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Evaluation of Fire Incidence in Spanish Forest Species

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Abstract

Forest fires are recurrent in Spain and affect tree species in different ways. Fire incidence in the main Spanish forest species, both native and alien, is estimated in this study based on actual fire occurrences. Indices of presence, burned area, fire extent, frequency, and recurrence were calculated for each species, and with them, fire incidence indices were obtained. Significant fire incidence was detected in *Pinus canariensis*, *P. pinaster*, *Eucalyptus globulus*, *Quercus robur*, *Betula* spp., *Castanea sativa*, *Pinus radiata*, and *Quercus pyrenaica*. Most of the species with the highest fire incidence are not located in the areas with the highest climatic hazard. There is limited correlation between flammability and fire extension, and this is not significant when considering fire incidence. The relationship between fire incidence and conifers is valid in absolute terms, but only partially in relative terms. Similarly, there is no general relationship between relative fire incidence and species with a natural or reforested origin. Some native hardwood species have unexpectedly high incidence, probably due to collateral damage caused by fires in nearby pine and eucalyptus stands. The fire incidence index of forest species is useful for forest management and for protecting species that are suffering severely from fire effects.

Keywords: forest fires; forest tree species; tree species fire incidence; wildfires in Spain

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1. Introduction

Forest fires are recurrent in the Mediterranean region and may become more intense as a result of climate change [1], a process also observed in other regions with a similar climate [2]. Rising air temperatures in this region are contributing to drier and more flammable fuels, which increase ignition probability, flame length, and fire spread potential [3–6]. Fires in Spain are currently more drought-drivenas compared to before the 1970s [7]. Although the annual number of wildfires has decreased significantly over the past 30 years in this country, the burned area has not followed the same trend, showing a minimal and statistically non-significant decline [8]; a decline was reported between 1985 and 2011 [9], but this is no longer the case, largely due to disastrous years such as 2012, 2017, and 2022, the latter being the year with the largest burned area in the last three decades. On average, large fires—those exceeding 500 hectares—account for half of the total burned area each year, although in 2022 this proportion rose to 82% [10]. Despite a reduction in the number of fires, climate change is likely to increase the risk and severity of large fires [11,12].

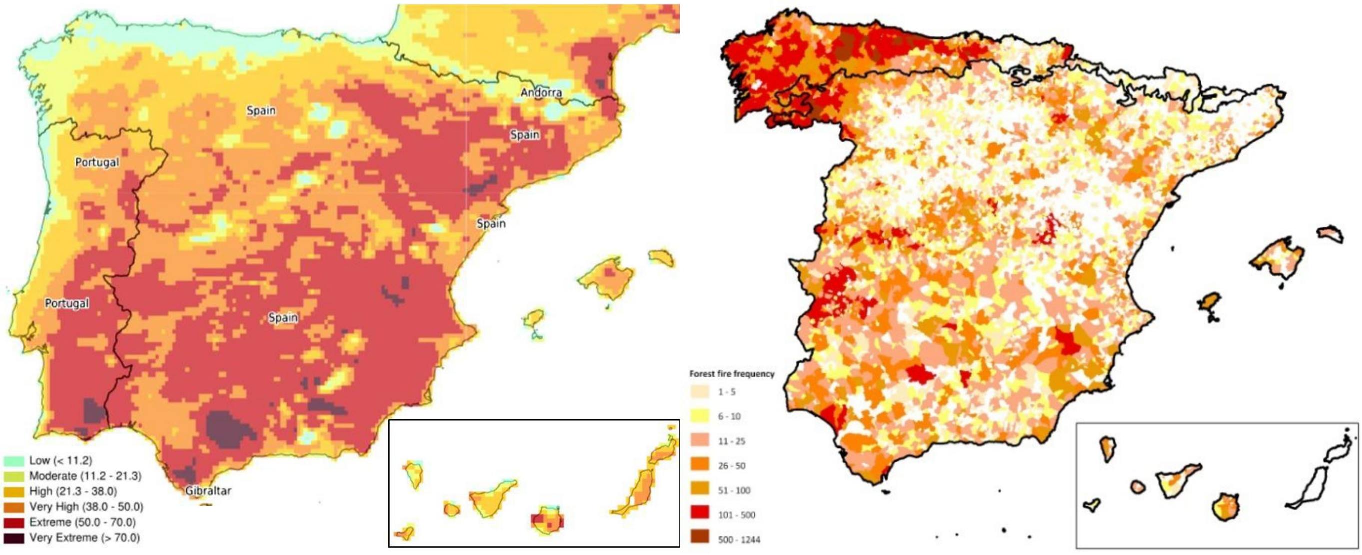
Fire risk is defined as the combination of hazard, i.e., the likelihood of a fire occurring at a specific location and time, determined by factors such as fuel, weather conditions, or terrain slope; exposure, i.e., the presence of people and assets that may be affected;

and vulnerability, i.e., the degree to which those assets are susceptible to harm from fire, which also depends on the accessibility and availability of firefighting resources [13–15]. However, terminology related to fire management is not always used consistently [16]. In this study, we use the term *fire incidence* to refer to the effective occurrence of wildfires within a given spatial unit over a defined time period, as documented in historical fire records. This variable represents the number and extent of wildfire events and does not refer to potential or risk, but to observed fire activity based on actual data [17–19].

Vegetation is a key aspect when analysing fire hazard, as its structure and fuel load are essential factors, commonly represented in a stylised form by fuel models [20,21]. At the species level, flammability is a multidimensional property that describes how easily a plant material ignites (ignitability), how well it sustains combustion (combustibility), and how long it continues to burn (sustainability) [22,23]. The composition and structure of forest stands can make them more or less prone to forest fires. Some types of vegetation are more prone to fire than others, with a particularly high risk in conifers, whose presence increases the likelihood of fire [24–26]. The structure of forest stands also influences fire hazard, with a greater spread of crown fires when there is vertical continuity in the fuel [27], and with greater biomass in the shrub layer [28]. The influence of the origin of forest stands on ignition risk has also been highlighted, with a higher incidence in reforested stands than in spontaneous (i.e., non-planted native) stands [27].

Weather is an important hazard factor, especially in climates where the dry and hot seasons coincide, as in the Mediterranean region during the summer. In Spain, the driest areas, which are also those most affected by climate change, present the highest climatic fire hazard, meaning that meteorological conditions are more favourable for triggering wildfires, as shown by the Fire Weather Index (FWI) [8] (Figure 1a). However, in practice, these areas are not the most affected by wildfires, which are instead concentrated in the northwest of Spain (Galicia), an Atlantic region that is significantly wetter than most of the country [29,30] (Figure 1b). Fire hazard and risk are not directly coupled, as other factors, particularly human action, play a significant role. Ignition probability and suppression capacity, both strongly influenced by human activities, can dramatically alter fire risk under similar hazard conditions [18]. Overlooking these dimensions can lead to overly reductionist management strategies that focus on species flammability or climatic risk while underestimating socio-economic drivers. Although 95% of forest fires in Europe are directly or indirectly linked to human action [18], research has traditionally prioritised biophysical variables over social drivers [31].

Human action has a major influence on vegetation and landscape, on exposure and on vulnerability, and therefore on fire risk. Most forest fires in Spain are intentional [32,33], which is particularly evident in Galicia, where the arson rate is much higher than in the rest of Spain [34]. The distribution of forest fires in Spain depends largely on local social conflicts [35]. Additionally, the rural exodus has led to land abandonment and livestock reduction, favouring shrub colonisation which has increased fuel loads and, consequently, fire hazard [11,32,36]. In Catalonia (NE Spain), the increasing occurrence of fires has been attributed to the decline of the traditional Mediterranean landscape mosaic [37]. Fire is natural in Mediterranean ecosystems, but land use changes that reduce farming mosaics and increase forest fuel loads drive the occurrence of mega-fires [38]. In northern Spain, the influence of landscape structure on fire risk is controversial: some authors associate a greater probability of fire occurrence with landscapes that exhibit a greater diversity of uses [39], while others associate the probability of fire—both in frequency and extent—with greater landscape homogeneity [40].



(**a**) (**b**)

Figure 1. (**a**) The Fire Weather Index (FWI) on 1 July 2025, a normal situation in the country during summer [8]; (**b**) the forest fire frequency in the period 2006–2015 [30].

Reduced investment in silviculture, especially in stands resulting from reforestation, may increase fire hazard and vulnerability due to excessive fuel accumulation. Silvicultural practices such as thinning and prescribed burning can reduce fuel loads and canopy variables, but thinning may increase some fine fuels and the surface fire flame length; consequently, these measures require careful planning, frequent maintenance, and integration within broader landscape strategies [41–45]. Between the 1940s and 1970s, about four million hectares were reforested in Spain [46], mostly with softwoods, but these areas have not been consistently maintained over time. The low market productivity of Mediterranean forests, as well as the abundance of small landholdings, makes them financially unprofitable [47,48], resulting in limited investment in maintenance. Additionally, although firefighting in Spain is very effective, it absorbs a large proportion of public forest management funds. As a consequence, many stands lack adequate silvicultural treatments, leading to high fuel loads in some areas.

Wildfire risk assessment commonly relies on models that evaluate hazard, exposure, and vulnerability in real time, typically with greater emphasis on hazard. However, conducting ex post analyses of actual fire events and their impacts on forest species also provides valuable insights for evidence-based decision-making, adaptive management, and addressing knowledge gaps in fire–landscape interactions [11].

This paper focuses on assessing the actual fire effects on the main forest species in Spain. Fire behaviour is determined by multiple environmental and anthropogenic factors, such as fuel moisture, slope, climate, and ignition sources. However, this study focuses exclusively on species-level fire incidence based on real fire records, rather than on modelling fire spread or intensity. The aim is to identify which species are more frequently affected by fire across the Spanish territory.

Fire incidence indices were used, as the actual occurrence of fires is analysed and not the potential for them to occur. Fire statistics showed a dominance of burned areas for pine and eucalyptus, where the greatest problems were concentrated. However, these absolute values did not take into account the relative risk of each species. A relative analysis, linking each species burned area, its presence in the country, and the recurrence of fires, allowed the identification of their real fire risk, and not only the absolute weight in the total burned area. This knowledge makes it possible to detect particularly sensitive tree species, which may require special attention in forest management.

2. Materials and Methods

2.1. Study Area

Spain has an area of 505,990 km^2, divided into four biogeographical regions [49] (Figure 2): Mediterranean (85.5%), Atlantic (11.1%), Alpine (1.9%), and Macaronesia (1.5%). Specific forest stands dominate each region. The climate of the Mediterranean region has dry and hot summers which are particularly prone to forest fires. In the Atlantic and Alpine regions, there is little to no summer drought, so the fire weather risk is lower. In Macaronesia, the climate is subtropical with irregular rainfall, resulting in both arid and forested areas. Despite the climatic differences, all biogeographic regions suffer forest fires, which are particularly intense in the Atlantic region, as noted above.

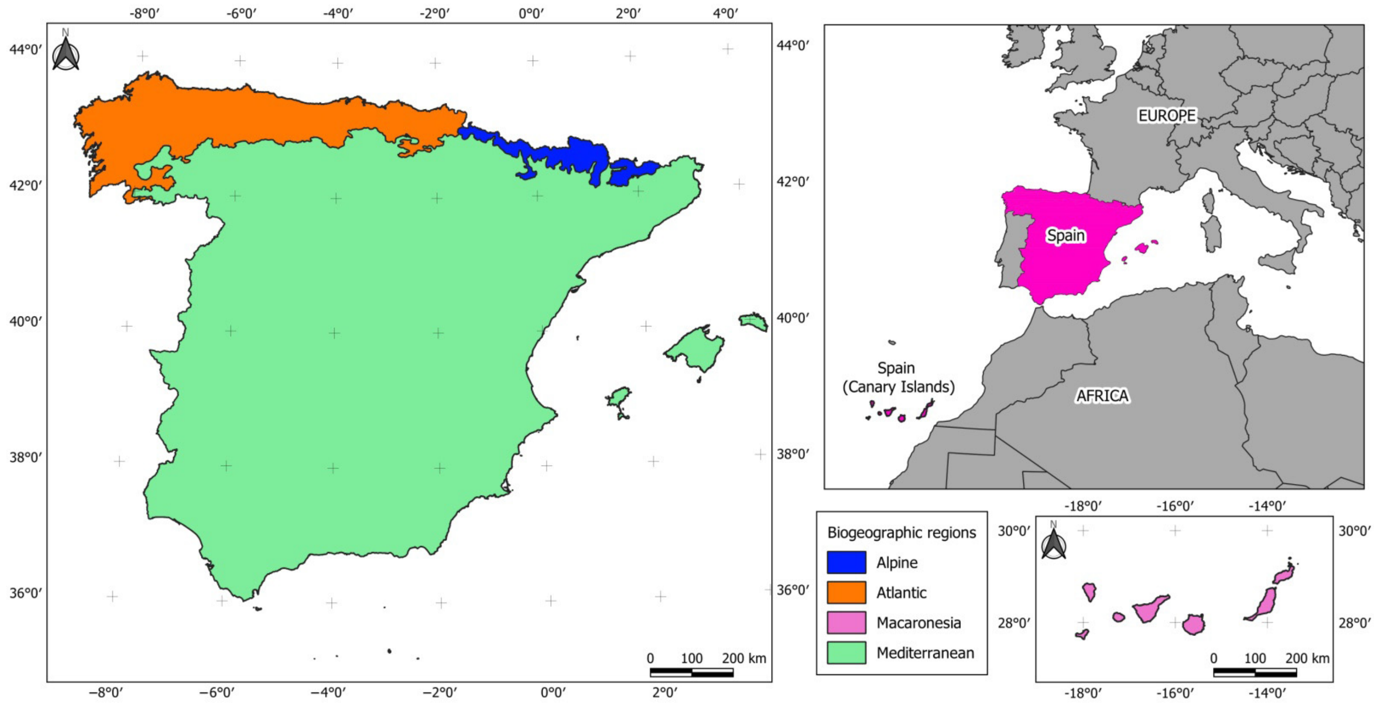


Figure 2. Biogeographic regions of Spain [49].

Forest communities in Spain vary markedly across biogeographic regions, shaping their composition, structure, and response to fire [38,50–53].

In the Mediterranean region, which covers much of the country (Figure 2), forests are typically dominated by *Quercus rotundifolia*, *Pinus halepensis*, *Pinus pinea*, *Quercus suber*, or *Quercus faginea*, and several species of *Juniperus*. Tree species exhibit a range of fire-related traits, including thick bark (e.g., *Quercus suber*), high resprouting capacity (e.g., most species of *Quercus*), or serotiny and post-fire regeneration through seeds (e.g., *Pinus halepensis*). In sub-Mediterranean areas, forests dominated by *Quercus pyrenaica* are common. In mountain regions, in addition to this species, *Pinus pinaster*, *P. nigra*, and *P. sylvestris* appear in increasing order of elevation. Some stands of these pines are natural, but most are the result of reforestation efforts carried out mainly between the 1950s and 1970s.

In the Atlantic region, forest types include temperate deciduous species such as *Fagus sylvatica*, *Quercus robur*, *Q. petraea*, or *Castanea sativa*, which show fewer fire-adaptive traits. These communities tend to be more mesic and less flammable, although fire frequency in this region is high due to social factors. This wetter region supports higher tree growth rates and has experienced intense forest management, including extensive plantations of

Mediterranean species (e.g., *Pinus pinaster*) and alien species such as *Eucalyptus globulus* or *Pinus radiata*, which can form large, continuous stands.

In the Alpine region, restricted to the Pyrenees, the dominant forest types include *Fagus sylvatica* and *Abies alba*, with *Pinus uncinata* occurring at higher elevations.

Finally, the Macaronesian region (the Canary Islands) hosts unique forest types, most notably dominated by *Pinus canariensis*, a species with exceptional fire resilience as it is the only Spanish pine capable of resprouting. This region also preserves remnants of laurel forests and *Myrica*-heath formations.

2.2. Studied Species

The main forest species of Spain, both native and alien, were considered (Table 1). The information on these species in forest statistics is sometimes grouped, especially in secondary or similar species; these groupings were applied in this study as well.

Table 1. Species analysed.

Group	Family	Species	Abbreviation	Region			
				Med	Atl	Alp	Mac
Softwoods (conifers)	*Pinaceae*	*Abies alba*	ABI ALB			N	
		Abies pinsapo	ABI PIN	N			
		Pinus canariensis	PIN CAN				N
		Pinus halepensis	PIN HAL	N			
		Pinus nigra (different subspecies) *	PIN NIG	N/I			
		Pinus pinaster	PIN PTR	N	I		
		Pinus pinea	PIN PIN	N			
		Pinus radiata	PIN RAD		I		
		Pinus sylvestris	PIN SYL	N	N	N	
		Pinus uncinata	PIN UNC			N	
		Pseudotsuga / Larix / Picea	PSE SPP	(I)	I		
	Cupressaceae	*Cupressus / Chamaecyparis*	CUP SPP	I	I		
		Juniperus oxycedrus / J. communis	JUN ENE	N	N	N	
		Juniperus phoenicea / J. thurifera	JUN SAB	N			
Hardwoods	*Aquifoliaceae*	*Ilex aquifolium*	ILE AQU	(N)	N		
	Betulaceae	*Betula* spp.	BET SPP	(N)	N	N	
		Corylus avellana	COR AVE	(N)	N		
	Fagaceae	*Castanea sativa / C. crenata*	CAS SAT	(I)	I		
		Fagus sylvatica	FAG SYL	(N)	N		
		Quercus faginea	QUE FAG	N			
		Quercus pyrenaica	QUE PYR	N	(N)		
		Quercus robur / Q. petraea	QUE ROB	(N)	N		
		Quercus rotundifolia	QUE ROT	N			
		Quercus suber	QUE SUB	N			
		Quercus (other species)	QUE SPP	N	N/I		
	Myrtaceae	*Eucalyptus* spp.	EUC SPP	I	I		
	Oleaceae	*Fraxinus* spp.	FRA SPP	N	N		
		Olea europaea (not cultivated)	OLE EUR	N/I			
Other	*Arecaceae*	*Phoenix* spp.	PHO SPP	I			N/I
	Salicaceae	*Populus* × *canadiensis*	POP CAN	I	(I)		
	Myrica-heath	*Myrica faya-Erica arborea*	MYR FAY				N

Region: Med—Mediterranean; Atl—Atlantic; Alp—Alpine; Mac—Macaronesia. **Codes:** N—native; I—introduced; (X)—limited presence. * Forest and fire statistics refer to *P. nigra* at the species level, although plantations include the native subsp. *salzmannii* and the introduced subsp. *nigra* and *laricio*.

2.3. Data Collection and Processing

The main data sources for analysing fire incidence on forest species were national forest statistics yearbooks and fire statistics, both published periodically by the Spanish government. The preparation of forest fire statistics used to involve a delay of two to three years, but in recent years this gap has widened. Although annual data on the number of wildfires and burned area—both nationally and by region—are still published up to the latest year (currently 2024), detailed breakdowns, such as the area affected by species, which are essential for this study, have not been produced since 2015. Therefore, the period considered in this study was the last 20 years with definitive data, 1996–2015. This study is based on real fire occurrence data rather than experimental measurements. While experimental flammability data may offer complementary insights, our focus is on estimating fire incidence at the species level using actual fire records.

The area covered by each forest species (A_{SP}) and the total forested area (A_T) were obtained from the forest statistics yearbooks [54]. The index of presence (I_P) was obtained by calculating the proportion of the area occupied by each species (A_{SP}) with respect to the total forested area (A_T), as seen in Equation (1).

$$I_P = A_{SP}/A_T \quad (1)$$

Based on forest fire statistics [55], the burned area by species (B_{SP}) and the total burned area (B_T) were obtained for each year. The burned area index (I_B) was calculated as the proportion of a species' burned area (B_{SP}) relative to the total burned area (B_T), as seen in Equation (2).

$$I_B = B_{SP}/B_T \quad (2)$$

The area affected by fire varies greatly between species. To facilitate concise comparison, a fire extent index (I_E) was defined using the mean B_{SP} value for the period, normalised to a 0–1 scale by Min–Max scaling Equation (3). The species with the highest fire extent in the period has an I_E of 1, and that with the lowest has an I_E of 0.

$$I_E = (B_{SP(speciesX)} - B_{SP(min)}) \ / \ (B_{SP(max)} - B_{SP(min)}) \quad (3)$$

The basic fire incidence index of each species (F_B) was calculated by dividing I_B by I_P, as seen in Equation (4). It indicates whether the species has a higher or lower fire incidence than expected. When I_B and I_P coincide (F_B = 1), the fire frequency is normal relative to the species' land cover. F_B values lower than 1 indicate a lower fire incidence than expected, and F_B values higher than 1 indicate a higher fire incidence than expected.

$$F_B = I_B \ / \ I_P \quad (4)$$

Another interesting indicator was fire recurrence. To quantify this, a frequency index (I_F) was defined in Equation (5), calculated as the number of years with fires recorded for a species (Y_{SP}) divided by the total number of years studied (Y_T). A value of 1 indicates that every year, at least some area covered by a particular species is burned.

$$I_F = Y_{SP} \ / \ Y_T \quad (5)$$

The recurrence index (I_R) was defined as the proportion of years in which IF_B exceeded 1 (R_{SP}) relative to the total number of years studied (Y_T), as seen in Equation (6). A value of 1 indicates that every year, the species experiences fires above the normal range, whereas a value of 0 implies that itdoes not suffer above-normal fire intensity.

$$I_R = R_{SP} \ / \ Y_T \quad (6)$$

The corrected fire incidence index (F_C) was calculated by multiplying F_B, I_F and I_R, as seen in Equation (7), thereby adjusting final values based on fire frequency and recurrence.

$$F_C = F_B \cdot I_F \cdot I_R \quad (7)$$

Tree flammability varies depending on the region, time of year or moisture content [56]. Values were obtained from the literature [57–67] and grouped into four categories: low (1), moderate (4), high (7), and very high (10). The flammability index (*Fm*) for each species was calculated by averaging the obtained values.

To determine whether there is a trend in the burned area of each species over the analysed period, a non-parametric Mann–Kendall test [68] was applied to each series individually. This test statistically assesses whether there is a monotonic upward or downward trend, which does not necessarily have to be linear. Two hypotheses were considered: the null hypothesis, which assumes no trend in the series, and the alternative hypothesis, which assumes an upward or downward monotonic trend. The sign of the test statistic indicates whether the trend is upward (positive) or downward (negative). This test does not require the data to follow a normal distribution and is not affected by gaps in the data, although results are more robust when applied to long time series [69].

Simple correlations between the indices I_P, I_E, F_C, and *Fm* were performed. These indices were chosen because they are the most indicative; I_B is similar to I_E but not normalised, and F_B, I_F, and I_R are auxiliary to calculate F_C. For each correlation, the *p*-value was calculated to determine whether it was statistically significant at the 95% level ($p < 0.05$), and Pearson's correlation coefficient and *R2* were computed. The results of I_P, I_E, F_C, and *Fm* were subjected to cluster analysis, producing dendrograms using Ward's method with squared Euclidean distances. Statistical calculations were conducted using Statgraphics 19® Centurion. Species with F_C greater than 1 (high fire incidence) were analysed in detail.

3. Results

3.1. Indices Calculation

According to the methodology described above, the different indices were calculated for the main Spanish forest species (Table 2).

Table 2. Fire-related indices of the analysed species.

Species	I_P	I_B	I_E	F_B	I_F	I_R	F_C
Pinus canariensis	0.0043	0.0555	0.2454	12.90	1.00	0.55	7.09
Pinus pinaster	0.0577	0.2253	1.0000	3.90	1.00	0.95	3.71
Eucalyptus spp.	0.0338	0.1267	0.5810	3.75	1.00	0.90	3.37
Quercus robur, *Q. petraea*	0.0133	0.0359	0.1197	2.70	1.00	0.90	2.43
Betula spp.	0.0021	0.0054	0.0177	2.59	1.00	0.80	2.07
Castanea sativa	0.0089	0.0216	0.0748	2.43	1.00	0.85	2.06
Pinus radiata	0.0144	0.0271	0.0936	1.88	1.00	0.75	1.41
Quercus pyrenaica	0.0454	0.0808	0.2576	1.78	1.00	0.75	1.33
Pinus halepensis	0.1126	0.1680	0.6471	1.49	1.00	0.65	0.97
Fraxinus spp.	0.0006	0.0008	0.0024	1.26	1.00	0.55	0.69
Quercus suber	0.0147	0.0223	0.1054	1.52	1.00	0.45	0.68
Pinus pinea	0.0222	0.0297	0.1260	1.35	1.00	0.35	0.47
Pinus nigra (different subsp.)	0.0387	0.0430	0.1832	1.11	1.00	0.30	0.33
Juniperus oxycedrus, *J. communis*	0.0062	0.0056	0.0113	0.90	1.00	0.15	0.14
Myrica faya, *Erica arborea*	0.0013	0.0010	0.0055	0.75	0.90	0.20	0.14
Pinus sylvestris	0.0562	0.0372	0.1483	0.66	1.00	0.20	0.13
Quercus rotundifolia	0.1421	0.0722	0.2865	0.51	1.00	0.15	0.08
Corylus avellana	0.0005	0.0002	0.0004	0.41	0.90	0.15	0.06
Populus × *canadiensis*	0.0054	0.0022	0.0093	0.40	0.95	0.10	0.04

Table 2. *Cont.*

Species	I_P	I_B	I_E	F_B	I_F	I_R	F_C
Ilex aquifolium	0.0002	0.0001	0.0003	0.51	0.45	0.15	0.03
Olea europaea (not cultivated)	0.0072	0.0021	0.0053	0.29	1.00	0.10	0.03
Quercus spp. (other species)	0.0120	0.0055	0.0191	0.45	1.00	0.05	0.02
Cupressus, *Cedrus*, *Chamaecyparis*	0.0001	$1 \cdot \times 10^{-5}$	0.0001	0.41	0.95	0.05	0.02
Quercus faginea	0.0175	0.0059	0.0244	0.34	1.00	0.05	0.02
Pinus uncinata	0.0053	0.0009	0.0026	0.16	0.95	0.05	0.01
Phoenix spp.	0.0001	0.0000	0.0003	0.36	0.40	0.05	0.01
Fagus sylvatica	0.0216	0.0044	0.0119	0.20	1.00	0.00	0.00
Juniperus phoenicea, *J. thurifera*	0.0141	0.0023	0.0090	0.16	0.95	0.00	0.00
Pseudotsuga, *Larix*, *Picea*	0.0160	0.0007	0.0019	0.04	1.00	0.00	0.00
Abies alba	0.0007	0.0000	0.0001	0.02	0.40	0.00	0.00
Abies pinsapo	0.0001	0.0000	0.0000	0.01	0.05	0.00	0.00

I_P: Presence index. I_B: Burned area index. I_E: Fire extent index. F_B: Basic fire incidence index. I_F: Fire frequency index. I_R: Recurrence index. F_C: Corrected fire incidence index.

The flammability index (*Fm*) was derived from the literature by assigning numerical values to flammability classes to obtain an indicator for each species (Table 3).

Table 3. The flammability of the analysed species.

Species	Flammability				
	Very High	High	Moderate	Low	*Fm*
Eucalyptus spp.	■				10.0
Pinus halepensis	■				10.0
Pinus pinaster	■	■			8.5
Pinus pinea	■	■			8.5
Quercus rotundifolia	■	■			8.5
Quercus suber	■	■			8.5
Castanea sativa	■	■	■		7.0
Quercus robur, *Q. petraea*	■	■	■		7.0
Juniperus phoenicea, *J. thurifera*		■			7.0
Pinus canariensis		■			7.0
Pinus nigra (different subsp.)		■			7.0
Pinus radiata		■			7.0
Pinus uncinata		■			7.0
Cupressus, *Cedrus*, *Chamaecyparis*		■	■		5.5
Pinus sylvestris		■	■		5.5
Quercus spp. (other species)		■	■		5.5
Olea europaea (not cultivated)		■	■	■	4.0
Abies alba			■		4.0
Abies pinsapo			■		4.0
Corylus avellana			■		4.0
Fraxinus spp.			■		4.0
Quercus faginea			■		4.0
Quercus pyrenaica			■		4.0
Betula spp.			■	■	2.5
Juniperus oxycedrus, *J. communis*			■	■	2.5
Myrica faya, *Erica arborea*				■	1.0
Populus × *canadiensis*				■	1.0
Fagus sylvatica				■	1.0

Fm: Flammability index Sources: [57–67].

3.2. Results by Indices

Four indices were especially useful for analysing fire effects on tree species: presence (I_P), fire extent (I_E), corrected fire incidence (F_C) and flammability (*Fm*). Statistical correlations were performed to evaluate relationships among them. Correlations showed significant relationships between pairs I_P-I_E, I_P-*Fm*, I_E-*F*, and I_E-F_C, while relationships between pairs I_P-F_C and *Fm*-F_C were not significant (Table 4).

Table 4. Statistical analysis of correlations.

	I_P	I_E	Fm	F_C
I_P	-	39.28%	23.56%	0.06%
	-	* 0.0003	* 0.0076	0.8977
I_E	39.28%	-	34.77%	27.94%
	* 0.0003	-	* 0.0008	* 0.0032
Fm	23.56%	34.77%	-	34.27%
	* 0.0076	* 0.0008	-	0.0687
F_C	0.06%	27.94%	11.74%	-
	0.8977	* 0.0032	0.0687	-

* Significant *p*-values.

For these four indices, cluster analyses were conducted which produced dendrograms for evaluation (Figure 3).

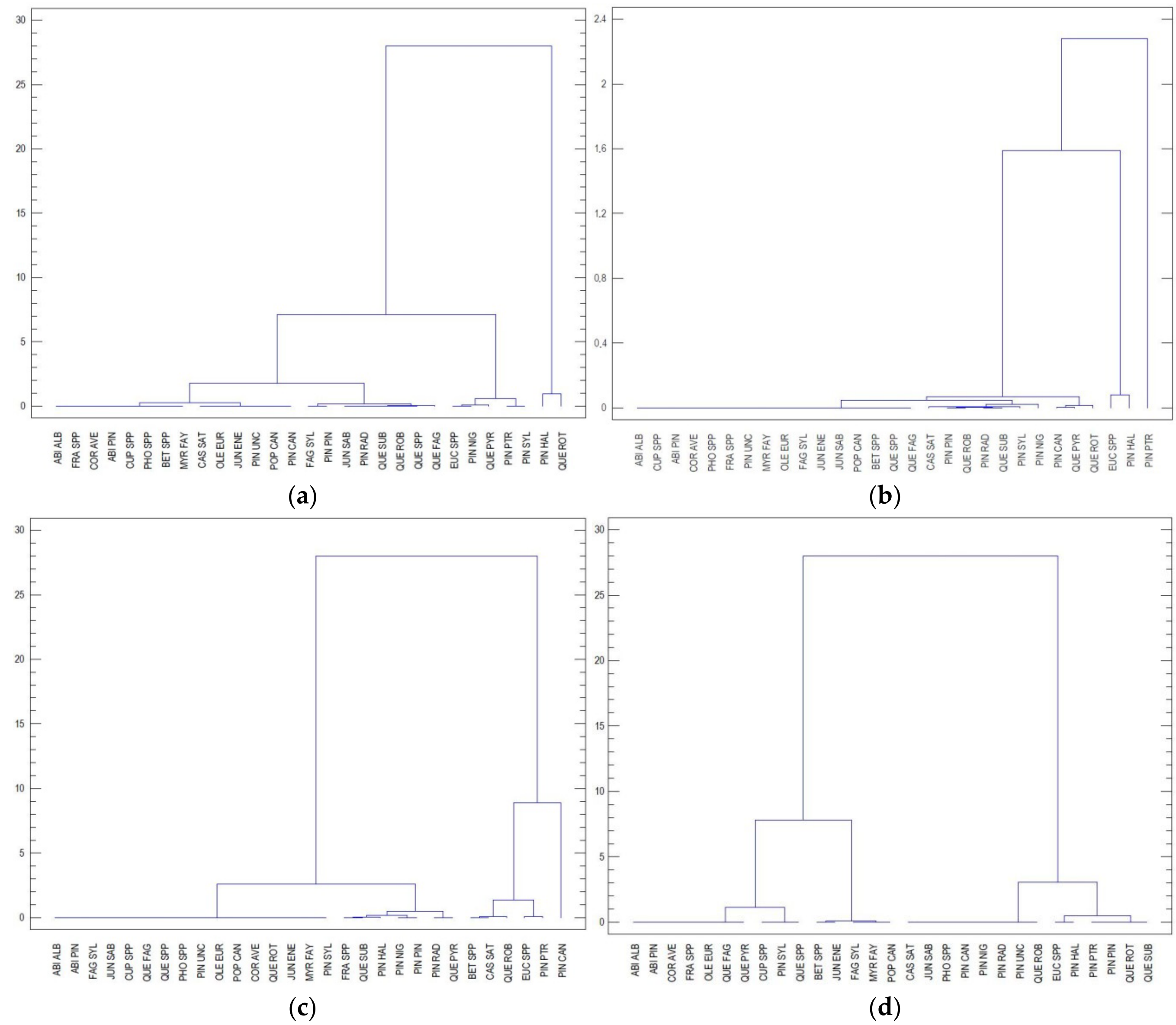


Figure 3. Cluster analysis: (**a**) index of presence (I_P); (**b**) fire extent index (I_E); (**c**) corrected fire incidence index (F_C); and (**d**) flammability (Fm). Abbreviations in Table 1.

The presence index (I_P) indicates species occurrence and is essential for determining the relative importance of burned areas. The two most abundant species are *Quercus rotundifolia* and *Pinus halepensis*, typically Mediterranean, and together account for a quarter of the country's forested area (Figure 3a). However, as discussed later, the relative fire incidence for these species is not high, particularly for the former.

The fire extent (I_E, Figures 3b and 4a) and the corrected fire incidence (F_C, Figures 3c and 4b) were particularly informative for assessing fire effects. The former reflects the risk based on the burned area, while the latter relates the burned area to species presence, fire frequency, and recurrence of exceptional fire years. Both indices exhibit a moderate, statistically significant correlation. I_E shows a significant correlation with I_P but only explains 39% of the variance in fire occurrence. Abundant species tend to burn more, but not always: *Quercus rotundifolia* ranks first in extent but fourth in burned area, whereas *Pinus canariensis* is the 22nd in extent but sixth in burned area. I_E also shows a significant correlation with flammability (*Fm*), but only explains 35% of the variance in fire occurrence. Mann–Kendall tests reveal no statistically significant trend in species' burned area, although the burned area of junipers has increased markedly in recent years.

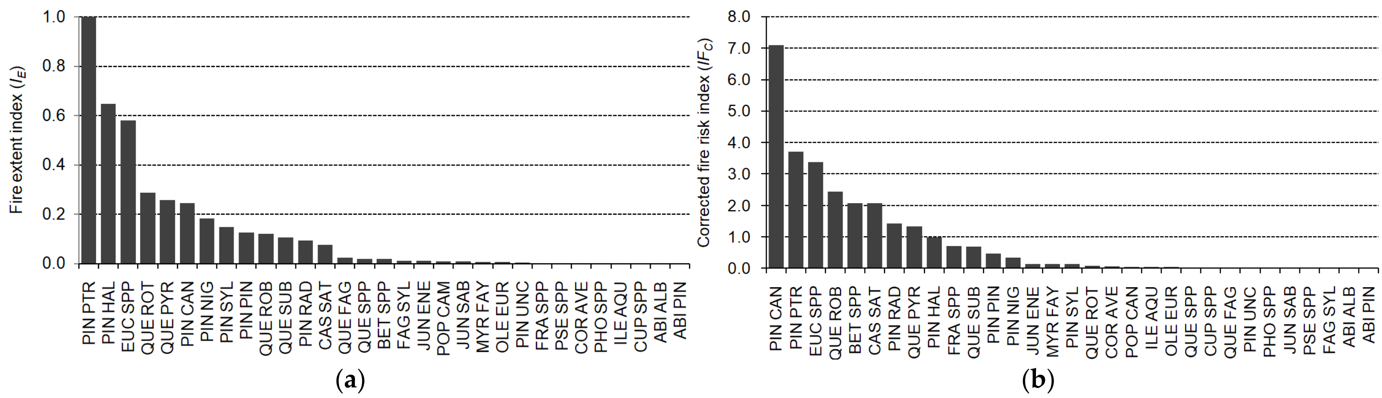


Figure 4. (**a**) Fire extent index (I_E); (**b**) corrected fire incidence index (F_C). Abbreviations in Table 1.

Pinus pinaster ranks highest in fire extent, followed by *Pinus halepensis* and *Eucalyptus* spp. (Figure 4a). While *P. halepensis* is typically Mediterranean, the other two species, despite occurring in the Mediterranean region, have the greatest land cover and fire occurrence in the Atlantic region.

Corrected fire incidence (F_C) is significantly, yet moderately, correlated with I_E (explaining 28%) but shows no significant correlation with flammability (p = 0.0687). Although the species with the highest F_C values are flammable, several species exhibit high F_C despite low *Fm*. Six species stand out by this index (Figure 4b). *Pinus canariensis* stands out in this index above all other species(7.09), reflecting a much greater burned area than expected due to large catastrophic fires in the Canary Islands, which disproportionately affected this species. Two other species also display notable values: *Pinus pinaster* (3.71) and *Eucalyptus* spp. (3.37). These species rank first and third in the total fire extent, concentrating the most severe fire impacts in Spain. They are followed by a group of hardwoods typical of the Atlantic region, with a fire incidence almost twice as high as expected: *Quercus robur* / *Q. petraea*, *Castanea sativa*, and *Betula* spp. Two additional species exceed expected values: *Pinus radiata*, an American pine planted in the Atlantic region, and *Quercus pyrenaica*, which attains its greatest extent in sub-Mediterranean areas of NW Spain. *Pinus halepensis* remains at the threshold of significance (0.97), indicating normal fire incidence relative to its distribution: it burns frequently because it occupies a large area.

The flammability dendrogram (Figure 3d) separates the species into two groups. Species with high F_C mostly fall within the most flammable group, except *Betula* spp. and

Quercus pyrenaica. This suggests the influence of external factors leading to higher-than-expected fire incidence, which is related to the location of most stands in areas with high anthropogenic fire incidence. The correlation of flammability with I_E is significant, but accounts for only 35% of its variance, while it is not significant for F_C, explaining just 12%.

3.3. Results by Species

Thirteen species have a higher than expected basic fire incidence ($F_B > 1$), eight of them with a corrected risk above normal ($F_C > 1$). The species with the highest risk values ($F_B = 12.90$; $F_C = 7.09$) is *Pinus canariensis*, endemic to the Canary Islands, where it represents 60% of forest, 80% of natural, and 20% reforested areas [70]. Fires above the normal threshold occur only 55% of the years; the high risk values result from the large-scale fires that occurred in five specific years in the Canary Islands, especially in 2007.

Pinus pinaster is a Mediterranean species widely used in plantations in Atlantic areas, where it is not native, and where most fires occur. It occupied the first place in burned area but fourth in presence. The figures for F_B (3.90) and F_C (3.71), along with the low error (9%) in the first index, indicate that the probability of fire is almost four times higher than that corresponding to its presence, with high annual regularity: fires affect this species every year, with 95% of those years exceeding the normal threshold.

Several species of *Eucalyptus* are used in plantations, especially in NW Spain, where fires are more frequent. Fire mainly affects *Eucalyptus globulus* (94%), the most widely planted species. These species rank third in burned area and eighth in presence. The values for F_B (3.75) and F_C (3.37) indicate a fire incidence 3 to 4 times higher than expected, with annual recurrence and 90% of the years exceeding the normal threshold.

Stands of *Quercus robur* and *Q. petraea* are spontaneous, occurring mainly in the Atlantic region. Although forest statistics group both species, the first one is much more abundant andis also more affected by fire (92%) than the second (8%). F_B was 2.70 and F_C 2.43; fires affect these species every year, with 90% of those years exceeding the normal threshold. Also spontaneous are the stands of *Quercus pyrenaica*, a sub-Mediterranean oak common in southern Galicia, where the highest fire concentration occurs. Fire incidence is above the expected level ($F_B = 1.78$; $F_C = 1.33$), with fires occurring every year, and 75% of those years exceeding the normal threshold.

Three birch species grow in Spain, *Betula celtiberica*, *B. pendula,* and *B. pubescens*, which are grouped in forest statistics. Birch stands are spontaneous and show a higher than expected fire incidence ($F_B = 2.59$; $F_C = 2.07$), with fires occurring annually and 80% of those years exceeding the normal threshold. They are mainly Atlantic species, so fires concentrate in northern and northwestern Spain. *Castanea sativa* was introduced to Spain in ancient times, and most stands are located in the Atlantic region; its fire incidence is more than twice the expected level ($F_B = 2.43$; $F_C = 2.06$).

Pinus radiata is an American pine used in plantations in the Atlantic region. Fire incidence is above the expected ($F_B = 1.88$; $F_C = 1.41$), with fires affecting this species every year and 75% of those years exceeding the normal threshold.

Pinus halepensis is a Mediterranean pine native to eastern Spain, where spontaneous forests are frequent, and it is widely used in reforestation in central Spain. It is the leading species in burned area and the second in presence. F_B is above the expected value (1.49), but F_C is at the significance threshold (0.97). Fires affect this species every year, but only 65% of those years exceed the normal threshold.

Four other species have F_B values greater than 1 but F_C values lower than 1, due to a strong annual variability of fire incidence. *Quercus suber*, forming natural stands, had an F_B of 1.52, with 45% of the years exceeding the normal threshold. *Pinus pinea*, with natural and reforested stands, had an IF_B of 1.35, but only for one-third of the years did the burned area exceed the normal value. Ash tree stands are formed by two species, *Fraxinus angustifolia*, Mediterranean, and *F. excelsior*, Atlantic; F_B was 1.26, with 55% of the years exceeding the threshold. *Pinus nigra* forms natural stands and has also been used massively in plantations; F_B was 1.11, but the normal threshold was exceeded in only one-third of the years.

The most abundant forest species in Spain is *Quercus rotundifolia*, which accounts for 14.2% of forested land (I_P). With such a large presence, the area burned each year (I_E) is also high, but only half of what could be expected (F_B = 0.51), with a very low corrected risk index (F_C = 0.08), as only 15% of years exceed the normal threshold. It grows in Mediterranean areas particularly prone to forest fires due to climatic reasons.

4. Discussion

Forest fires are a relevant problem in southern Europe. The Mediterranean climate, in which dry and warm periods coincide, is particularly prone to the outbreak of forest fires, as shown by the adaptation of many plant species. Climate change is increasing the intensity of summer heat waves in this region, thus elevating the fire climate hazard. However, climate is not the most relevant factor in explaining forest fires in Spain, as the highest concentration of fires occurs in the reduced Atlantic region, which is among the wettest areas in Europe.

Four species that are high risk grow mainly in the Atlantic region (*Quercus robur*/*Q. petraea*, *Betula* spp., *Castanea sativa,* and *Pinus radiata*), two grow in the Atlantic and Mediterranean regions but with higher fire incidence in the former (*Pinus pinaster* and *Eucalyptus* spp.), and one is sub-Mediterranean (*Quercus pyrenaica*). The most abundant Mediterranean species, *Quercus rotundifolia*, on the other hand, presents a lower risk than expected, despite being highly adapted to fire, with intense and rapid regeneration from basal shoots even after high-severity fires, and higher rates of photosynthesis in resprouting individuals [71,72].

Therefore, although the Mediterranean region is climatically prone to forest fires, a simple relationship between Mediterranean species and fire incidence cannot be established, as human action plays a more important role.

Managing forest fire risk requires the use of models to assess hazards. At the community level, fuel models are mainly used, and at the species level, flammability models are used. However, flammability only explains 35% of the occurrence of fires by species, and considering relative values, it only explains 12%, with no significant correlation. It is therefore a useful tool, but it is limited in its predictive capacity.

The burned area of each forest species is a useful risk management indicator, but it is strongly influenced by the species' absolute distribution, which limits its ability to detect problems for less widespread species. Using relative indices that relate burned area to territorial extension allows the identification of issues that may be critical for certain species, even if they are not significant at the national scale. The proposed fire incidence index, calculated at a broad spatial scale, quantifies the relative impact of fires on different species in relation to their distribution, highlighting those disproportionately affected beyond what the general fire frequency or burned area data reveal. This information enables managers to prioritise targeted interventions such as fuel management, restoration, or protection measures for the most affected species. Additionally, the index can help guide monitoring programs by identifying vulnerable species that require closer observation, thereby improving the efficiency of fire mitigation strategies. For example, birch stands—uncommon in Spain, mainly located in Atlantic regions, and with low flammability—burn twice as much as expected; if this trend continues, their presence in the country could be compromised.

Relative fire indices may explain some adaptive strategies of the forest species. *Pinus canariensis* has exceptionally high risk indices; although fires above the expected threshold occur only in half the years, they are often devastating. However, this is the only resprouting pine in Spain, which allows it to recover after these extensive fires. In contrast, *Pinus halepensis* has a relatively normal risk level, somewhat high considering the basic index, probably due to its frequent use in plantations. Large areas of this pine burn every year in eastern Spain where the species is native, but it regenerates well from seed after fires [73,74], greatly facilitated because it is a serotinous species.

Relative indices also identify the most problematic species in Spain (*Pinus pinaster* and *Eucalyptus* spp.), which proves its validity as a management tool. The Iberian populations of *Pinus pinaster* exhibit variable adaptive traits in response to fire: some have thin bark and a high level of serotiny, adapted to frequent crown fires, while others have thick bark and low or no serotiny, having evolved in areas with low fire frequency [75]. A significant problem is that many reforestation efforts carried out in the last century did not take this aspect into account, which led to the introduction of ecotypes poorly adapted to the local fire regime in some places. As a consequence, the response of plantations of this species to fire is often unpredictable. *Eucalyptus globulus* is a species that burns easily, although it has the capacity to resprout; post-fire regeneration is due to basal resprouting in more than 89% of cases [76]. In any case, these are stands with very low naturalness, which, after a fire, are often replanted.

An analysis of forest fires in three provinces of Morocco over a 20-year period [77] concluded that the species with the largest burned areas were *Quercus rotundifolia* (82 ha) and *Pinus halepensis* (64 ha), but these are absolute values, so they do not reflect whether fire incidence is normal or higher than expected; affected areas are quite moderate compared to an average of 2400 ha and 5400 ha burned annually in Spain.

Several authors have indicated that fire risk is particularly high in conifers and eucalyptus, and lower in hardwoods [24–26,78]. This is true in absolute terms, but only partially in relative terms, as some hardwood species have a higher fire incidence than some softwood species. Moreover, the adaptive traits of pines show an evolution according to different fire regimes, with frequent crown fires in serotinous species such as *Pinus halepensis* and *P. pinaster*, and soil or infrequent fires in non-serotinous species such as *P. nigra* and *P. pinea* [79–81].

Similarly, it is not possible to establish a general relationship between relative fire incidence and the native or non-native origin of the species. Concerning the eight species with the most significant fire incidence, two are alien, planted mainly since the mid-20th century (*Eucalyptus* spp., *Pinus radiata*), one is also alien but was introduced centuries ago (*Castanea sativa*), one is native in the country but is widely used in plantations outside its native areas (*Pinus pinaster*), and four are native (*Pinus canariensis*, *Quercus robur/Q. petraea*, *Betula* spp., and *Quercus pyrenaica*). Fires in *Eucalyptus globulus* and *Pinus pinaster* stands in NW Spain, where both species are introduced, are the main concern in Spain, but there are also native species with a high relative fire incidence.

The high relative risk for oak, birch, and chestnut trees is a notable result, although it is already targeted in other areas for oaks [82]. This result is probably due to the vegetation structure of northern Spain, mosaics of grasslands, plantations (mainly *Eucalyptus globulus*, *Pinus pinaster,* and *P. radiata*) and copses of native species (such as *Quercus robur*, *Q. petraea*, or *Betula* sp.), where *Castanea sativa* is also frequent. Fires that affect pine and eucalyptus stands also do so by extension to oak, birch or chestnut stands, so the high risk detected in these hardwoods would be considered collateral damage. *Quercus pyrenaica* has its largest areas in sub-Mediterranean areas bordering the Atlantic region, precisely where the highest concentration of fires occurs [83]. Intentional fires are rare in oak stands, with traditional forest and livestock use, but they are affected by fires in adjacent pine and eucalyptus plantations, often considered by the local population as an appropriation of grazing areas [34]. Again, this would be collateral damage from pine and eucalyptus fires.

It has been pointed out that fire incidence is higher in plantation stands [27]. *Pinus pinaster* and *Eucalyptus globulus* occupy the first and third places in terms of fire extent; most stands of the former and all of the latter are plantations. However, *Pinus halepensis* occupies the second place, with native and reforested stands affected by fire, and *Quercus rotundifolia*, in fourth place, has nearly all natural stands. In terms of the corrected fire incidence index (F_C), *Pinus pinaster* and *Eucalyptus globulus* occupy the second and third places, but the species with the highest relative risk is *Pinus canariensis*, with 80% of natural stands, and fourth and fifth places were occupied by oaks and birches, both native and rarely planted.

5. Conclusions

Forest fires affect tree species differently. In this study, fire incidence indices for the main Spanish forest species were determined, considering their distribution, burned area, and fire frequency and recurrence. The two species with the highest presence, which also occupy the climatically most fire-prone areas, are not the ones with the highest relative fire incidence. There is a limited relationship between areas with high climatic hazards and species with high risk. In addition, there is also a limited correlation between flammability and fire extension, and it is not significant when considering relative fire incidence.The association between fire risk and conifers is valid in absolute terms (burned area), but only partially in relative terms. Similarly, there is no general relationship between relative fire incidence and origin (native or alien) of the species, or with a natural or reforested origin; the species with the highest risk, the Canary Island pine, is native with mostly natural stands. The high relative risk index detected in oaks, birches, and chestnut trees is likely to be a collateral effect caused by fires in pine and eucalyptus forests, which also spread to stands of these species. Human influence on fire occurrence is far greater than climatic and physiological aspects. Wildfire defence in Spain is primarily addressed through the provision of human and material resources to prevent and, above all, to extinguish forest fires with increasing efficiency. However, an effective wildfire strategy should include, in addition to these resources, the sustainable management of natural resources, as well as the implementation of awareness-raising, outreach, training, and the promotion of sustainable environmental management practices—adapted to the local population—that help to change social behaviour [84].

Relative fire incidence indices are useful for forest management, allowing special attention to be paid to species that are suffering severely from fire effects—even when this impact is not immediately obvious—helping managers identify hidden vulnerabilities and adapt strategies accordingly.

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