climatolóxico Ano. 2022. Available online: https://www.meteogalicia.gal/datosred/infoweb/clima/informes/estacions/anuais/2022_gl.pdf (accessed on 16 October 2023).
77. Ministerio para la transición ecológica y reto demográfico. Avance Estadística Forestal 2021. 2023. Available online: https://www.miteco.gob.es/content/dam/miteco/es/biodiversidad/estadisticas/avance_aef_2021_web_tcm30-561531.pdf (accessed on 16 October 2023).
78. Bisquert, M.M.; Sánchez, J.M.; Caselles, V. Fire danger estimation from MODIS Enhanced Vegetation Index data: Application to Galicia region (north-west Spain). *Int. J. Wildl. Fire* **2011**, *20*, 465–473. [CrossRef]
79. Peris-Llopis, M.; González-Olabarria, J.R.; Mola-Yudego, B. Size dependency of variables influencing fire occurrence in Mediterranean forests of Eastern Spain. *Eur. J. For. Res.* **2020**, *139*, 525–537. [CrossRef]
80. Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **2017**, *202*, 18–27. [CrossRef]
81. Key, C.H. Ecological and sampling constraints on defining landscape fire severity. *Fire Ecol.* **2006**, *2*, 34–59. [CrossRef]
82. Keeley, J.E. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *Int. J. Wildl. Fire* **2009**, *18*, 116–126. [CrossRef]
83. Key, C.H.; Benson, N.C. The Normalized Burn Ratio (NBR): A Landsat TM Radiometric Measure of Burn Severity, Report. U.S. Geological Survey Boulder, Colorado. 2005. Available online: http//nrmsc.usgs.gov/research/ndbr.htm (accessed on 10 October 2023).
84. Llorens, R.; Sobrino, J.A.; Fernández, C.; Fernández-Alonso, J.M.; Vega, J.A. A methodology to estimate forest fires burned areas and burn severity degrees using Sentinel-2 data. Application to the October 2017 fires in the Iberian Peninsula. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *95*, 102243. [CrossRef]
85. Sobrino, J.A.; Llorens, R.; Fernández, C.; Fernández-Alonso, J.M.; Vega, J.A. Relationship between soil burn severity in forest fires measured in situ and through spectral indices of remote detection. *Forests* **2019**, *10*, 457. [CrossRef]
86. Twele, A.; Barbosa, P. *Post-Fire Vegetation Regeneration. The Case Study of the "Massif de l'Etoile" Fire*; European Commission: Brussels, Belgium, 2004.
87. Van Wagner, C.E. *Development and Structure of the Canadian Forest Fire Weather Index System*; Government of Canada: Ottawa, ON, Canada, 1987.
88. Mann, H.B. Nonparametric tests against trend. *Econom. J. Econom. Soc.* **1945**, *13*, 245–259. [CrossRef]
89. Sen, P.K. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
90. Pohlert, T. Trend: Non-Parametric Trend Tests and Change-Point Detection_. R Package Version 1.1.5. 2023. Available online: https://CRAN.R-project.org/package=trend (accessed on 2 November 2023).
91. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: https://www.R-project.org/ (accessed on 10 December 2021).
92. Fernández-Guisuraga, J.M.; Suárez-Seoane, S.; Calvo, L. Modeling Pinus pinaster forest structure after a large wildfire using remote sensing data at high spatial resolution. *Forest Ecol. Manag.* **2019**, *446*, 257–271. [CrossRef]
93. García-Llamas, P.; Suárez-Seoane, S.; Fernández-Manso, A.; Quintano, C.; Calvo, L. Evaluation of fire severity in fire prone-ecosystems of Spain under two different environmental conditions. *J. Environ. Manag.* **2020**, *271*, 110706. [CrossRef]
94. Breiman, L. Random forests. *Mach. Learn.* **2001**, *45*, 5–32. [CrossRef]
95. Liaw, A.; Wiener, M. Classification and regression by randomForest. *R News* **2002**, *2*, 18–22.
96. Cutler, D.R.; Edwards, T.C., Jr.; Beard, K.H.; Cutler, A.; Hess, K.T.; Gibson, J.; Lawler, J.J. Random forests for classification in ecology. *Ecology* **2007**, *88*, 2783–2792. [CrossRef] [PubMed]
97. Rodriguez-Galiano, V.F.; Ghimire, B.; Rogan, J.; Chica-Olmo, M.; Rigol-Sanchez, J.P. An assessment of the effectiveness of a random forest classifier for land-cover classification. *ISPRS J. Photogramm. Remote Sens.* **2012**, *67*, 93–104. [CrossRef]
98. Kursa, M.B.; Rudnicki, W.R. Feature selection with the Boruta package. *J. Stat. Softw.* **2010**, *36*, 1–13. [CrossRef]
99. Speiser, J.L.; Miller, M.E.; Tooze, J.; Ip, E. A comparison of random forest variable selection methods for classification prediction modeling. *Expert Syst. Appl.* **2019**, *134*, 93–101. [CrossRef] [PubMed]
100. Probst, P.; Boulesteix, A.-L. To tune or not to tune the number of trees in random forest. *J. Mach. Learn. Res.* **2018**, *18*, 6673–6690.
101. Kuhn, M.; Wing, J.; Weston, S.; Williams, A.; Keefer, C.; Engelhardt, A.; Cooper, T.; Mayer, Z.; Kenkel, B. Caret: Classification and Regression Training. R Package Version 6.0-86. 2020. Available online: https://CRAN.R-project.org/package=caret (accessed on 14 October 2023).
102. Greenwell, B.M. pdp: An R package for constructing partial dependence plots. *R J.* **2017**, *9*, 421. [CrossRef]
103. Regos, A.; Díaz-Raviña, M. A Storyboard of Wildfires in Galicia. In *The Environment in Galicia: A Book of Images: Galician Environment Through Images*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 551–596.
104. Modugno, S.; Balzter, H.; Cole, B.; Borrelli, P. Mapping regional patterns of large forest fires in Wildland–Urban Interface areas in Europe. *J. Environ. Manag.* **2016**, *172*, 112–126. [CrossRef]

105. Camia, A.; DURRANT, H.T.; San-Miguel-Ayanz, J. *Harmonized Classification Scheme of Fire Causes in the EU Adopted for the European Fire Database of EFFIS*; Publications Office of the European Union: Luxembourg, 2013.
106. Ganteaume, A.; Camia, A.; Jappiot, M.; San-Miguel-Ayanz, J.; Long-Fournel, M.; Lampin, C. A review of the main driving factors of forest fire ignition over Europe. *Environ. Manag.* **2013**, *51*, 651–662. [CrossRef]
107. Vázquez, A.; Moreno, J.M. Patterns of lightning-, and people-caused fires in peninsular Spain. *Int. J. Wildl. Fire* **1998**, *8*, 103–115. [CrossRef]
108. Fang, L.; Yang, J.; Zu, J.; Li, G.; Zhang, J. Quantifying influences and relative importance of fire weather, topography, and vegetation on fire size and fire severity in a Chinese boreal forest landscape. *For. Ecol. Manag.* **2015**, *356*, 2–12. [CrossRef]
109. Harvey, B.J. Human-caused climate change is now a key driver of forest fire activity in the western United States. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 11649–11650. [CrossRef] [PubMed]
110. Miller, J.D.; Safford, H. Trends in forest fire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. *Fire Ecol.* **2012**, *8*, 41–57. [CrossRef]
111. San-Miguel-Ayanz, J.; Moreno, J.M.; Camia, A. Analysis of large fires in European Mediterranean landscapes: Lessons learned and perspectives. *For. Ecol. Manag.* **2013**, *294*, 11–22. [CrossRef]
112. Fernandes, P.M. Combining forest structure data and fuel modelling to classify fire hazard in Portugal. *Ann. For. Sci.* **2009**, *66*, 1–9. [CrossRef]
113. Penman, T.D.; Collins, L.; Price, O.F.; Bradstock, R.A.; Metcalf, S.; Chong, D.M.O. Examining the relative effects of fire weather, suppression and fuel treatment on fire behaviour–A simulation study. *J. Environ. Manag.* **2013**, *131*, 325–333. [CrossRef] [PubMed]
114. Fernandes, P.M.; Pacheco, A.P.; Almeida, R.; Claro, J. The role of fire-suppression force in limiting the spread of extremely large forest fires in Portugal. *Eur. J. Forest Res.* **2016**, *135*, 253–262. [CrossRef]
115. Fernandes, P.M. Variation in the Canadian Fire Weather Index Thresholds for Increasingly Larger Fires in Portugal. *Forests* **2019**, *10*, 838. [CrossRef]
116. Cruz, M.G.; Alexander, M.E. The 10% wind speed rule of thumb for estimating a forest fire's forward rate of spread in forests and shrublands. *Ann. For. Sci.* **2019**, *76*, 44. [CrossRef]
117. Lecina-Diaz, J.; Alvarez, A.; Retana, J. Extreme fire severity patterns in topographic, convective and wind-driven historical forest fires of Mediterranean pine forests. *PLoS ONE* **2014**, *9*, e85127. [CrossRef] [PubMed]
118. Coll, J.R.; Aguilar, E.; Ashcroft, L. Drought variability and change across the Iberian Peninsula. *Theor. Appl. Climatol.* **2017**, *130*, 901–916. [CrossRef]
119. Gaitán, E.; Monjo, R.; Pórtoles, J.; Pino-Otín, M.R. Impact of climate change on drought in Aragon (NE Spain). *Sci. Total Environ.* **2020**, *740*, 140094. [CrossRef]
120. Chappaz, F.; Ganteaume, A. Role of land-cover and WUI types on spatio-temporal dynamics of fires in the French Mediterranean area. *Risk Anal.* **2023**, *43*, 1032–1057. [CrossRef] [PubMed]
121. Barros, A.M.G.; Pereira, J.M.C. Forest fire selectivity for land cover type: Does size matter? *PLoS ONE* **2014**, *9*, e84760. [CrossRef]
122. Fernandes, P.M.; Loureiro, C.; Guiomar, N.; Pezzatti, G.B.; Manso, F.T.; Lopes, L. The dynamics and drivers of fuel and fire in the Portuguese public forest. *J. Environ. Manag.* **2014**, *146*, 373–382. [CrossRef]
123. Fernandes, P.M.; Monteiro-Henriques, T.; Guiomar, N.; Loureiro, C.; Barros, A.M.G. Bottom-Up Variables Govern Large-Fire Size in Portugal. *Ecosystems* **2016**, *19*, 1362–1375. [CrossRef]
124. Marques, S.; Borges, J.G.; Garcia-Gonzalo, J.; Moreira, F.; Carreiras, J.M.B.; Oliveira, M.M.; Cantarinha, A.; Botequim, B.; Pereira, J.M.C. Characterization of forest fires in Portugal. *Eur. J. For. Res.* **2011**, *130*, 775–784. [CrossRef]
125. Harvey, B.J.; Donato, D.C.; Turner, M.G. Drivers and trends in landscape patterns of stand-replacing fire in forests of the US Northern Rocky Mountains (1984–2010). *Landsc. Ecol.* **2016**, *31*, 2367–2383. [CrossRef]
126. Cansler, C.A.; McKenzie, D. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecol. Appl.* **2014**, *24*, 1037–1056. [CrossRef] [PubMed]
127. Zald, H.S.J.; Dunn, C.J. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. *Ecol. Appl.* **2018**, *28*, 1068–1080. [CrossRef] [PubMed]
128. Lydersen, J.M.; Collins, B.M.; Brooks, M.L.; Matchett, J.R.; Shive, K.L.; Povak, N.A.; Kane, V.R.; Smith, D.F. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. *Ecol. Appl.* **2017**, *27*, 2013–2030. [CrossRef] [PubMed]
129. Anderson, W.R.; Cruz, M.G.; Fernandes, P.M.; McCaw, L.; Vega, J.A.; Bradstock, R.A.; Fogarty, L.; Gould, L.; McCarthy, G.; Marsden-Smedley, J.B.; et al. A generic, empirical-based model for predicting rate of fire spread in shrublands. *Int. J. Wildland Fire* **2015**, *24*, 443–460. [CrossRef]
130. Calviño-Cancela, M.; Chas-Amil, M.L.; García-Martínez, E.D.; Touza, J. Wildfire risk associated with different vegetation types within and outside wildland-urban interfaces. *For. Ecol. Manag.* **2016**, *372*, 1–9. [CrossRef]
131. Baeza, M.J.; De Luís, M.; Raventós, J.; Escarré, A. Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce forest fire risk. *J. Environ. Manag.* **2002**, *65*, 199–208. [CrossRef]
132. Beltrán-Marcos, D.; Calvo, L.; Fernández-Guisuraga, J.M.; Fernández-García, V.; Suárez-Seoane, S. Wildland-urban interface typologies prone to high severity fires in Spain. *Sci. Total Environ.* **2023**, *894*, 165000. [CrossRef]
133. Moreira, F.; Ascoli, D.; Safford, H.; Adams, M.A.; Moreno, J.M.; Pereira, J.M.C.; Catry, F.X.; Armesto, J.; Bond, W.; González, M.E. Forest fire management in Mediterranean-type regions: Paradigm change needed. *Environ. Res. Lett.* **2020**, *15*, 11001. [CrossRef]

134. Oliveira, A.S.; Silva, J.S.; Guiomar, N.; Fernandes, P.; Nereu, M.; Gaspar, J.; Lopes, R.F.R.; Rodrigues, J.P.C. The effect of broadleaf forests in forest fire mitigation in the WUI–A simulation study. *Int. J. Disaster Risk Reduct.* **2023**, *93*, 103788. [CrossRef]
135. Fernandes, P.M. Fire-smart management of forest landscapes in the Mediterranean basin under global change. *Landsc. Urban Plan.* **2013**, *110*, 175–182. [CrossRef]
136. Hamilton, B.A. Quadrennial Fire Review: Final Report. Fire & Aviation Management USDA Forest Service, Office of Wildland Fire, Department of the Interior. 2014. Available online: https://www.forestsandrangelands.gov/documents/qfr/2014QFRFinalReport.pdf (accessed on 8 October 2023).
137. Duane, A.; Aquilué, N.; Canelles, Q.; Morán-Ordoñez, A.; De Cáceres, M.; Brotons, L. Adapting prescribed burns to future climate change in Mediterranean landscapes. *Sci. Total Environ.* **2019**, *677*, 68–83. [CrossRef]