environments

MDPI

Article

Mapping Forest Fire Risk at a Local Scale—A Case Study in Andalusia (Spain)

Ismael Vallejo-Villalta *, Estefanía Rodríguez-Navas and Joaquín Márquez-Pérez

Departmen of Physical Geography and Regional Geographical Analysis, University of Seville, 41004 Seville, Spain; esrodrnav@gmail.com (E.R.-N.); jmarper@us.es (J.M.-P.)

* Correspondence: ivallejo@us.es; Tel.: +34-954-551-372

Received: 11 February 2019; Accepted: 26 February 2019; Published: 2 March 2019

check for updates

Abstract: Forest fires are a critical environmental problem facing current societies, with serious repercussions at ecological, economic and personal safety levels. Detailed maps enabling identification of areas liable to be affected is an indispensable first step allowing different prevention and protection measures vis-à-vis this kind of phenomenon. These maps could be especially valuable for use in land management and emergency planning at a municipality scale. A methodology is shown for producing local maps of mid- and short-term forest fire risk, integrating both natural and human factors. Among natural factors, variables normally used in hazard models are considered as fuel models, slopes or vegetation moisture stress. From the human perspective, more novel aspects have been evaluated, meant either to assess human-induced hazard (closeness to forestland of causative elements or the ability of people to penetrate the forest environment), or to assess vulnerability, considering the population's location in urban centres and scattered settlements. The methodology is applied in a municipality of Andalusia (Spain) and obtained results were compared to burned areas maps.

Keywords: forest fire; risk; hazard; vulnerability; GIS

1. Introduction

Forest fires are one of the main problems threatening forest ecosystems worldwide, with severe repercussions for societies occupying these environments. The years 2017 and 2018 were marked by the very serious cases of California and the Iberian Peninsula, where forest fires caused more than 100 deaths and thousands were forced to evacuate, indicating quite clearly that besides being an environmental problem of the first order, such phenomena pose a major threat to people's safety [1].

Even though in Spain the last decade witnessed a notable reduction in the number of such phenomena and the affected surface area [2], forest fire´s statistics are still worrying, as shown by the data published by the Ministry of Agriculture, Fisheries and Environment (MAPAMA) for the year 2017. According to that data, in Spain, a total of 13,793 incidents occurred, 8705 fire alarms (<1 ha) and 5088 fires (>1 ha), affecting a total of 178,234 ha. In Andalusia, a total of 968 incidents occurred, 761 fire alarms and 207 fires, and a total of 15,608 ha of scrubland and woodland were affected. What is truly alarming in that context is not so much the number of incidents but their recurrence and violence [3]; in the last year with complete data and analysis (2017), 98,072 ha (55%) of the total burned surface in Spain occurred in large forest fires or LFF (fires affecting an area larger than 500 hectares) [2].

The greater frequency and intensity of forests fires that are occurring results from the symbiosis between some natural conditions (terrain, climate and state and type of vegetation) that favour the outbreak and spread of fire [4] and the depth transformations experienced by societies and the rural and/or natural environment in recent decades. These changes have led to mass abandonment of traditional activities in these areas (farming, livestock-raising and forest utilisation), favouring the accumulation of combustibles prone to catching fire. This, added to other factors, such as the increase of uncontrolled property speculation, changed uses, disputes, hunting interests, the creation of pastures, rural depopulation, certain pathologies associated with fire and the increasingly more notable effects of climate change, are turning our forests into a perfect setting for the outbreak and spread of fire [4–6]. Along with those factors basically linked to hazard, the occupation of rural environments by other uses mainly associated to rural tourism and second homes [7,8] has, in recent times, led to an increase in human vulnerability vis-à-vis forest fires.

Regarding the ascertainment of a fire's origin, it is noteworthy that in most cases the immediate cause is never made entirely clear [9]; although, there is sufficient evidence to determine that the hand of man is either directly (intentional) or indirectly (accidents and negligence) behind 96% of the forest fires that occur every year in Spain and more than 80% of those that happened in Andalusia in the last year. That data notably contrasts with the scant 2% of fires that originate from natural causes, probably due to lightning, which is actually the only natural factor that causes fires in our country [6,10].

It is no easy task to define what risk is, owing to multiple current acceptances and the lack of a common terminology accepted by the entire scientific community [11]. However, one of the most broadly used definitions is the one employed in the field of natural disasters [1], where risk is conceived from an integral standpoint that would encompass in one single concept both the hazard or likelihood of an extraordinary event occurring [12] and the vulnerability or social, economic or ecologic susceptibility to natural or technological dangers [13,14]. Following these premises, if we transfer these definitions to the scope of forest fires, fire risk could thus be defined as being the probability of a forest fire occurring in a given place (hazard) and the potential damage that the fire might cause in that place (vulnerability).

The importance of studying such risks lies in the serious consequences, not just environmental (ecosystem degradation and loss of natural heritage) but also economic (costs derived from prevention, extinction, protection of the population and post-fire regeneration) and social (loss of property, personal belongings and in extreme cases, life), caused by a fire. It has, therefore, become increasingly necessary to generate and handle maps that identify and categorise areas more likely to be affected by an eventual fire. Such mapping is an essential requisite for planning and managing prevention measures, and also, for detecting and ending such events. In this regard, geographic information technologies (GIT) have shown, with multiple examples, that they are very effective tools for producing such mapping. Remote sensing, as a source of information for evaluating types and states of vegetation, and geographic information systems (GIS), as the most appropriate environment for integrating and processing data from multiple origins [15–17].

Research projects and works on wildfire hazard and risk mapping are numerous and diverse; complete compilations on such studies can be found in [18–20]. Regarding the scale, these studies include long-term, short-term and real-time approaches, from the time scale point of view, while global, regional, and local scales may be used as spatial scales. On the one hand, long-term risk is linked to features of a territory that do not vary periodically (topography or vegetation types) and is more suitable for strategic ends such as planning fixed anti-fire infrastructures or indicating a given number of personnel for a specific area [21]. On the other hand, short-term risk is linked to changeable factors (vegetation stress or climate conditions) and is updated using a time scale that can eventually be on a daily or even hourly basis (real-time), with tactical and mainly operative usefulness [22]. From a geographic point of view, global wildfires studies are usually linked to long-term approaches and are mainly focused on world fire regimes identification or on the assessment of climate change influence over these regimes [23,24]. In the same way, regional risk mapping includes a wide range of spatial scenarios—several hundred thousand to millions of square kilometers [25]; they might include international [26,27], national [28] or subnational approaches [29], and they are suitable for national and regional orientation of environmental and forest polices and legislation. Local risk mapping [30,31] refers to extensions below those aforementioned and obtained maps are especially suitable to be included in land management, wildfire risk information and communication, and emergency planning at the municipal or local community level [32–35].

This article presents a methodology for generating local-scale mapping of mid- and short-term forest fire risks. The mapping results from combining in a GIS environment the two groups of factors that determine the fire risk, i.e., hazard and vulnerability. Accordingly, for the case of hazard, structural (long-term) and evolving aspects were taken into account. Among the structural factors of natural order, slope gradients and fuel models were considered, while as human-induced structural factors (induced hazard), the closeness of certain elements that can be potential focal points of fires (transport and power infrastructures, settlements and scattered buildings, dump sites and recreational areas) were essentially considered, as well as human penetration capacity inside forest areas. As an evolving hazard factor, the moisture stress affecting vegetation, derived by processing of Landsat Enhanced Thematic Mapper Plus (ETM+) satellite images, was basically taken into account; no meteorological or weather data were considered, as they are only used to simulate daily or hourly conditions (mainly temperature and wind conditions) for higher extensions and the available data does not contribute to spatial discrimination in this sort of local fire hazard mapping.

For its part, an eminently human focus was used for the case of vulnerability, only considering the possible impact of fires on population centres and scattered settlements and isolated dwellings, as well as on power and communication networks.

The model was applied to the municipal territory of Algodonales in Cádiz province, with the idea of analysing, comparing and showing variations in the spatial distribution of risk on different dates in the selected period.

2. Materials

2.1. Study Area

The selected study area corresponds to the municipal territory of Algodonales; although, it was extended by 1 km in the surrounding area to take into account the influence that elements outside the municipality may have on fire risk. Algodonales is situated in the northeastern end of Cádiz province where it borders the province of Seville. It pertains to the Sierra de Cádiz region and has a surface area of 135 km^2, see Figure 1.

The municipal territory of Algodonales appears in the appendix of the INFOCA Plan (Andalusian Region Forest Fire Plan), which lists municipalities totally or partially affected by fire risk [36]. This is possibly due a priori to its biophysical characteristics: Average slope gradient of 28%, forest surface occupying 50% of the territory, formed mainly by highly inflammable Mediterranean sclerophyllous species (holm oak, wild olive, carob, mastic, gorse and rosemary, etc.), and a Mediterranean climate with a prolonged dry season (mean rainfall less than 4 mm) and high summer temperatures (mean temperature 24.5 °C). All this gives rise to a symbiosis of natural factors, which together with others of socioeconomic nature, such as the blend of human-induced and forest uses resulting from agro-forestry activity in the area, make Algodonales a suitable setting for the outbreak and spread of an eventual fire. The INFOCA Plan chose this municipality to locate some of its infrastructures used to detect, fight and prevent fires: Two watch posts situated on two of the highest points in the municipality (Picacho peak at 690 m and Sierra de Líjar at 1050 m) and a Forest Defence Centre [36].

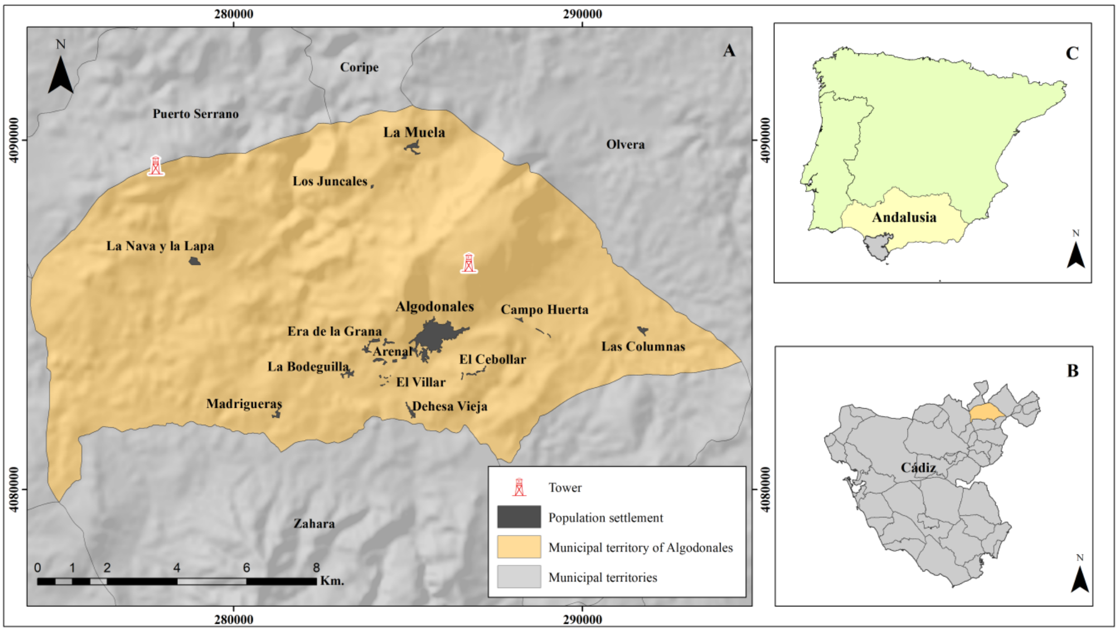

Figure 1. Study area (**A**) Municipality of Algodonales; (**B**) Algodonales in the province of Cadiz; (**C**) Province of Cadiz in Andalusia (Spain).

2.2. Data

To produce the proposed risk model, it was necessary to obtain data of distinct nature and origin. The data used is set out in Table 1.

Table 1. Data description and sources.

Data Description	Source	Format Type
Digital Elevation Model with 5-metre spatial resolution	IGN [1]	Raster
Pages 1035, 1036 and 1050 of the 0.5 metre RGB photography of PNOA 07–10	Line@ [2]	Raster
Landsat 7 ETM+ imagery corresponding to scene Path 201/Row 034	USGS [3]	Raster
Map of Plant Uses and Coverage (2007)	REDIAM [4]	Vector data (polygon features)
Information of the Andalusian Forest Plan (2007) WMS Service for Areas affected by fire obtained by means of remote sensing (1975–2014)	REDIAM [4]	OGC service
Urban system, roads *, paths *, railways *, power lines *, power stations, urban solid waste facilities, land uses, administrative divisions, economic/production fabric and services (2013)	DERA [5]	Vector data (polygon and lines * features)

[1] National Geographical Institute (Spain); [2] Spatial Information Localiser of Andalusia (Andalusia); [3] U.S. Geological Survey; [4] Environmental Information Network of Andalusia (Andalusia); [5] Reference Spatial Data of Andalusia (Andalusia). * vector line data.

The coordinate reference system (CRS) for the data is ETRS89 UTM Zone 30N and the spatial resolution for raster data is 5 m. The GIS software used for the modelling is ArcGis® version 10. Preprocesing. Processing and analysis of Landsat 7 ETM+ images, were carried out with ENVI® version 5.0 software. Finally, when it was necessary to identify or verify one or another aspect in situ, Google Earth® Street View® was used as support.

Before employing the Landsat 7 ETM+ images used to estimate the amount of plant humidity and produce fuel models maps, several geometric and radiometric corrections were made to eliminate alterations that might affect the imagery due to various factors such as the Earth's rotation, atmospheric effects or internal problems of the sensor itself [37], and owing to the existing correlation between the variables of interest (humidity) and the state of the atmosphere [38]. In sum, the procedure followed is indicated below and shown in Figure 2.

- Due to failure of the Scan-Line Corrector (SLC) on board Landsat 7 ETM+ on 31 May 2003, a gap-filling process was executed using the triangulation method available in ENVI.
- Re-projection of the image to the used CRS.
- Transformation of DNs (digital numbers) into radiance values;
- Correction of atmospheric effects to eliminate distortions that might cause an atmospheric effect in the image; for this correction the FLAASH module (Fast Line of Sight Atmospheric Analysis of Spectral Hypercube) in ENVI has been used [38].

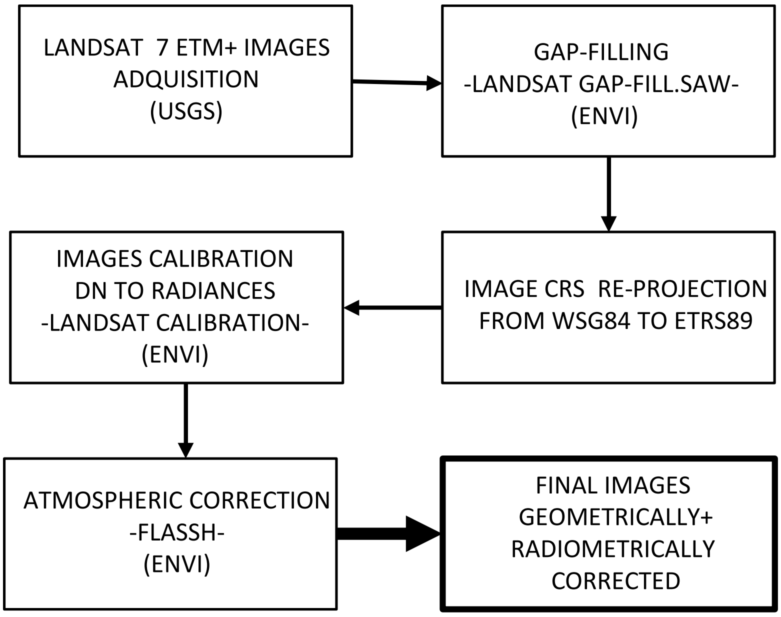

Figure 2. Preprocessing of satellite images.

3. Methodology

To estimate this sort of flexible term (mid/short-term) risk maps, two kinds of factors have to be considered, namely static and dynamic. In the case of natural hazard elements, static or fixed factors are (i) slope gradient and (ii) combustible type, while for the more time-dynamic factor (iii) moisture stress of the vegetation was chosen. To obtain induced hazard, only fixed factors are considered; thus, (iv) the closeness of causative elements [36] was taken into account, both as a distance or as a travel time on foot from some of those elements (roads, paths, settlement and recreation areas), as a way to estimate people's penetration capacity in the forest environment. Finally, (v) vulnerability was calculated taking into account how prone certain considered elements were before an eventual fire. The methodology is detailed below, see Figure 3.

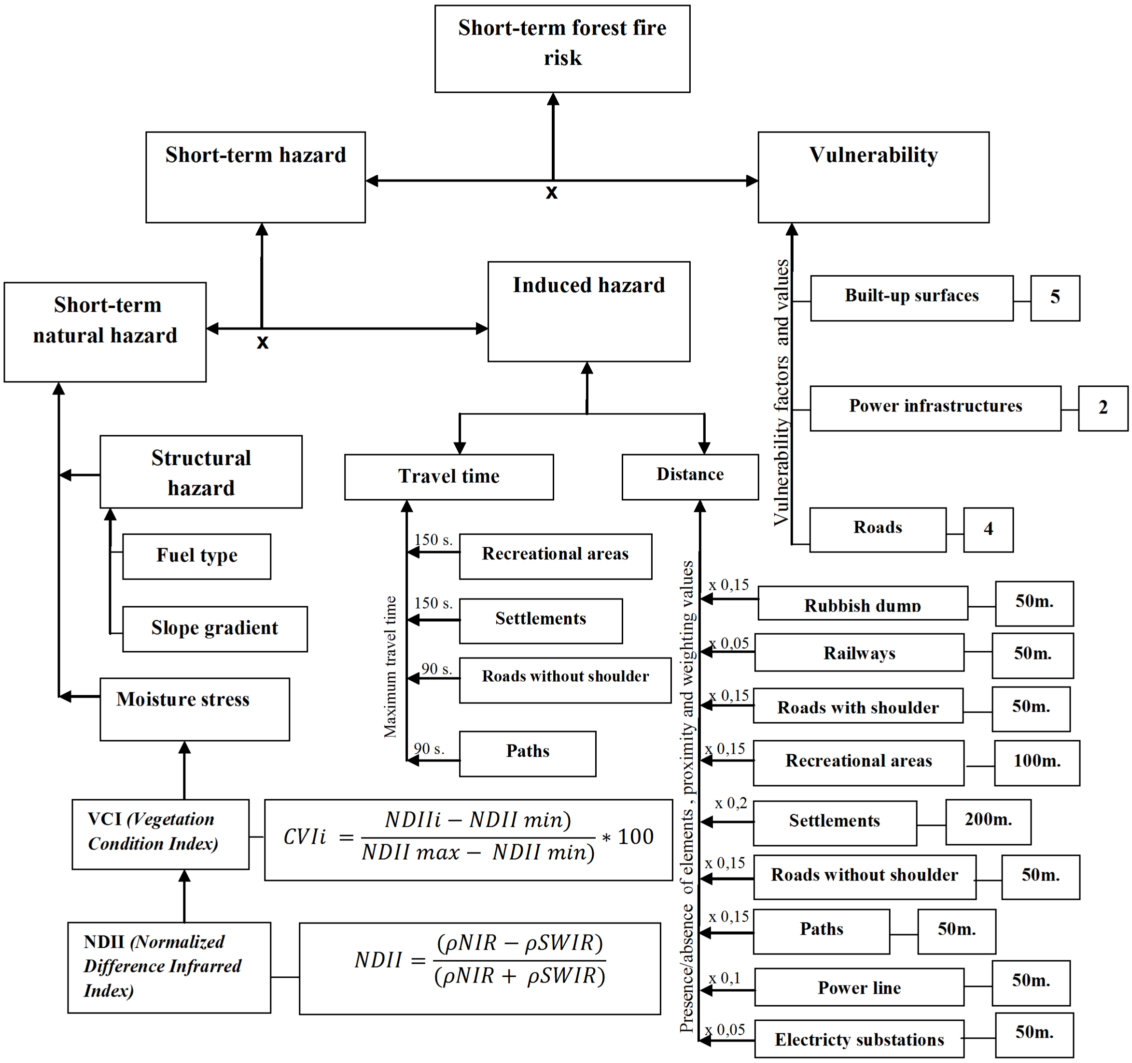

Figure 3. Methodology diagram.

3.1. Obtaining Natural Hazard

3.1.1. Slope Gradient

Slope gradient is one of the topographic features that most influences the speed and spread direction of a fire in so far as it favours the vertical fuel continuity and hence the upward spread of flames [4,35]. Following the model applied by the INFOCA Plan, five hazard levels according to slope steepness (expressed in percentage) have been established here (0–10, 10–20, 20–30, 30–50, and higher than 50).

3.1.2. Type of Combustible

The type of combustible or fuel is another key factor in fire behaviour because it affects the speed and intensity of flame propagation and determines the difficulty of controlling the fire [39–41]. Multiple vegetation characteristics can influence the fire's spread: Spatial distribution, combustibility, horizontal or vertical continuity, etc. Hence, and to facilitate fire prediction work, several fuel models have been duly created, the aim being to classify plants according to their characteristics and see how they influence the speed and intensity of flame propagation. One of the classifications most used was proposed by Rothermel in 1972 [42]; ICONA (Nature Conservation National Institute) adopted it for the entire national territory. That classification distinguishes among 13 fuel models depending on the flame-spreading element. Those 13 models are grouped in four broad categories: Pastures, scrub, leaf litter under trees and cutting debris and forestry operations [36,39,43]. From these original 13 fuel models, only 11 have been correctly identified in Andalusia [36], and from these 11 types, only 9 exist in the study area.

Due to the lack of classification or mapping of fuel models at the chosen scale, a decision was made to produce one in this work. For that purpose, a supervised classification was undertaken using the algorithm of maximum probability [44,45] based on a Landsat 7 ETM+ image dated 12 July 2014. The result obtained was subject to visual verification with the help of fieldwork and Street View®, showing an appropriate correspondence between model and reality, see Figure 4.

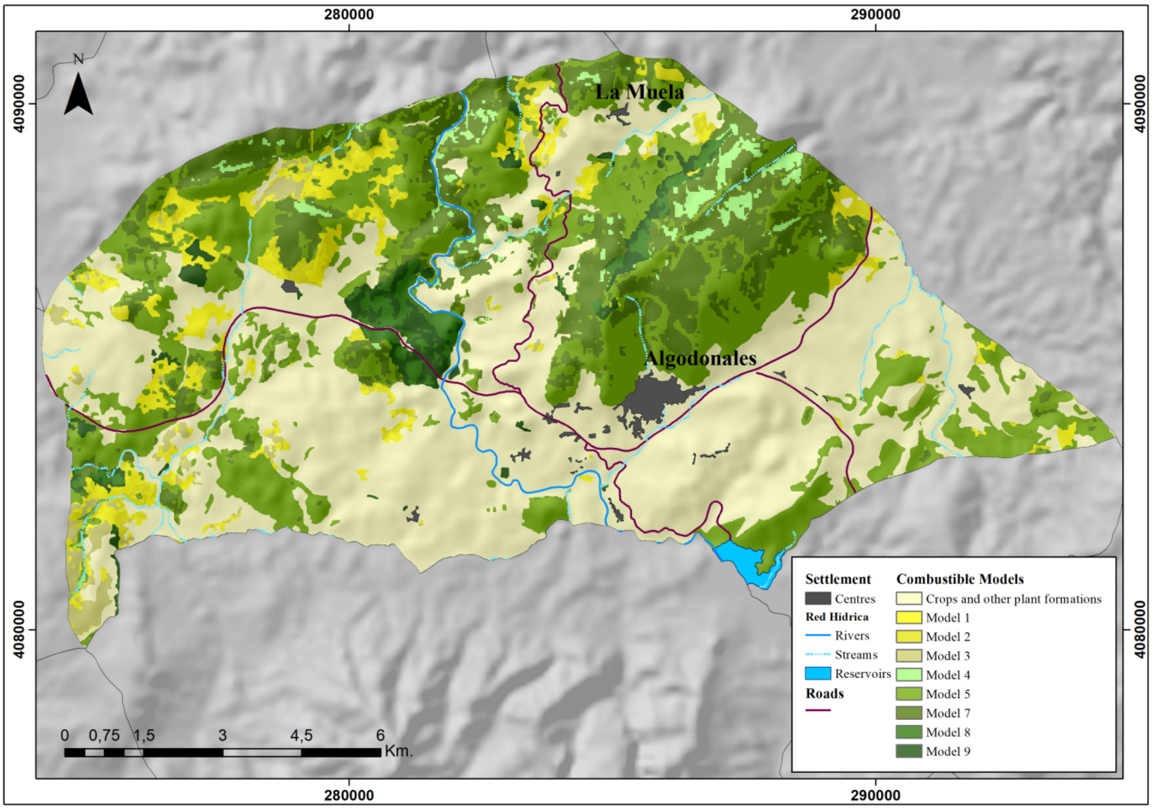

Figure 4. Fuel/combustible models.

Based on the mapping of fuel models, the hazard per combustibility was obtained, assigning a numeric value from 1 to 5, see Table 2, according to the dynamic and energetic characteristics of the fire on the combustible, depending on reaction intensity (IR), speed of propagation (SP), linear intensity (LI), heat per area unit (heat/s) and flame length (FL) [36].

Table 2. Hazard classification of fuel models.

Fuel Model [1]	Hazard Class Per Combustibility	Numeric Value
No combustible	Very low	1
8-5	Low	2
9-1-3	Moderate	3
7-6-2	High	4
4	Very high	5

[1] Fuel model number according to [34].

3.1.3. Vegetation Moisture Stress

To introduce the short term or the dynamic component of natural hazard, the moisture stress on vegetation was considered. Along with the combustible's characteristics, the vegetation's moisture content is another decisive factor for the outbreak and behaviour of a fire [46]. The extensive coverage in both space and time offered by different sensor types has made remote sensing a useful tool for studies of vegetation [16] and respective conditions, enabling changes to be detected in them, such as those examined here linked to moisture content [47].

The Vegetation Indexes (VIs) are calculated based on the reflectance values in different wavelengths, trying to ensure that atmospheric and ground influences are minimal [48]. In this paper, the NDII (Normalised Difference Infrared Index) was calculated first, and afterwards, the relative Vegetation Condition Index (VCI) was calculated [49].

In this work, it was decided to use the NDII for two reasons: First, because the wavelengths of near (NIR)- and short (SWIR)-infrared channels participate in its estimation, the latter more sensitive to the absorption and variability of plant water content [50]. Second, because studies such as the one conducted by Cocero, Salas and Chuvieco [51] have shown that this index is more sensitive to humidity changes compared to others such as the NDVI or SAVI (Soil Adjusted Vegetation Index). To obtain the NDII for a specific image, the respective formula was applied:

$$\mathrm{NDII} = (\varrho\mathrm{NIR} - \varrho\mathrm{SWIR})/(\varrho\mathrm{NIR} + \varrho\mathrm{SWIR}), \quad (1)$$

where ϱNIR is reflectance in near infrared (band 4 in Landsat 7 ETM+ and ϱSWIR is reflectivity in medium infrared (band 5 in Landsat 7 ETM+). This index provides values between −1 and 1, where a value close to −1 indicates less water content (more dryness) and a value close to 1 indicates more water content (more moisture).

The VCI (Vegetation Condition Index) was subsequently calculated; this index has been used in numerous studies to assess how dryness affects vegetation and the impact of climate conditions on them [52]. Its formula is based on the NDVI [53]; although, in this article the NDVI was logically replaced by the NDII as it is the index used to determine moisture stress. The formula applied is the following:

$$\mathrm{VCI_i} = [(\mathrm{NDII_i} - \mathrm{NDII_{min}})/(\mathrm{NDII_{max}} - \mathrm{NDII_{min}})] \times 100, \quad (2)$$

where VCIi is the Vegetation Condition Index for each date; NDIIi is the index for dryness on the date in question; NDIImin is the index of minimum dryness from the 2010–2014 time series and NDIImax is the index of maximum dryness from the 2010–2014 time period.

The VCI gives values between 0 and 100 and reflects the relative variability in vegetation conditions, whereby values close to zero indicate severe dryness conditions while those close to 100 indicate optimal humidity conditions [54,55]. The VCI for each date was later reclassified in five classes with the same range (every 20). Those classes were established based on the humidity conditions obtained by interpreting the aforementioned VCI. For each class, a numeric index was accordingly established, as shown in Table 3.

Table 3. Classification of the Vegetation Condition Index (VCI).

VCI Range	Numeric Index	Dryness Level
(0–20)	5	Extreme
(20–40)	4	Severe
(40–60)	3	Moderate
(60–80)	2	Light
(80–100)	1	Very light

The natural short-term hazard results from integration of the three factors considered the slope gradient, combustible type and moisture stress, see Tables 4 and 5. The combination of the first two is known as structural hazard [36]. When moisture stress is added, the structural hazard acquires the short-term scale according to the nature of this last factor. Therefore, to generate a natural short-term hazard, the hazard per gradient and per combustible was first integrated, resulting in the structural hazard, see Table 4, which was later integrated with moisture stress, see Table 5.

Table 4. Structural hazard.

		Slope Intervals (%) and Their Hazard Classification				
		0–10%	10–20%	20–30%	30–50%	>50%
Fuel Models (FM) and Their Hazard Classification		**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Other natural spaces	**(1)**	1	2	3	3	4
FM 5 and 8	**(2)**	1	2	3	4	5
FM 1, 2, 9 and 11	**(3)**	1	3	4	4	5
FM 6 and 7	**(4)**	1	3	4	5	5
FM 4	**(5)**	2	3	4	5	5

Table 5. Natural short term hazard.

Moisture Stress Intervals and Their Hazard Classification		**Structural Hazard (from Table 4)**				
		(1)	**(2)**	**(3)**	**(4)**	**(5)**
100–80	**(1)**	1	2	3	3	4
80–60	**(2)**	1	2	3	4	5
60–40	**(3)**	1	3	4	4	5
40–20	**(4)**	1	3	4	5	5
20–0	**(5)**	2	3	4	5	5

3.2. Obtaining Induced Hazard

As commented previously, a high percentage of fires are caused by human actions and activities. To envision this factor, certain elements with cartographic portrayal were considered, based on which the induced hazard was estimated. The causative elements to calculate the induced hazard were chosen according to statistical data on forest fire causes in Andalusia [36]:

- Electric power lines and substations: Downed lines or vegetation coming into direct contact with those infrastructures as well as substation short circuits;
- Transport infrastructures (roads, paths, trails and railway): Eventual accidents, garbage accumulated on or by platforms, lit cigarette butts or railway sparks;
- Dumps: Uncontrolled burning of garbage and the proliferation of illegal dumps in or near forest areas;
- Recreational areas and lookout points: Garbage accumulation, lit cigarette butts or badly extinguished barbecues in such areas, which are often situated in forest areas for recreational use;
- Population centres and scattered rural buildings: Badly extinguished hearths, the burning of stubble or agricultural waste, plant destruction by farming interests, disputes, hunting interests, etc.

The factors of induced hazard were considered based on the location of these elements. On the one hand, the distance or closeness of these elements was calculated, and on the other, the travel time on foot from some of them, thereby introducing the capacity of human penetration in forestland. Regarding the latter, it must be borne in mind that the slope gradient influences movement on foot; the flatter the surface, the greater the distance travelled in a given time [56,57]. Naturally, travel times and distances were only calculated for those elements from which people can make incursions into the forest environment, such as the cases of paths, roads without shoulders, recreation areas, lookout points, population centres and scattered rural buildings.

On the other hand, and because the frequency associated with these elements in fire occurrence is not the same (e.g. fires produced by substation short-circuits or electric generators are relatively rare, while those caused by contact of power lines with vegetation or due to their falling abound [53]), each element was assigned a weighting coefficient that was proportional to the importance of this element in fire outbreaks [36].

Table 4 details the maximum times and distances calculated in each case per the review of national and regional statistics on fire causes. With respect to the maximum time values, they are dependent on what is estimated to be possible per given circumstances. After consulting a group of forest fire fighters (oral communication), it was considered relatively unlikely for a person to stray more than a minute-and-a-half away from a path in such wildland areas, whereas in recreation areas and lookout points—rest places—it is easier to go farther (100 m) or do so for more time (two-and-a-half minutes). For the cases of population centres and scattered rural buildings, they were assigned a distance and time of 200 m and two-and-a-half minutes, respectively, given that the activities that can take place there are most liable to create a focal point of fire.

The methodology for obtaining the induced hazard consisted of two different processes; thus, for all elements, the next sequence was followed:

- Calculation of the Euclidean distance around all elements, establishing the corresponding maximums;
- Standardisation of values between 1 and 5;
- Values were inverted, due to the inverse relationship between hazard and distance;
- Weighing of the values (according to Table 6).

Table 6. Causative elements (induced hazard).

Causative Element	Weighting Coefficient	Distance (m)	Time (s)
Electric power lines	0.1	50	-
Electricity substations	0.05	50	-
Paths	0.15	50	90
Roads without shoulder	0.15	50	90
Roads with shoulder (regional)	0.15	50	-
Railway	0.05	50	-
Dumps	0.15	50	-
Recreation areas and lookout points	0.15	100	150
Settlements	0.2	200	150

In the cases where travel time on foot was also considered, a set of different steps was necessary:

- Calculation of time (in seconds) of travel (T) on foot depending on slope gradient ($\Delta h/\Delta d$), applying the Naismith Rule [51]:

$$T = 0.746 + ((3600 \times [(\Delta h/\Delta d)])/609.6), \tag{3}$$

- Calculation of distance (in metres) depending on the time established above;
- Standardisation, inversion and weighing of values as set out in Table 6;
- Choice of the maximum value of length among those provided per Euclidean distance, see Figure 5A, and travel time, see Figure 5B: In areas with steep slopes, the maximum length reached was 50 m, whereas, in flatter areas, 208 m was reached, see Figure 5C.

Finally, the induced hazard results from the sum of the weighted values of distance and travel time of each element. That sum was reclassified in equal ranges which were assigned a value between

1 (no hazard) and 5 (maximum hazard), with the aim of making the values of that hazard compatible with the natural hazard obtained in the previous section.

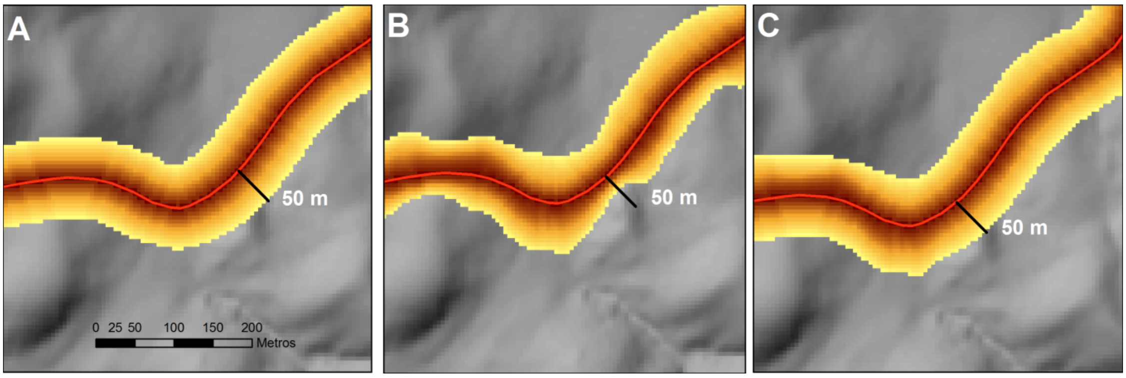

Figure 5. Ability of people to penetrate the forest environment (induced hazard). (**A**) Length provided per Euclidean distance. (**B**) Length provided per travel time estimation. (**C**) Selection of maximum length provided per A or B.

3.3. Obtaining Final Hazard

The final hazard map results from the product of the natural hazard and induced hazard. That hazard, whose values waver between 0 and 25, was reclassified in six classes; a class for 0 (nule hazard) was included for those areas where fuel is absent.

3.4. Vulnerability

For the purposes of this paper, to determine vulnerability, only certain human-induced elements which can be damaged by fires and lead to personal and/or economic loss were taken into account. Other kinds of potential economic or ecologic losses linked to specific effects on vegetation were thus excluded. The elements considered in the end were hence the following:

- Electric power infrastructures: power lines and electrical substations;
- Roads, as they are people's main safe evacuation routes;
- Built-up surfaces: main and secondary urban centres, scattered rural buildings, dispersed settlements and industrial areas.

All these elements were assigned a value indicating the kind of damage that would result from their loss or from suffering effects due to fire, see Table 7; the resulting final vulnerability is the sum of the values of spatially coincident elements.

Table 7. Factors for vulnerability estimation.

Vulnerable Elements	Type	Value
Built-up surfaces	Main and secondary urban centres Scattered rural buildings Dispersed settlements Industrial fabric	5
Energy infrastructures	Power lines Electrical substation	2
Routes of communication	Roads	4

3.5. Obtaining Final Forest Fire Risk

The final risk map of the forest fire is the result of multiplying the two components integrating the risk: short term hazard and vulnerability. In this work, the resulting values waver between 0 and 45 and were reclassified between 1 and 5. The value 0 remains on the margin as it indicates no risk.

4. Results

The exposed methodology was applied to a total of 20 different images during the 2010–2014 time period, this means that 20 different VCI images were derived, see Figure 6, from which the same number of hazard and risk maps were obtained. Due to the volume of information, it was decided to show the corresponding results for two different dates in the year 2013, when the greatest seasonal contrast occurred and thus a higher variation in the spatial distribution of risk could be observed.

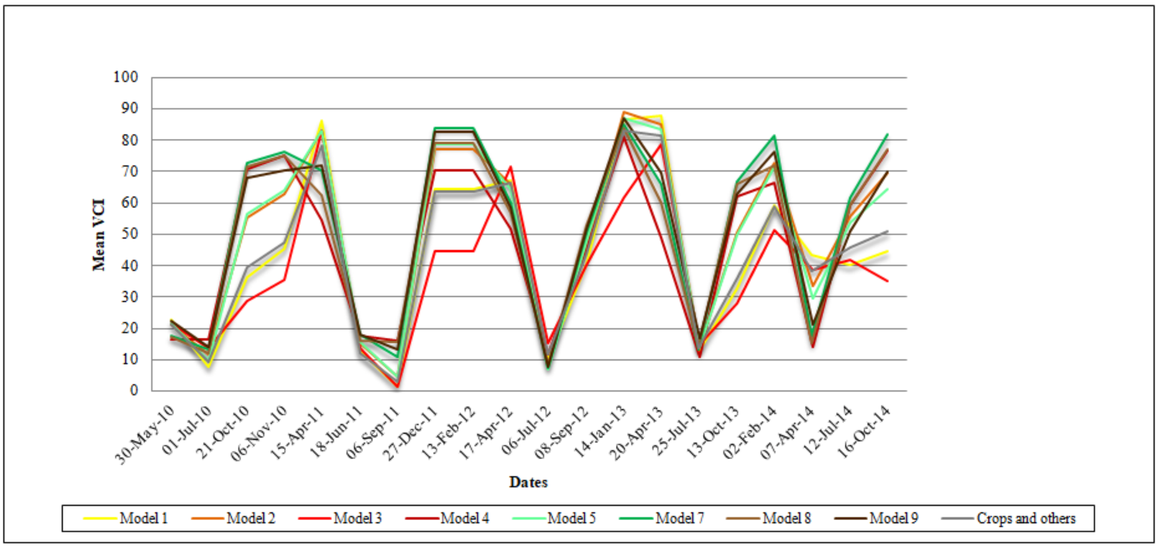

Figure 6. Vegetation Condition Index evolution (2010–2014) by fuel model.

4.1. Natural Forest Fire Hazard

When natural short-term fire hazard maps for the dates 14 January and 25 July 2013 are observed, it can be seen how hazard level and distribution totally change from one date to another, see Figure 7. Thus, while on 14 January (winter), the hazard is very low in practically the whole municipal territory, see Figure 7A, for 25 July (summer) the situation is the opposite: The hazard is extreme throughout the municipality, with no areas of low/very low hazard, see Figure 7B. The explanation is that in the latter season, the vegetation reaches its maximum stress due to scant precipitation (0.2 mm in June and July 2013), contrary to what happens in January when the vegetation shows optimal humidity conditions, a situation in accordance with rain measurement data gathered in the area for the months immediately before the date.

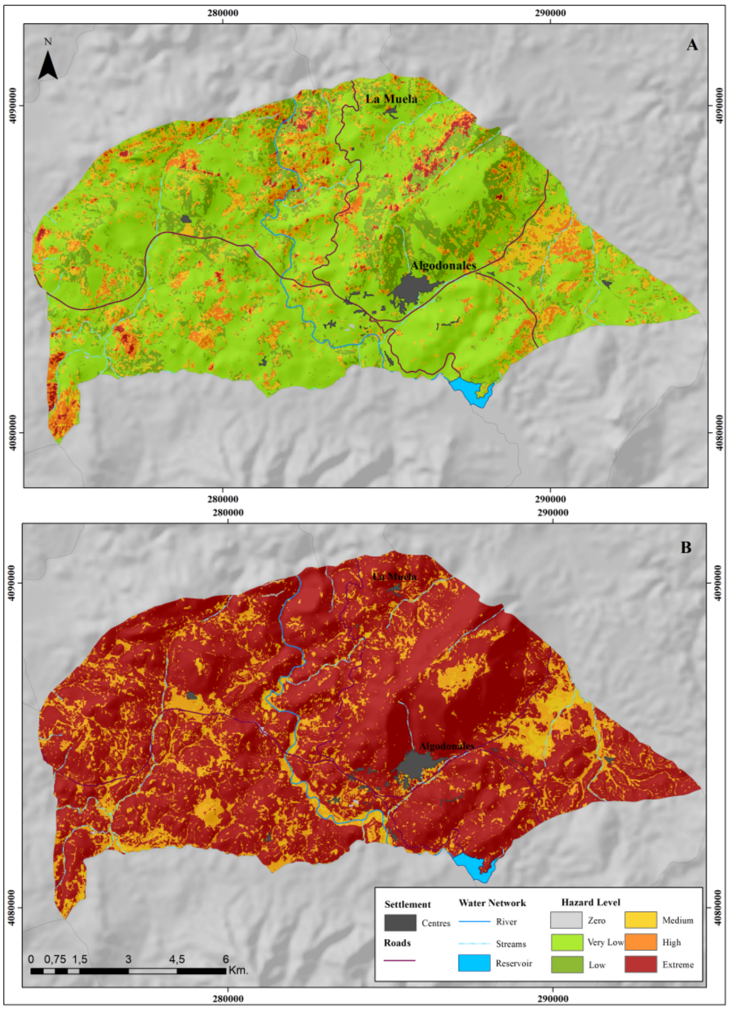

Figure 7. Short-term natural hazard maps. (**A**) 14 January 2013. (**B**) 25 July 2013.

4.2. Induced Forest Fire Hazard

The mapping of induced hazard obtained after implementing the proposed methodology shows different hazard levels based on the presence/absence of causative elements, their proximity and human penetration capacity in the forest environment. The mapping hence shows that the areas with higher induced hazard correspond to areas that are greatly affected by humans, where the concentration and intersection of various causative elements occur. These areas are mainly located in the municipality’s southern quadrant, around the main centre; although, also around the secondary centre of La Muela and close to dispersed settlements situated west of the main centre, see Figure 8. The areas with medium hazard are those close to routes of communication and extend to where a person is able to travel in the maximum stipulated time. The fact that the areas with maximum hazard are found near infrastructures such as routes of communication or population centres is significant in so far as those are the areas where a fire is more likely to break out and within a short time affect some of those elements, with serious consequences: blocked roads or damage to settlements.

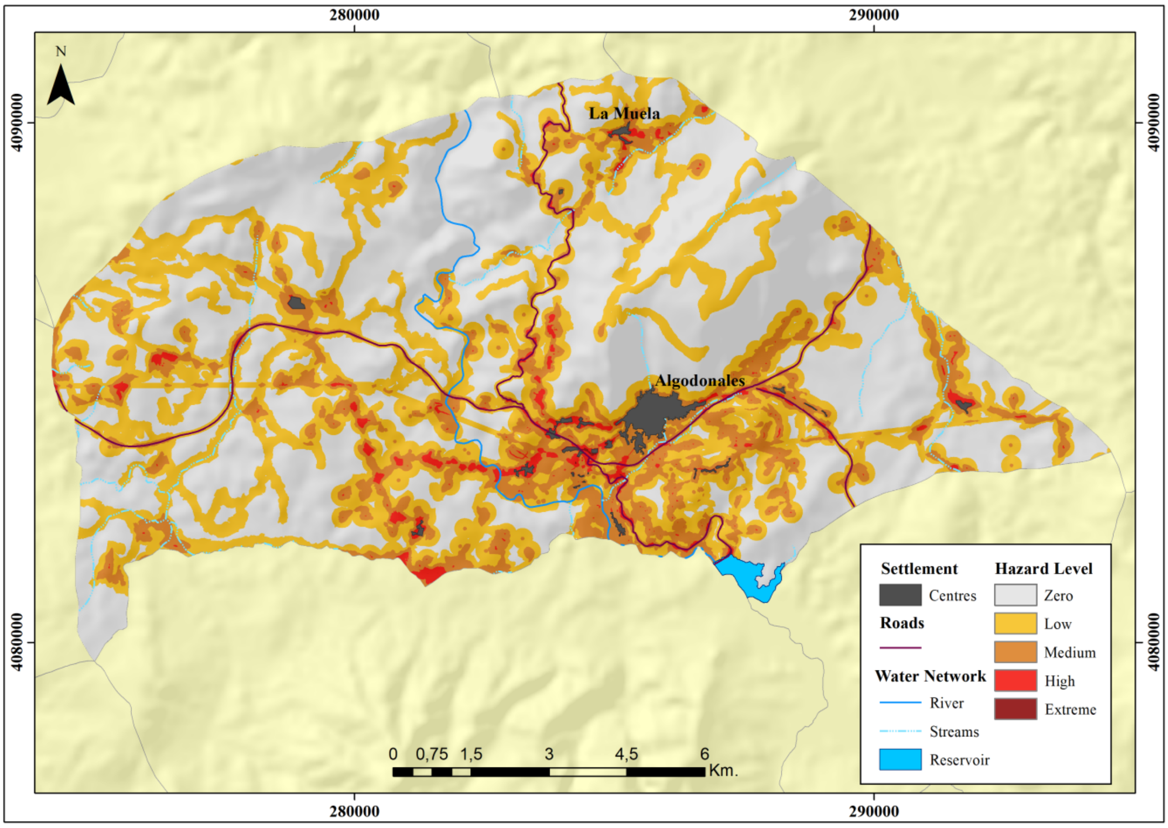

Figure 8. Induced hazard map.

4.3. Final Forest Fire Hazard

The obtained maps show the spatial distribution of fire outbreak hazards, see Figure 8. In general, the variations produced are closely related to the natural short-term hazard; as expected, the hazard is higher in July, see Figure 9B, than in January, see Figure 9A, when there are no areas with high/extreme hazard. In July, as opposed to January, the large presence of high-hazard areas around roads, paths and settlements is noteworthy; there is no area with a low hazard. The highest concentration of such areas is seen in the municipality's southern quadrant, around the main centre where the confluence of causative elements and some extreme natural conditions specific to the time of year determine the high degree of hazard.

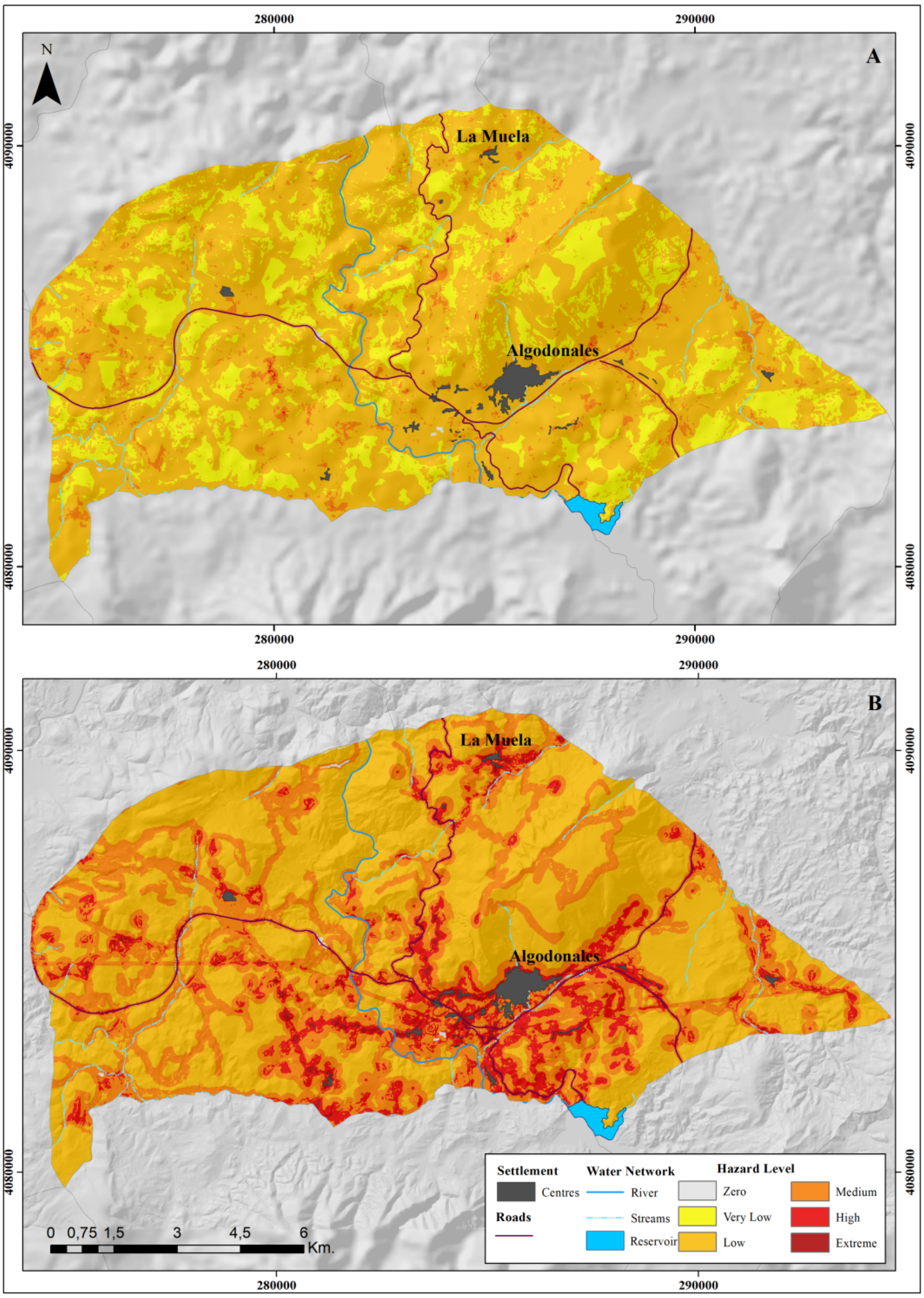

Figure 9. Final hazard map (natural + induced). (**A**) 14 January 2013. (**B**) 25 July 2013.

4.4. Vulnerability

The vulnerability map shows areas most liable to suffer some damage when affected by a fire, see Figure 10. Given that to obtain the vulnerability in this article, only very specific elements associated to humans were taken into account; the highest vulnerability levels are found in areas where there is a spatial coincidence of several of those vulnerable elements (settlements, routes of communication, electric power infrastructures). Most of the population settlements present more vulnerability than the other elements because the losses that can be caused by fire, besides the material ones, can be personal. Such areas are very exposed to possible fire in summer as shown by the July hazard mapping, where the areas with most hazard are found close to population settlements and routes of communication.

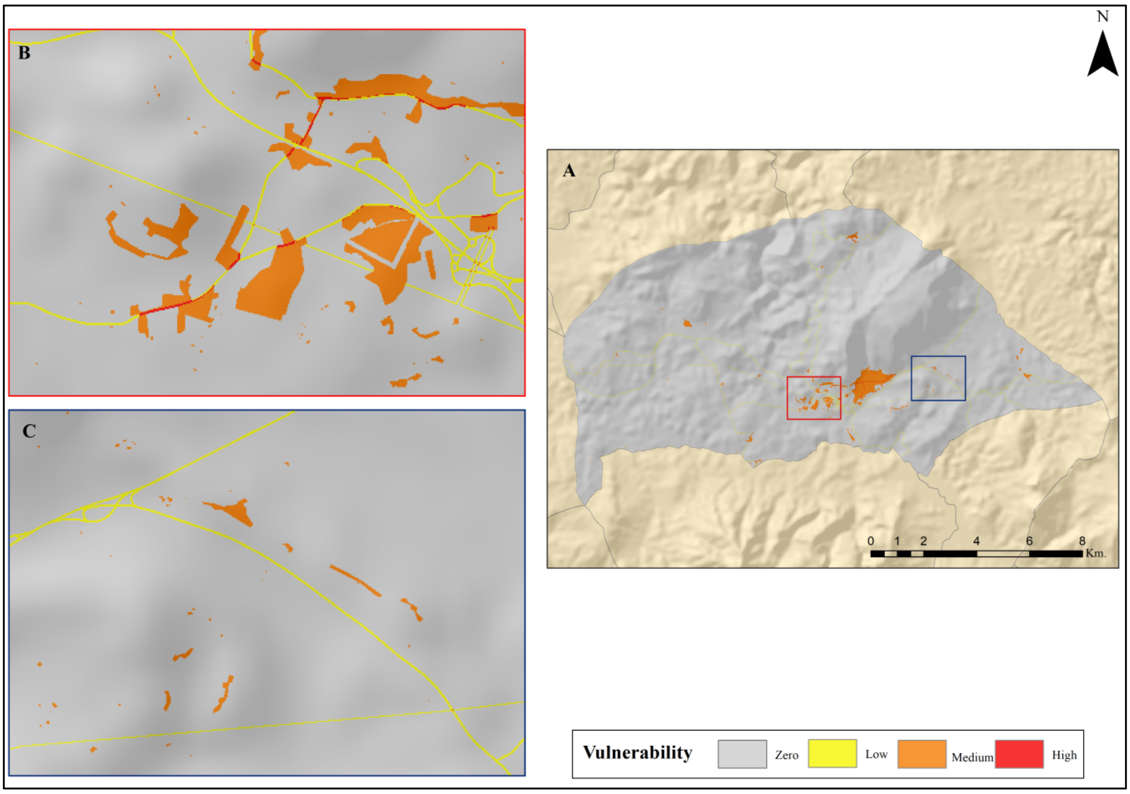

Figure 10. Vulnerability map.

4.5. Short-Term Forest Fire Risk

The mapping of short-term fire risk shows the differences in the spatial distribution of risk from one date to another, see Figure 11. In January, the risk is very low in practically the entire municipality; low risk is only seen around some roads that cross the municipality, see Figure 11A. The risk situation in July varies considerably in so far as there is a greater presence of areas with medium/high risk, see Figure 11B. These areas are again concentrated around scattered settlements, the secondary centre of La Muela, the main centre of Algodonales, and in areas at the foot of the eastern and western slopes of the Sierra de Líjar. The rest of the municipality has low/very low risk. The differences between one period of the year and another are quite substantial, which is fundamental for planning and managing prevention measures and the mobilisation of the number of fire-fighting and watch personnel, especially in areas with maximum exposure, which in the case of Algodonales coincide with major population centres such as the main centre and the hamlet of La Muela. These variations reflect the natural and, especially, climatic conditions which, although not taken directly into account in the methodology, were actually considered indirectly by introducing the moisture stress on vegetation, a variable that depends on accumulated climate conditions when the picture was taken.

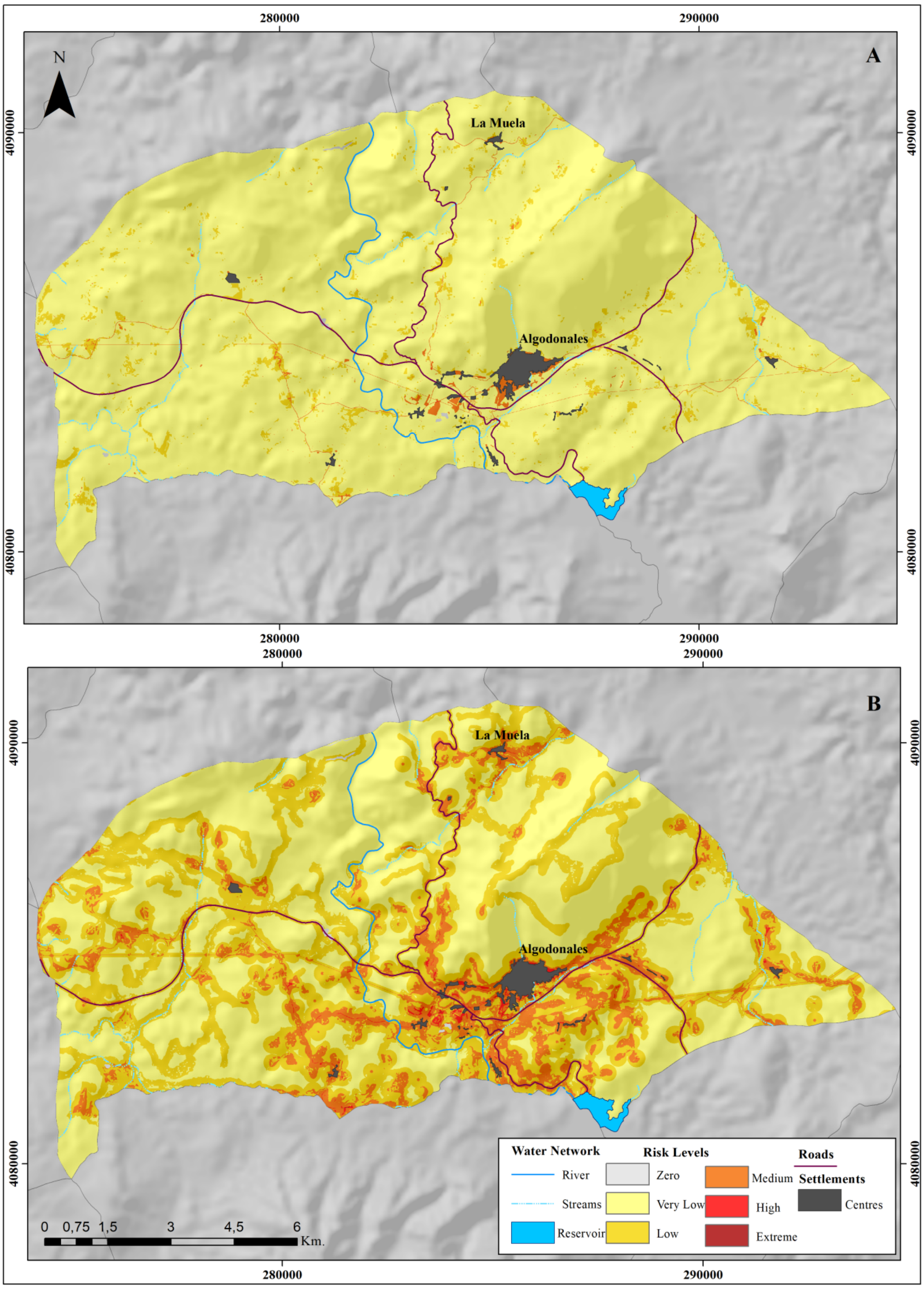

Figure 11. Short Terms Risk maps. (**A**) 14 January 2013. (**B**) 25 July 2013.

The sole presence of these conditions does not explain variations in the surface occupied by each risk level; the greater or lesser presence of causative elements is also a variable that impacts risk. The high-risk areas in July result from extreme natural conditions marked by very high moisture stress, where the concentration of causative elements aggravates the ignition and outbreak of a fire, while in January, the lack of risk is associated with climate conditions that are generally more humid and where, despite the presence of causative elements, the likelihood of a fire breaking out and spreading is more remote.

5. Discussion and Concluding Remarks

The amount and diversity of variables that directly or indirectly influence the outbreak and behaviour of fire, as well as the difficulty of modelling many of these variables (especially those associated with human behaviour), make it hard to design a fire risk model that is able to generate sufficiently reliable mapping.

The fire hazard mapping obtained enables, on the one hand, the identification and localisation of areas with higher hazard on a long/ medium term basis that allows local authorities to improve their capacities for planning fixed anti-fire infrastructures (watch towers allocation, firebreaks construction). On the other hand, it shows the spatial variability of the hazard on different dates in a specific year (the year 2013 in this study), clearly reflected in the short-term hazard mapping for the study period. The importance of this multi-time approach of short-term fire hazards is manifested here, in so far as knowing how the spatial hazard pattern changes at different times during the year or from one year to the next year(s) is useful so that, depending on the season, more attention can be paid to certain areas during a given time or period. Even on a weekday basis, certain measures such as patrol route planning or specific sites communication for certain activities prohibition could be undertaken considering this detailed information and specific extreme weather early warnings.

Although the municipality of Algodonales was not affected by forest fires in the studied period, a comparison has been made among obtained maps and burned areas data (1975–2014) available from REDIAM, see Figure 12. In spite of the unknown causes of these specific forest fires, it can be observed that most of the fire perimeters include areas of high hazard level from where outbreaks of fire can take place; thus, in a first approximation, these areas should be considered in incoming fire prevention planning.

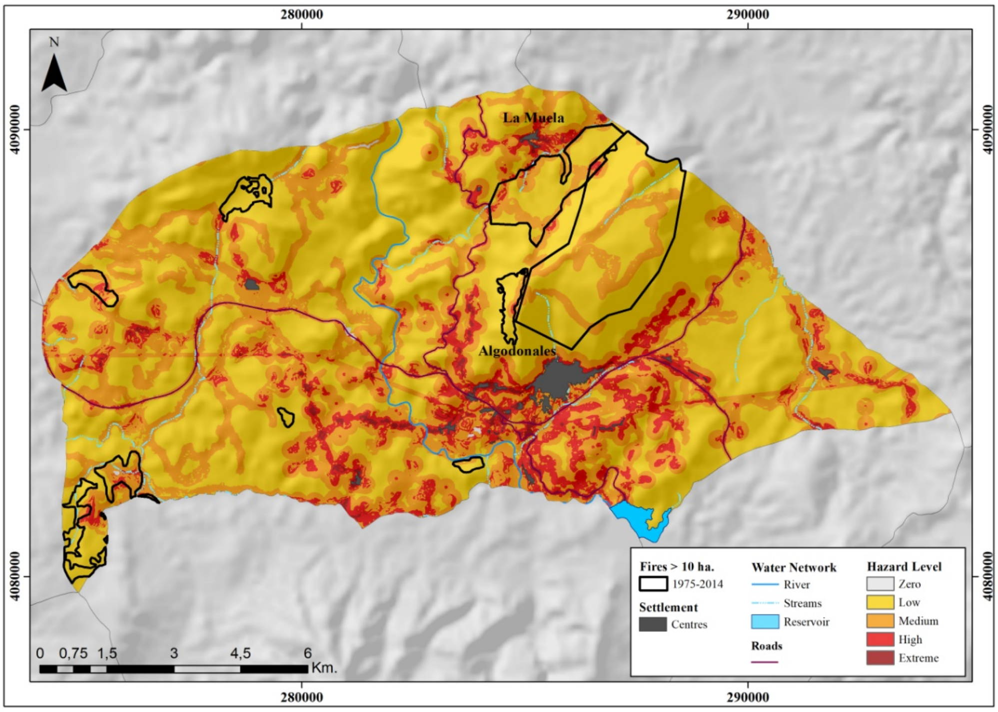

Figure 12. Final hazard map in July 2023 (Figure 8B) and occurred fires in the study area (Burned areas data extracted from REDIAM).

In the same way, in the case of risk maps, they should be considered in future fire emergency plans, as they outline sectors of main and scattered settlements, as well as transport and power infrastructures that could likely be affected by wildland fires.

In general terms, the simplicity of the proposed method and the availability of the required data, allows its straightforward application to a wide range of regions. With a view to future applications, some improvements could be undertaken that could address the main limitations. Related to fuel models, the use of different images from different seasons could improve the classification of fuel types, as phenology would be taken into account for the distinction of vegetation types. Field checking of obtained fuel classification should be another way to improve the results. In the case of topography, other variables should be considered in addition to slope (i.e aspect). Regarding the short-term induced hazard, other sources of data could be used such as cadastre spatial information, as it provides more precise localization and identification of building in rural areas. In this sense, data related to the seasonal occupation of natural/rural second houses or any other type of tourist facilities (camp sites, resting areas, trails) or about seasonal road traffic should improve their characterisation as hazard elements.

Regarding vulnerability, the above-mentioned use of cadastre spatial information should enhance the identification of potentially affected elements. In addition to this, an overall vulnerability could be designed that includes not just specific elements of the territory but also environmental factors and other variables such as the closeness of routes of communication (from the standpoint of speed of putting out a fire) or the difficulty/ease of access to vulnerable areas, as there are conditions that can make access to those areas difficult. These questions can be approached in greater detail by means of maps of isochrones generated from cost/distance surfaces, or by analysing transport networks.

Author Contributions: Work coordination, conceptualization, methodology and supervision, I.V.-V.; Data gathering, remote sensing images processing and writing, E.R.-N.; GIS analysis, E.R.-N. and J.M.-P.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNISDR. Wildfire Hazard and Risk Assessment. Available online: https://www.unisdr.org/files/52828_06wildfirehazardandriskassessment.pdf (accessed on 10 July 2018).
2. MAPAMA. Incendios Forestales 01/01/2017–31/12/2017. AVANCE INFORMATIVO. Available online: https://www.mapa.gob.es/va/desarrollo-rural/estadisticas/iiff_2017_def_tcm39-446071.pdf (accessed on 20 January 2019).
3. Araque, E. Medio siglo de grandes incendios forestales en Andalucía (1961–2011). *Méditerranée* **2013**, *121*, 41–52. [CrossRef]
4. Verdú, F.; Salas, J. Caracterización de las variables biofísicas en los incendios forestales mayores de 25 ha. de la España peninsular (1991–2005). *Bol. Asoc. Geógr. Esp.* **2011**, *57*, 79–100.
5. Lloret, F. Régimen de incendios y regeneración. In *Ecología del Bosque Mediterráneo en un Mundo Cambiante*; Valladares, F., Ed.; Ministerio de Medio Ambiente: Madrid, Spain, 2004; pp. 101–126. ISBN 978-84-80-14738-5.
6. Martínez, J.; Martínez, J.; Martín, M.P. El factor humano en los incendios forestales: Un análisis de factores socio-económicos relacionados con la incidencia de incendios forestales en España. In *Nuevas tecnologías para la Estimación del Riesgo de Incendios Forestales*; Chuvieco, E., Martín, M.P., Eds.; Consejo Superior de Investigaciones Científicas (CSIC): Madrid, Spain, 2004; pp. 102–142. ISBN 978-84-00-08275-8.
7. Prados, M.J. Naturbanización y patrones urbanos en los parques nacionales de Andalucía. *Bol. Asoc. Geógr. Esp.* **2012**, *60*, 19–44.
8. Galiana, L. Las interfaces urbano-forestales: Un nuevo territorio de riesgo en España. *Bol. Asoc. Geógr. Esp.* **2012**, *58*, 205–226.
9. WWF. Incendios Forestales ¿Por qué se Queman los Montes Españoles? Available online: http://assets.wwf.es/downloads/incendios_20051_1.pdf (accessed on 12 July 2018).
10. Pacheco, C.E.; Aguado, I.; Nieto, H. Análisis de ocurrencia de incendios forestales causados por rayo en la España peninsular. *Rev. Int. Cienc. Tecnol. Inf. Geogr.* **2009**, *9*, 232–249.

11. Vicente, F.J. Diseño de un Modelo de Riesgo Integral de Incendios Forestales Mediante Técnicas Multicriterio y su Automatización en SIG. Una Aplicación en la Comunidad Valenciana. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2012.
12. Bachmann, A.; Allgöwer, B. A consistent wildland fire risk terminology is needed! *Fire Manag. Today* **2001**, *61*, 28–33.
13. Cutter, S.L.; Boruff, B.; Shirley, W.L. Social Vulnerability to Environmental Hazards. *Soc. Sci. Q.* **2003**, *84*, 242–261. [CrossRef]
14. Gaither, C.J.; Poudyal, N.C.; Goodrick, S.; Bowker, J.M. Wildland fire risk and social vulnerability in the Southeastern United States: An exploratory spatial data analysis approach. *For. Policy Econ.* **2011**, *13*, 24–36. [CrossRef]
15. Chuvieco, E.; Congalton, R. Application of remote sensing and Geographic Information System to forest fire hazard mapping. *Remote Sens. Environ.* **1989**, *29*, 147–159. [CrossRef]
16. Cocero, D.; Riaño, D.; Meza, E.; Chuvieco, E. *Cartografía del tipo y estado de los combustibles, In Nuevas Tecnologías para la Estimación del Riesgo de Incendios Forestales*; Chuvieco, E., Martín, M.P., Eds.; Consejo Superior de Investigaciones Científicas (CSIC): Madrid, Spain, 2004; pp. 33–62. ISBN 978-84-00-08275-8.
17. Teodoro, A.C.; Duarte, L. Forest fire risk maps: A GIS open source application—A case study in Norwest of Portugal. *Int. J. Geogr. Inf. Sci.* **2013**, *27*, 699–720. [CrossRef]
18. Chuvieco, E.; Martín, M.P. *Nuevas Tecnologías para la Estimación del Riesgo de Incendios Forestales*; Consejo Superior de Investigaciones Científicas (CSIC): Madrid, Spain, 2004; p. 192. ISBN 978-84-00-08275-8.
19. Keane, R.E.; Drurya, S.A.; Karaua, E.C.; Hessburgb, P.F.; Reynolds, K.M. A method for mapping fire hazard and risk across multiple scales and its application in fire management. *Ecol. Model.* **2010**, *221*, 2–18. [CrossRef]
20. Valdez, M.C.; Chang, K.T.; Chen, C.F.; Chiang, S.H.; Santos, J.L. Modelling the spatial variability of wildfire susceptibility in Honduras using remote sensing and geographical information systems. *Geomat. Nat. Hazards Risk* **2017**, *8*, 876–892. [CrossRef]
21. Torres-Rojo, J.M.; Magaña-Torres, O.; Ramírez-Fuentes, G. Índice de peligro de incendios forestales de largo plazo. *Agrociencia* **2007**, *41*, 663–674.
22. DaCamara, C.C.; Calado, T.J.; Ermida, S.L.; Trigo, I.F.; Amraoui, M.; Turkman, K.F. Calibration of the Fire Weather Index over Mediterranean Europe based on fire activity retrieved from MSG satellite imagery. *Int. J. Wildland Fire* **2014**. [CrossRef]
23. Chuvieco, E.; Giglio, L.; Justice, C. Global characterization of fire activity: Toward defining fire regimes from Earth observation data. *Glob. Chang. Biol.* **2008**, *14*, 1488–1502. [CrossRef]
24. Meng, Y.; Deng, Y.; Shi, P. Mapping Forest Wildfire Risk of the World. In *World Atlas of Natural Disaster Risk*; Shi, P., Kasperson, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 261–275. ISBN 978-3-662-45429-9.
25. Chuvieco, E.; Salas, J.; de la Riva, J.; Pérez, F.; Lana-Renault, N. Métodos para la integración de variables de riesgo: El papel de los sistemas de información geográfica. In *Nuevas Tecnologías para la Estimación del Riesgo de Incendios Forestales*; Chuvieco, E., Martín, M.P., Eds.; Consejo Superior de Investigaciones Científicas (CSIC): Madrid, Spain, 2004; pp. 143–158. ISBN 978-84-00-08275-8.
26. Koutsias, N.; Allgöwer, B.; Kalabokidis, K.; Mallinis, G.; Balatsos, P.; Goldammer, J.G. Fire occurrence zoning from local to global scale in the European Mediterranean basin: Implications for multi-scale fire management and policy. *iForest* **2015**, *9*, 195–204. [CrossRef]
27. 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] [PubMed]
28. Nunes, A.N.; Lourenço, L.; CastroMeira, A.C. Exploring spatial patterns and drivers of forest fires in Portugal (1980–2014). *Sci. Total Environ.* **2016**, *573*, 1190–1202. [CrossRef] [PubMed]
29. Chuvieco, E.; Aguado, I.; Yebra, M.; Nieto, H.; Martín, P.; Vilar, L.; Salas, J. Generación de un modelo de peligro de incendios forestales mediante teledetección y SIG. In *Teledetección Hacia un Mejor Entendimiento de la Dinámica Global y Regional*; Rivas, R., Crissoto, A., Sacido, M., Eds.; Martin: Buenos Aires, Argentina, 2007; pp. 19–26. ISBN 978-987-543-126-3.
30. Bonazountas, M.; Kallidromitou, D.; Kassomenos, P.A.; Passas, N. Forest Fire Risk Analysis. *Hum. Ecol. Risk Assess.* **2005**, *11*, 617–626. [CrossRef]
31. Mozumder, P.; Helton, R.; Berrens, R.P. Provision of a wildfire risk map: Informing residents in the wildland urban interface. *Risk Anal.* **2009**, *29*, 1588–1600. [CrossRef] [PubMed]

32. Harris, L.M.; McGeea, T.K.; McFarlane, B.L. Implementation of wildfire risk management by local governments in Alberta, Canada. *J. Environ. Plan. Manag.* **2011**, *54*, 457–475. [CrossRef]
33. Gazzard, R.; McMorrow, J.; Aylen, J. Wildfire policy and management in England: An evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Phil. Trans. R. Soc. B* **2016**, 371. [CrossRef] [PubMed]
34. Schoennagel, T.; Balch, J.K.; Brenkert-Smith, H.; Dennison, P.E.; Harvey, B.J.; Krawchuk, M.A.; Witlock, N. Adapt to more wildfire in western North American forests as climate changes. *Proc. Natl. Acad. Sci. USA* **2016**, *114*, 4582–4590. [CrossRef] [PubMed]
35. Kocher, S.D.; Butsic, V. Governance of Land Use Planning to Reduce Fire Risk to Homes. Mediterranean France and California. *Land* **2017**, *6*, 24. [CrossRef]
36. CMA (Consejería de Medio Ambiente). *Plan INFOCA. Un Plan de Acción al Servicio del Monte Mediterráneo Andaluz*; Consejería de Medio Ambiente: Sevilla, Spain, 2003; p. 353. ISBN 84-95785-88-9.
37. Chuvieco, E. *Teledetección Ambiental*; La Observación de la Tierra desde el Espacio: Ariel, Barcelona, 2010; p. 528. ISBN 978-84-34-43498-1.
38. Aguilar, H.; Mora, R.; Vargas, C. Metodología para la corrección atmosférica de imágenes ASTER, RAPIDEYE, SPOT 2 y LANDSAT 8 con el módulo FLAASH del software ENVI. *Rev. Geogr. Am. Cent.* **2017**, *53*, 39–59.
39. Brizuela, A.; Aguirre, C.; Velasco, I. Aplicación de métodos de corrección atmósferica de datos Landsat 5 para análisis multitemporal. In *Teledetección Hacia un Mejor Entendimiento de la Dinámica Global y Regional*; Rivas, R., Crissoto, A., Sacido, M., Eds.; Martin: Buenos Aires, Argentina, 2007; pp. 207–214. ISBN 978-987-543-126-3.
40. Chuvieco, E.; Martin, P.; Salas, J.; Martínez, J. Geografía e incendios forestales. *Ser. Geogr.* **1998**, *7*, 11–18.
41. Allgöwer, B.; Carlson, J.D.; Van Wagtendonk, J.W. Introduction to fire danger rating and remote sensing. Will remote sensing enhance wildland fire danger rating? In *Wildland Fire Danger Estimation and Mapping. The Role of Remote Sensing Data*; Chuvieco, E., Ed.; World Scientific Publishing: Singapore, 2003; pp. 1–19. ISBN 978-981-238-569-7.
42. Duff, T.J.; Keane, R.E.; Penman, T.D.; Tolhurst, K.G. Revisiting Wildland Fire Fuel Quantification Methods: The Challenge of Understanding a Dynamic, Biotic Entity. *Forests* **2017**, *8*, 351. [CrossRef]
43. Rothermel, R.C. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*; Research paper INT-115; USDA Forest Service: Ogden, UT, USA, 1972; p. 48.
44. Dean, A.M.; Smith, G.M. An evaluation of per-parcel landcover mapping using maximum likelihood class probabilities. *Int. J. Remote Sens.* **2003**, *24*, 2905–2920. [CrossRef]
45. Dean, A.M.; Yamaguchi, Y. Using remote sensing and GIS to detect and monitor land use and land cover change in Dhaka Metropolitan of Bangladesh during 1960–2005. *Environ. Monit. Assess* **2009**, *150*, 237–249. [CrossRef] [PubMed]
46. Salas, J.; Cocero, D. El concepto de peligro de incendio. Sistemas actuales de estimación del peligro. In *Nuevas Tecnologías para la Estimación del Riesgo de Incendios Forestales*; Chuvieco, E., Martín, M.P., Eds.; Consejo Superior de Investigaciones Científicas (CSIC): Madrid, Spain, 2004; pp. 23–32. ISBN 978-84-00-08275-8.
47. Yebra, M.; Santis, A.; Chuvieco, E. Estimación del peligro de incendios a partir de teledetección y variables meteorológicas: Variación temporal del contenido de humedad del combustible. *Recur. Rurais Rev. Inst. Biodivers. Agrar. Desenvolv. Rural* **2005**, *1*, 9–19.
48. Gilalbert, M.A.; González-Piquera, J.; García-Haro, J. Acerca de los índices de vegetación. *Rev. Teledetec.* **1997**, *8*, 1–10.
49. Kogan, F.N. Remote sensing of weather impacts on vegetation in non-homogeneous areas. *Int. J. Remote Sens.* **1990**, *11*, 1405–1419. [CrossRef]
50. Riaño, D.; Salas, J.; Chuvieco, E. Cartografía de modelos de combustible con teledetección: Aportaciones a un desarrollo ambiental sostenible. *Estud. Geogr.* **2001**, *243*, 309–333. [CrossRef]
51. Kogan, F.N. Application of vegetation index and brightness temperature for drought detection. *Adv. Space Res.* **1995**, *15*, 91–100. [CrossRef]
52. Cocero, D.; Salas, J.; Chuvieco, E. El sensor SPOT-VEGETATION, una alternativa a la estimación de la humedad de la vegetación. In *Teledetección: Medio Ambiente y Cambio Global*; Martínez, J.A., Rosell, J.I., Eds.; Universitat de Lleida-Ed. Milenio: Lleida, Spain, 2001; pp. 179–182. ISBN 978-84-9743-001-2.
53. Bhuiyan, C.; Singh, R.P.; Kogan, F.N. Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. *Int. J. Appl. Earth Observ. Geoinf.* **2006**, *8*, 289–302. [CrossRef]

54. Kogan, F.N. Drought of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bull. Am. Meteorol. Soc.* **1995**, *76*, 655–668. [CrossRef]
55. Kogan, F.N.; Gitelson, A.; Zakarin, E.; Spivak, L.; Lebed, L. AVHRR-Based Spectral Vegetation Index for Quantitative Assessment of Vegetation State and Productivity: Calibration and Validation. *Photogramm. Eng. Remote Sens.* **2003**, *69*, 899–906. [CrossRef]
56. Márquez, J.; Vallejo, I.; Álvarez, J.I. Estimación del tiempo de demora en rutas pedestres: Comparación de algoritmos. *GeoFocus* **2015**, *15*, 47–74.
57. Márquez, J.; Vallejo, I.; Álvarez, J.I. Estimated travel time for walking trails in natural areas. *Geogr. Tidsskr.-Dan. J. Geogr.* **2017**, *117*, 53–62. [CrossRef]