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The Fire in the Mediterranean Region: A Case Study of Forest Fires in Portugal

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Abstract

Forest fires are a common disturbance in many forest systems in the world and in particular in the Mediterranean region. Their origins can be either natural or anthropogenic. The effects in regard to the time trends, vegetation, and soil will be reflected in the species distribution, forest composition, and soil potential productivity. In general, it can be said that the larger the fire and the shorter the time between two consecutive occurrences, the higher the probability to originate shifts in vegetation and soil degradation. In the Mediterranean region, the number of fire ignitions does not reflect the burnt area due to the occurrence of very large fires. The latter occur in a very small proportion of the number of ignitions, but result in very large burnt areas. Also there seems to be an increasing trend toward larger fires in the Mediterranean region due mainly to climatic and land use changes. This case study highlights the importance of vegetation regrowth a short time after the fire to maintain both forest systems and soil conservation.

Keywords: Portugal, burnt area, number of fires, spatial dynamic, temporal dynamic, vegetation

1. Introduction

Mediterranean forest types can be characterized by their heterogeneity, whether climatic, edaphic, geomorphologic, floristic, biogeographic or historical, and instability and vulnerability, consequences of the former and due to genetic and ecological factors as well as to the anthropogenic actions [1]. The Mediterranean flora is composed of a wide variety of tree, shrub, and herbaceous species, and their distribution depends on the edaphoclimatic conditions and on human intervention [1, 2]. The climatic conditions that are most influential on the species distribution and growth are the temperature and the precipitation, as well as

their interactions. In the Mediterranean basin the mean annual temperatures vary between 5 and 8°C and the mean annual precipitation ranges from 300 mm to more than 2500 mm [1] with a marked seasonal and annual variability. As a result, droughts are frequent and vary between a couple of weeks and more than six months [1, 2]. In addition, rain falls frequently in torrential short-duration events mainly in autumn and in winter. Thus, growth is limited to mainly spring and autumn, and when the moisture balance is favorable, the growth can be luxurious [2]. Nonurban land use in the Mediterranean basin is distributed in a mosaic pattern with the three most frequent uses being forest, pasture, and agricultural cultures. This spatial arrangement is composed of very small areas with diffuse edges [1–3].

Fire was, and still is, a common feature in the Mediterranean landscape. Historically, fire has been described as having two main forces of ignition: natural, to a lesser extent, caused usually by summer lightning storms, not considered to be significant as frequently is followed by torrential rainfall [2]; and anthropogenic, in earlier times to clear areas for pasture, hunting, grazing, and/or agriculture [1, 2], though in ancient times it was also considered a war weapon [2].

Fires are common in many forest systems around the world, and in particular in the Mediterranean region. Forest fires can be a minor or major disturbance in forest ecosystems depending on their intensity and result in stand's species composition and structure changes [4, 5]. Thus the analysis of the spatial distribution and temporal frequency of forest fires and their relation to vegetation—trees, shrubs and herbaceous plants—is of utmost importance. In this chapter, a review of the origins (Section 2); of the effects of the time trends, on vegetation and on soil (Section 3); of the evaluation of pre- and post-fire vegetation dynamics with remote sensing (Section 4); and of the analysis of the fires, number, and burnt area, for the Mediterranean region and for Portugal (Section 5) is made. A case study is also presented to compare the vegetation prior the fire with that of regeneration after the fire (Section 6).

2. Origins of forest fires in the Mediterranean region

Forest fires are a driving force in the evolution, distribution, and organization of the forests around the world [4–6]. Fires may have a strong effect both on the vegetation and on the soil carbon sequestration and sinks as they may reduce regeneration and, consequently, the potential biomass accumulation [7–9], carbon stocks [10], and timber [4, 5]. Forest fires are one of the primordial factors affecting the Mediterranean-type ecosystems [11], causing more destruction to trees than all the other hazards, such as diseases, insects, wind throws, and frosts [12].

Humans have been using fire since ancient times [13, 14] and since 10,000 years ago have influenced their regime [15]. While in earlier times fire was linked to land management, currently other causes prevail. Since a couple of decades, an intensification in the fire occurrences has been observed, due to the combined effects of climate change [16–21] and alterations in the land use, such as the abandonment of agricultural lands, decrease in grazing, urban areas increase, and the interaction between the urban and the wildland areas [11, 22–36]. As a result, change in the vegetation structure and species composition occurred

[30, 36]. Forest fires in the Mediterranean ecosystems have complex effects on the ecological processes due to the differential responses to the vegetation structures and fire regimes [37–39]. The post-fire evolution of vegetation community is a consequence of its resilience [40, 41] which can be linked to biodiversity (e.g. [30, 42]), vegetation structure (e.g. [43]), and ecosystem functions (e.g. [44]).

Fire damages can be evaluated by their direct impacts that are the physical changes in the flora and fauna of the ecosystems affected; and the indirect losses, consequence of the former and which relate to the impacts on the economy and environment of both the burnt and the neighboring areas. Noteworthy are also the tangible losses that can be expressed in monetary terms, and the intangible losses of difficult quantification though affecting both the environment and the economy [45].

Any fire regime can be described as the function of a suite of variables. The most commonly used ones to describe a fire regime are the nature, pattern (size), season, intensity (energy released), and recurrence. Of notice are the features regarding fire recurrence, namely frequency, which is characterized by the number of fires within a life span in an area; and the mean fire return interval, that is the time interval between successive fires [46]. Fire frequency has a major role in the vegetation due to its effects on the regeneration and recruitment of plants, especially of trees, after a fire. In the Mediterranean basin, many fire regimes have a mean fire return interval of 15–20 years [36, 47], which can reduce the number of species because sexual maturity is not reached, and consequently no seed is available to enable plant regeneration and recruitment [48, 49]. Fire effects can be evaluated by fire intensity, fire severity, and burn severity [50, 51]. The latter is the more frequently used [52–55].

3. Effects of fires on the Mediterranean stands and forests

3.1. Time trends on forest fires

Most of the detected fires are small and can be seen as minor disturbances. However, large fires, though in a much smaller number, can be considered as major disturbances and can cause considerable impacts both at the landscape level with the destruction of large areas of vegetation and at the economic and social levels [56, 57]. According to the affected vegetation strata, fires can be classified as ground, surface, and crown fires [58]. The surface fires are recognized as having less impact on the vegetation communities and are sometimes used to control vegetation as prescribed burnings. They can be more easily controlled and extinguished [5]. On the contrary, when a fire evolves to a crown fire, its suppression is almost always impossible, causing also major impacts on the vegetation [59]. The transition from surface to crown fire is related to the vertical and horizontal arrangement of the vegetation. While a vegetation community with continuous horizontal and vertical spatial distribution can enhance fire spread into crowns, their discontinuity can reduce it [60–63]. The effects of heterogeneous vegetation structures in the fire behavior [64–68], as well as the "ladder effect" [69], result from the vegetation vertical and horizontal connectivity.

The term "megafire" is often used to classify very large fires, though no definition exists. They are frequently derived from several large fires, resulting in very large burnt areas and high damage levels, both in the vegetation and at the socioeconomic level. Megafires can be classified using three criteria: (i) fire behavior, corresponding to their intensity and spread rate [70]; (ii) resistance to control by suppression activities [71]; and (iii) fire severity, corresponding to the affected area, fatalities, burn severity, and economic losses [72]. San-Miguel-Ayanz et al. [11] analyzed megafires in Portugal, Spain, and Greece, and refer that each megafire was a singular event, with a set of large fires concentrated in time and space in one fire season. These events seem to be linked with extreme meteorological conditions, for example very high temperatures, very low humidity, and lightning storms. The same authors refer that the number of ignitions and the fast spread of fire (due to vegetation and topographic conditions) can be of major importance. The behavior of megafires makes it difficult to control their spread and suppress them [71, 73], and their control and extinction is only possible when they spread to lower fuel load vegetation or when the weather turns cooler and wetter [74].

3.2. Vegetation

Vegetation can be characterized according to their fire proneness. The typical vegetation of the Mediterranean regions is one of the most fire prone [14, 75]. In these vegetation types, fire had, and still has, a key role in its dynamics and structure. The role of fire dates back to the early Holocene [76] with a continuous role onward [14, 77, 78]. Fire has been recognized as affecting the landscape at the long term; however, its effects vary as function of the regeneration patterns of the vegetation, topography, and fire history [24, 79]. Vegetation community resilience has been verified as a significant proportion of these communities were able to maintain their characteristics [24].

Several authors refer that the fire risk is expected to increase in a frame of climate change in the Mediterranean region, especially in the European part (e.g. [80, 81]) as a consequence of the increase in drought events [82]. Thus the knowledge of soils and plant communities' behavior after fire is of utmost importance [78, 83–85]. Also, the foreseen longer and more frequent drought events along with the higher temperatures might enhance the expansion of plants better adapted to those climatic conditions [86, 87].

The plants' post-fire regeneration depends on their adaptive traits, which can be divided into: (i) resprouters, plants that have protected buds that are able to develop after the fire; and (ii) seeders, which correspond to plants that are affected by fires but have seed banks either in the canopy and/or in the soil that are able to maintain the germination ability [4, 9]. Additionally, there is a suite of factors controlling the development of the post-fire vegetation development: (i) the pre-fire plant species composition [88–92]; (ii) the severity and intensity of fire [6]; (iii) the season of fire occurrence [93]; (iv) the regeneration ability, by resprouting or seed bank in the canopy, and soil [9, 94, 95].

The post-fire dynamics of vegetation community is a very slow process that can be divided into three stages: initial, transition, and advanced. The initial stage is characterized by an intensive regeneration of the vegetation existing prior to the fire, including trees, shrubs, climbers, and herbaceous plants [88–92, 96] either by resprouting or by seed germination. The growing

space let available by the fire is rapidly occupied, and about two years after the fire the species richness reaches a maximum [89, 90]. However, the spatial arrangement of the plants shows a high heterogeneity, characteristic of the Mediterranean ecosystems [89, 97]. This variability is also related to the site characteristics, with low species diversity been found in the sites where water is the main limiting factor [89, 98]. With time, competition for growing space increases gradually, limiting the regeneration of new seedlings, while some saplings tend to disappear, resulting in a decrease of species diversity [89]. The transition stage is the consequence of the increasing competition with the less-competitive plants (frequently herbaceous plants) disappearing while others gradually increase their frequency, such as shrubs, climbers, and some trees species [89]. The advanced stage is the consequence of the species characteristics (especially growth rate and life span) and site characteristics (especially temperature, water, and nutrient availability). At this stage, species with low growth rates and long life cycles are found (mainly trees but also some shrubs and climbers), while species of fast growth and shorter life spans tend to disappear [77, 89].

Short-time fire intervals may have a strong effect on the presence and abundance of species [36, 99–102] and may originate shifts in the predominant species in the Mediterranean eco-systems [103, 104]. As a result, infrequent fires or fires with medium and long return intervals tend to promote tree plant communities, while short return interval fires originate shrub- and herbaceous-dominant communities and also an intensification of the fire regime [8, 9, 46, 81, 99, 105].

3.3. Soil

The effects of fire on vegetation are easily perceived as they can be seen. However, the effects of fire on the soil are more difficult to recognize. Several authors [55, 106–108] refer the impacts of fire on the chemical, physical, and biological properties of the soils.

After a fire the soil properties can be affected by precipitation: total precipitation, intensity, and its temporal patterns [108]. Torrential rainfalls, characteristic to the Mediterranean region, are of special importance due to their negative effect on soil fertility as it increases the risk of runoff, erosion, and nutrient losses [32, 109–111]. As a result of the burning of the vegeta-tion, some nutrients increase their availability immediately after the fire, such as nitrogen [106, 112], phosphorous [55, 106–108], and potassium [108]. Nonetheless, all three nutrients decrease about one year after the fire, explained, at least partially, by the losses originated by the rainfall. However, these effects are partially minimized under drought conditions [106]. Contrarily, soil carbon is partially or almost completely destroyed during the fire. As fires frequently occur during the hot dry months, the soil carbon after the fire will be recovered at a slow rate [106, 108, 113, 114], and similarly the carbon mineralization rate is also quite low under drought [106, 115–118].

The effect of vegetation on soil conservation is well known [119–121], and soil erosion and land degradation processes depend on it [122]. Also, erosive processes tend to increase after the occurrence of fires as soil is exposed [123], and the risk increases with the increase in the time needed for the vegetation to develop to a minimum ground cover threshold [122–124]. Several authors referred that most of the post-fire sediments are observed in the first year [123, 125, 126]

and that the highest susceptibility to soil erosion occurs 4–6 months after the fire [125]. The protective effects of vegetation on soils [119–121] are due to both the ground cover and the improvement of the hydrological properties of the soil [125]. Contrarily, repeated fires in the same area, due to the direct effect of the fire on soil properties and the loss of vegetation, originate higher risk of water erosion and consequently increase soil degradation processes [125].

Fires are frequently followed by salvage cuttings in order to attain some timber economic return. These cuttings have two disadvantages in the short term; one is that it might increase soil erosion risk [127, 128]; and the other is that the damaged wood will not decompose *in situ* and consequently does not restore or increase the soil carbon stocks [129]. In the medium and long terms, it may further increase the erosion hazard [130] and reduce the soil seed bank, the establishment of seedlings, and the belowground resprouting organs [131–133].

In studies in *Pinus pinaster* stands, several authors [129, 134–136] stress that in unburnt stands the aboveground biomass, and thus the carbon stock, is considerably higher than in those that have burnt one or more times. On the contrary, in the latter the most important carbon stocks seem to be the soil organic carbon [134, 137, 138]. These findings are important in forest management, as after the fire the risk of soil erosion increases [139] and considerable soil losses may occur [140–143].

Fire occurrence, spread, and burnt area can be minimized with management practices that go toward the heterogeneity of the landscape [144]. Fuel loads and vertical and horizontal spatial distribution of the vegetation communities can promote or reduce the fire risk. Oak-dominated stands or forests may enhance the opportunities to reduce the burnt area [145] or reduce the fire risk [18]. However, the opposite is encountered in pine stands or forests and shrublands [146] where the vegetation structure has a higher degree of continuity [147]. Gutierrez and Lozano [148] state that according to their analysis carried out from 1980 to 2010, about 35% of the damages caused by forest fires could have been avoided if appropriated practices had been set out. The same authors refer also that there are significant differences between southern European countries (France, Greece, Italy, Portugal, and Spain) that were more efficient in controlling the fire damage in 2007 and 2009–2010 than other European countries (Austria, Bulgaria, Croatia, Cyprus, Estonia, and Finland).

4. Remote sensing evaluation of pre- and post-fire vegetation dynamics

Remote sensing has a primary role in the assessment [149–153] of pre- and post-fire vegetation [154] as it can be used even in the inaccessible areas or where the costs of fieldwork are prohibitive [155]. Time series of satellite images that can be used in monitoring the dynamics of vegetation are also of major importance [154, 156].

Pre- and post-fire vegetation have different spectral and spatial responses which allow their dynamics evaluation with remote sensing [157]. Though many methodologies and techniques exist, the most frequently used are image classification, vegetation indices, and spectral mixture analysis. Image classification enables the transformation of remotely sensed data into land cover/use classes, using either supervised or unsupervised techniques [154].

Vegetation indices have a strong relation with biomass and leaf area index, thus suitable for vegetation evaluation both prior and after fire events, whether spatially or temporally [52, 154, 158–166]. One of the most frequently used indices is Normalized Difference Vegetation Index (NDVI) [52, 167–169]. Other vegetation indices are also widely used, such as Soil Advanced Vegetation Index (SAVI) and Transformed Soil Advanced Vegetation Index (TSAVI) [52, 154, 157, 170]. Spectral mixture analysis enables the discrimination of the different fraction in each pixel. It is especially important in low and medium spatial resolution satellite images where each pixel is almost always composed of vegetation, soil, or other land cover/use. Thus it is suited for the post-fire analysis of the vegetation regrowth as instead of one spectral signature, it detects the cover fraction within each pixel [49, 158, 171]

5. Dynamics of fire

5.1. Mediterranean region

The statistics of forest fires in the Mediterranean basin countries had started in 1980s for France, Greece, Italy, Portugal, and Spain, while for Croatia, Morocco, and Turkey, the first data are from the 1990s; for Cyprus and Slovenia, from the 2000s; and for Algeria and the former Yugoslav republic of Macedonia around 2010s. Lebanon data are available for two years (2012 and 2015) and no data are available for Albania, Egypt, Israel, Libya, Montenegro, Syria, and Tunisia [172]. The larger number of fires per year is found in Portugal and Spain, more than 10,000 per year, followed by Italy, between 5,000 and 10,000 (**Figure 1**, top). These three countries have more than 100,000 ha of burnt area annually (**Figure 1**, center). There seems to be a trend toward larger number of fires and burnt area for the Iberian Peninsula. When analyzing the mean burnt area per fire and per country (**Figure 1**, bottom), it can be seen that for Slovenia, France, Turkey, Portugal, and Morocco, areas are smaller than 10 ha; in Algeria, Spain, Italy, and Cyprus, the mean burnt area per fire between 11 ha and 15 ha is found, while for former Yugoslav republic of Macedonia, it is 23 ha, for Greece, 31 ha, and for Croatia, 47 ha. These results point to the rather large number of small fires and a small number of fire events with very large burnt areas or megafires, as referred in other studies (e.g. [11, 74]). Another study [23] refers that for many European countries the more frequently affected areas are the wildland-urban interface, though regional variability is observed.

The temporal analysis of the number of fires and burnt area per country will be focused on the five European Mediterranean countries which have data available from 1980 onward. For this evaluation, from 1980 to 2015, four classes of five-year period and one of six-year period were considered. There seems to be a different trend for the number of fires and for the burnt area. France and Greece have the lowest number of fires with a rather small annual fluctuation values while Portugal and Spain have the highest values and an increasing trend up to 1995–1999 with a decreasing trend onward. Italy has an increasing trend up to 1990–1994 and decreasing afterward (**Figure 2**). The burnt area variability per country is larger than that of the number of fires. Similar to the number of fires, France and Greece have the lowest values of burnt area, but the variability between all time periods is larger, with an ascending trend during the 1980s, decreasing in the 1990s onward, except during 2000–2004 for France

and irregular for Greece. Italy has predominantly descending trend in the burnt area values, especially noticeable from 1990–1994 onward. Portugal has an increasing trend of burnt area values up to 2000–2004, where the highest value was attained, and a rather constant value in the next two time periods. Spain has burnt area value increases from the first to the second time periods and a decreasing trend in the following two time periods and a rather constant trend afterward. The highest aforementioned values seem to be linked to the occurrence of megafires, namely in Italy in 1989; in Spain in 1989, 1994, and 2006; in Portugal in 2003 and 2005; and in Greece in 2007 [11, 74]. Furthermore, the changes in land use, in particular the decrease in or abandonment of agricultural, pastoral, and forestry activities, seem to have promoted the increase in the number of fires and burnt area [11, 22–30, 33, 34]
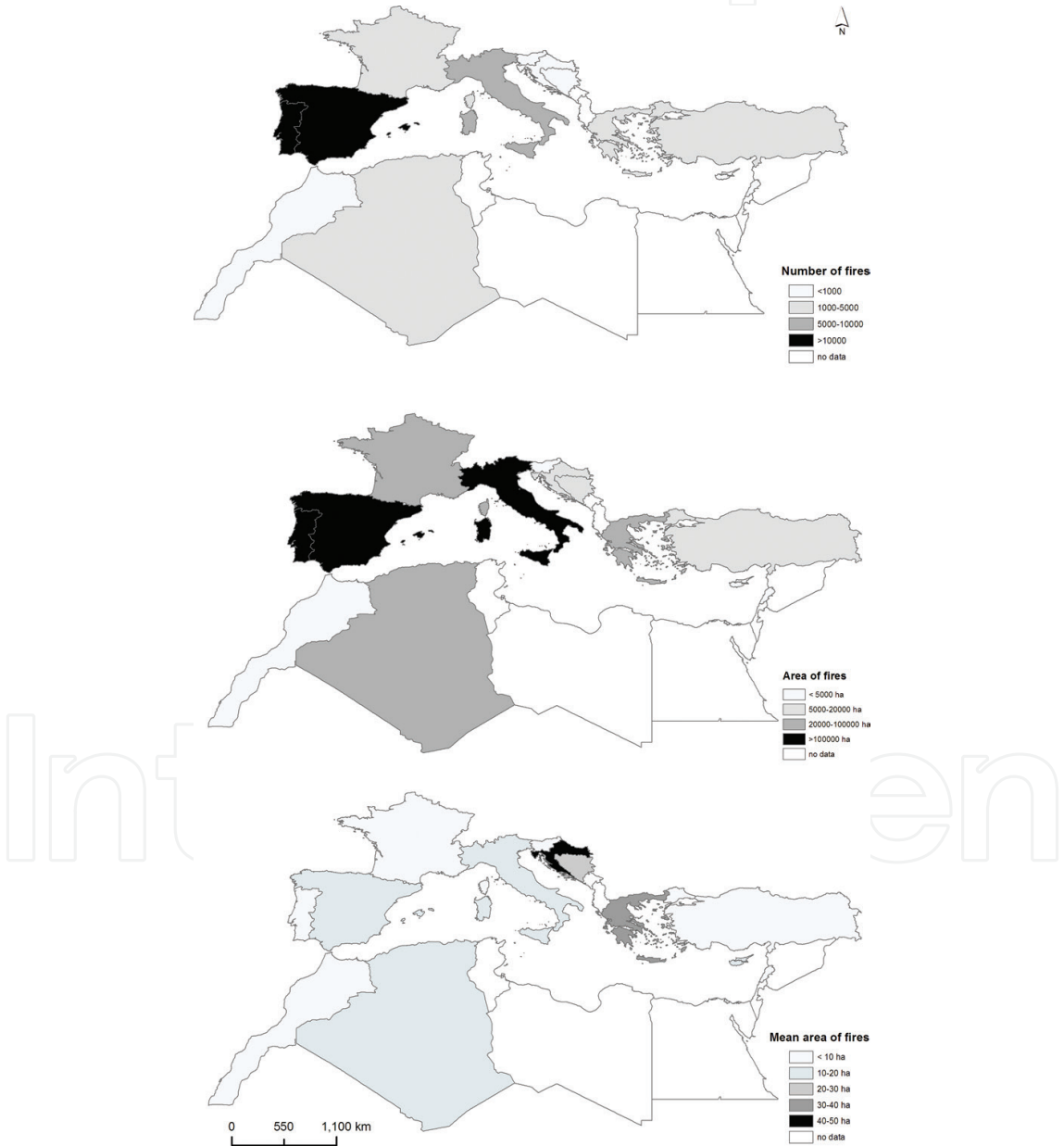

Figure 1. Average number of fires (top), average area of fires (center) and mean dimension of burnt area per fire per year (bottom), per country, in the period 1980–2015.
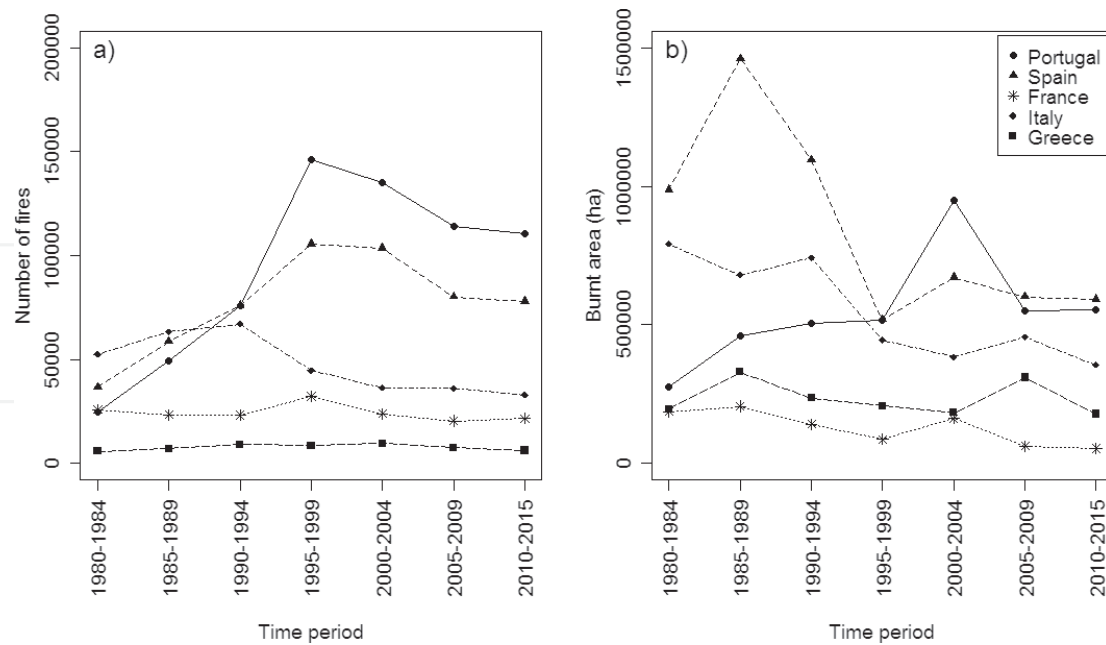
Figure 2. Number of fires (a) and burnt area (b) per country per five-year periods.

5.2. Portugal

A more detailed analysis for the dynamics of forest fires for Portugal for the time series data of 1980–2015 [173] was done, aggregating the burnt area per fire in the classes: <1, 1–25, 25–100, 100–500, and >500 ha. Most fires (66.5%) have burnt areas of less than 1 ha, corresponding to the lowest proportion of the total burnt area (3%). Contrarily, fires with burnt areas of more than 500 ha have the smallest number of events (0.5%), but have the largest proportion of burnt area (50%). The observed relation for the remaining classes is the following: the smaller the number of fires, the larger the burnt area (29.3, 2.5, 1.2% and 14, 12, 22%, respectively for burnt areas of 1–25, 25–100, and 100–500 ha). Other research describes similar trends [11, 174].

When the number of fires and burnt area is analyzed per NUT3 territorial units, it can be seen that the highest values are in northern and central Portugal (**Figure 3**). Though with different methodologies, several authors attained similar results [22, 174, 175]. In addition, a similar trend of inverse proportionality between the number of fires and burnt area is observed for all 23 NUT3 regions, with some variability for the five aforementioned classes of burnt area. Yet, variability is also observed within each of the NUT3 regions, if a smaller territorial unit is considered, for example the municipality (**Figure 4**). There seems to be more homogeneity in the municipalities of the northeastern and central eastern Portugal and more heterogeneity for those of coastal Portugal. This variability can be related to the occurrence of large fires, such as those referred by Fernandes et al. [73] and Tedim et al. [74]. And also with land use, especially the composition, structure and fuel loads of the forest systems [22, 174, 175]. The lower number of fires and burnt area corresponds to the agrofor-estry systems, which are characterized frequently by a tree cover of evergreen oaks (*Quercus suber* and *Quercus rotundifolia*), and pasture with extensive grazing [176, 177] thus with a horizontal and vertical discontinuity [174, 178, 179]. At the other edge are the forest systems
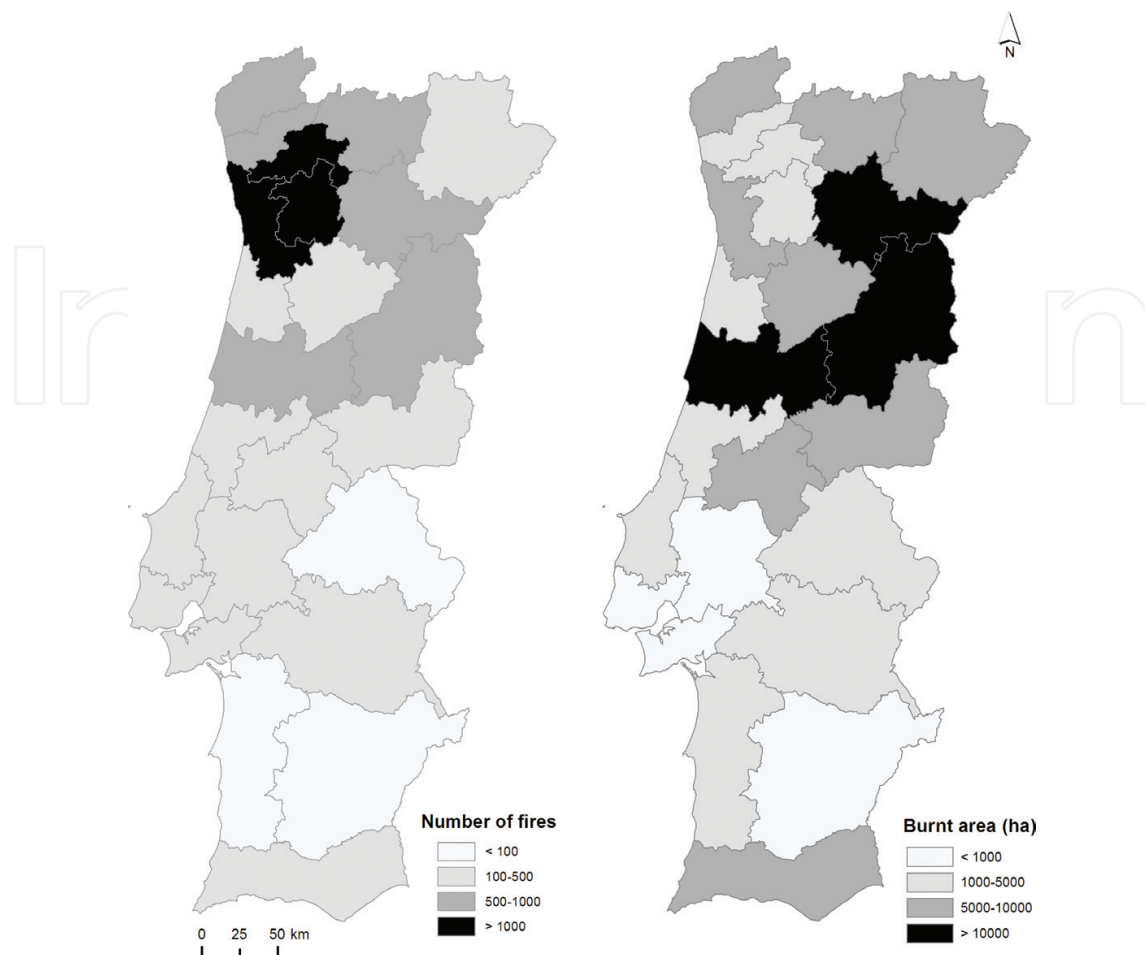
Figure 3. Average number of fires (left) and burnt area (right) per NUT3 region of Portugal in the period 1980–2015.

composed mainly of maritime pine (*Pinus pinaster*) and/or Tasmanian blue gum (*Eucalyptus globulus*), especially those with a well-developed shrub layer [178] corresponding to systems with higher horizontal and vertical continuity, and larger fuel loads, where the higher number of fires and larger burnt area occurs [22, 174, 175]. A similar trend was described for *Pinus halepensis* in Spain [60]. The temporal dynamics of the burnt area presents a rather large variability, increasing from the smallest to the largest class of burnt area (**Figure 5**), showing a similar trend to the observed by San-Miguel-Ayanz et al. [11]. There seems to be an inverse relation between the burnt area of the fires larger than 500 ha and that of the remaining classes, that is smallest burnt areas per year for the class larger than 500 ha correspond to the highest burnt areas per year in the other five classes (**Figure 5**). Noteworthy are the peaks of 2003 and 2005, as already referred, which are linked with the occurrence of megafires [11, 74].

It seems that the temporal and spatial patterns of fires are linked with the vegetation community structure both in density of ignitions [22] and burnt area [22, 175] with a positive trend for the former in Portugal since the 1980s [106, 174, 180]. The shrublands are among the vegetation communities mostly affected by fire due to the high rate of spread and low firefighting priority [27, 28, 181–185].
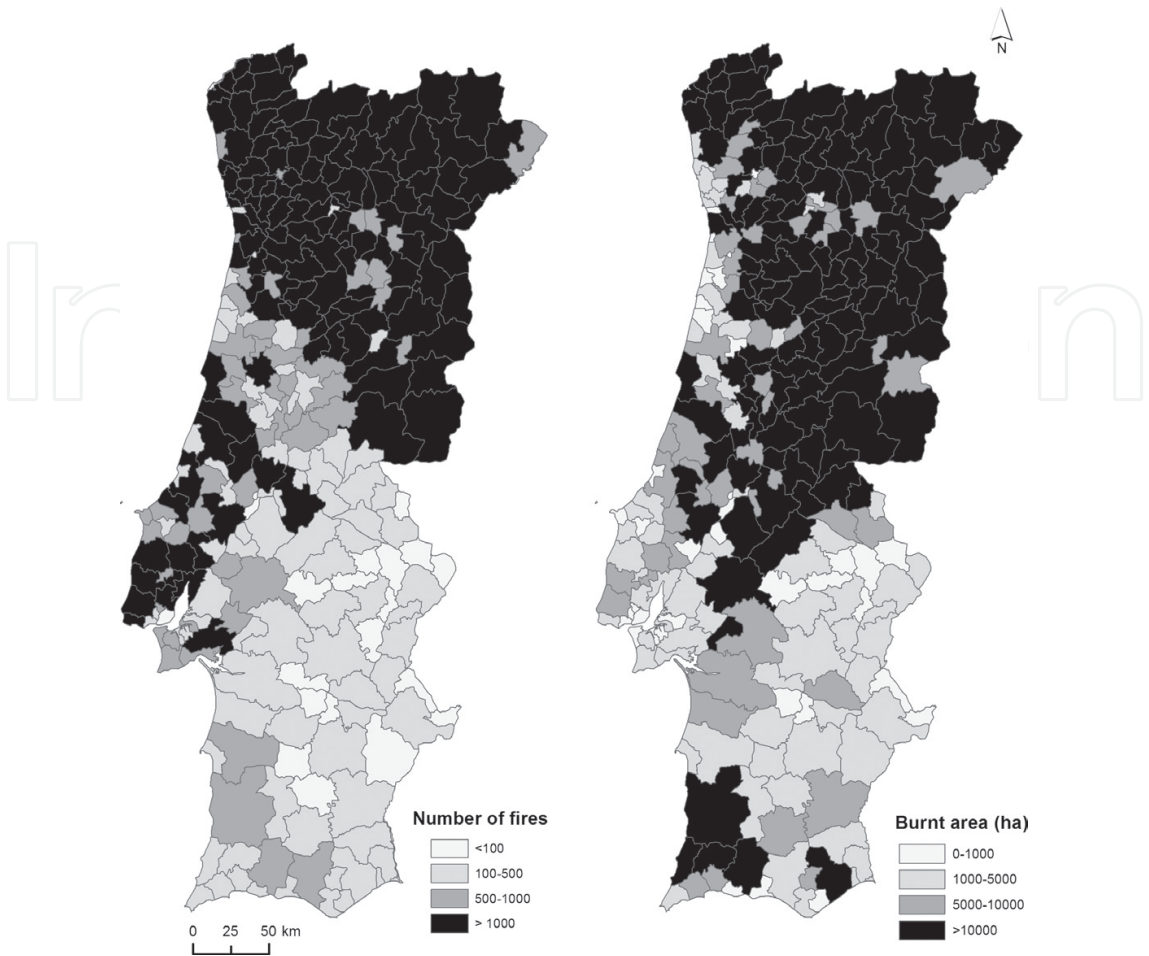
Figure 4. Average number of fires (left) and burnt area (right) per municipality region of Portugal in the period 1980–2015.
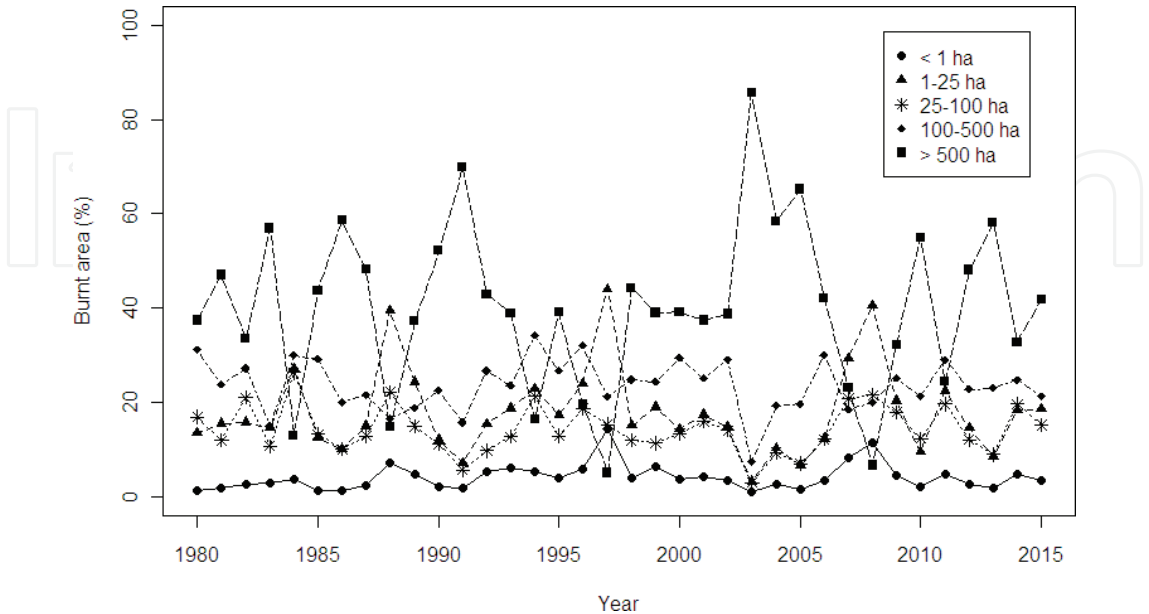

Figure 5. Burnt area per class of burnt area and per year.

6. Case study

6.1. Study area and remote sensing data

Mapped burnt areas in 2013 by the Portuguese Forest Services were used to study the vegetation recovery, which also encompass the affected main land cover/use types. The analyses of the vegetation recovery for large fire scars were carried out, using the vegetation index NDVI calculated with Landsat 8 images for the four years: 2013, 2014, 2015, and 2016.

The study area is located in northern central Portugal (**Figure 6**), one of the most affected regions by forest fires (cf. **Figures 3** and **4**) in the summer during dry season (June to September). The climate is Mediterranean, with a mean precipitation per month of 120 mm in the rainy season (December and May), decreasing in summer to 30 mm per month [186]. According to the land use map of Portugal (COS06), the studied areas are mainly composed of *Pinus pinaster* (37%), pastures (20%), *Eucalyptus globulus* (19%), annual crops (20%), oak (5%), and other broadleaved species (6%).
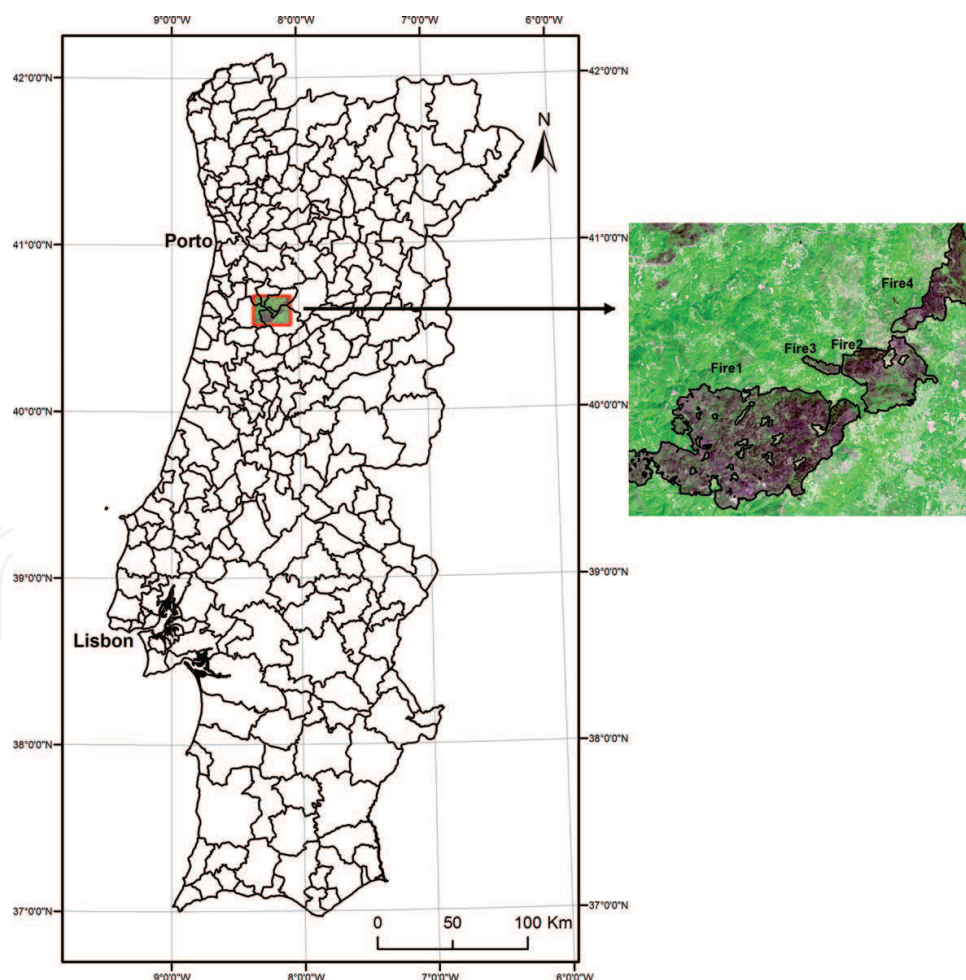

Figure 6. Study areas location (a) and false color composite Landsat image (RGB—SWIR, NIR, Red) (b).

Remote sensing data was available from Landsat 8 satellite images (**Table 1**) obtained from the United States Geological Survey (USGS), Glovis Visualization Viewer (GLOVIS) platform. A temporal time series of four years, of 2013 (fires' occurrence year), 2014, 2015, and 2016, was used (**Table 2**). The images were selected considering a similar acquisition date, to minimize cloud cover and phenological stage effects. Four fires were considered. The image of 2013 (6 july, 2013), covering Fire1, Fire2, and Fire4, corresponds to pre-fire image, and the other images to the post-fire, one, two, and three after the fire. As to Fire3 that occurred at the beginning of June of 2013 all images are post-fire. Thus, the time series enables the temporal vegetation analyses for a time frame of three years after the fire event. The satellite images were geometrically adjusted, image to image, considering that of 2013 as reference, to ensure a minimum geometric pixel deviation.

Landsat 8 OLI and TIR bands			
Bands		**(µm)**	**Spatial resolution (m)**
b1	Coastal	0.433–0.453	30
b2	Blue	0.450–0.515	30
b3	Green	0.525–0.600	30
b4	Red	0.630–0.680	30
b5	Near Infrared (NIR)	0.845–0.885	30
b6	Short Wave Infrared (SWIR1)	1.560–1.660	30
b10	Thermal Infrared I (TIR1)	10.6–11.19	100
b11	Thermal Infrared II (TIR2)	11.5–12.51	100
b7	Cirrus	0.500–0.680	30
b8	Short Wave Infrared (SWIR2)	2.100–2.300	30
b9	Pan	0.503–0.676	15

Table 1. Band characterization of the Landsat 8 Operational Land Imager (OLI) satellite.

Satellite/sensor	Acquisition date	Fire	Month of fire event	Area (ha)
Landsat 8 OLI	06/07/2013	Fire1	July	6391
		Fire2	August	1496
		Fire3	June	123
		Fire4	August	1348
	09/07/2014			
	26/06/2015			
	28/06/2016			

Table 2. Date of Landsat 8 images acquisition (WRS-2 204/32) and burnt area of the four fires.

6.2. Methodology

For this study four burnt areas were extracted using the fire perimeter provided by the Portuguese Forest Services [173]. **Figure 7** shows the fire scars with false-color composite images for the four years and an image with two active fires (Fire2 and Fire4).

The vegetation indices based on red (RED) and near infrared (NIR) bands are directly related to the vegetation photosynthetic activity [187], which is highly reflective in the NIR region and strongly absorbing in the RED [188]. As already referred, one of the mostly used indices to evaluate the vegetation changes, especially after fire, is NDVI [188]. It is particularly used to assess vegetation regeneration after the fire [52, 157, 170, 189]. This index is rather sensitive to vegetation activity presenting a strong decrease after fire due to the partial or total destruction of the vegetation, thus it is indicative of the fire damage [52].
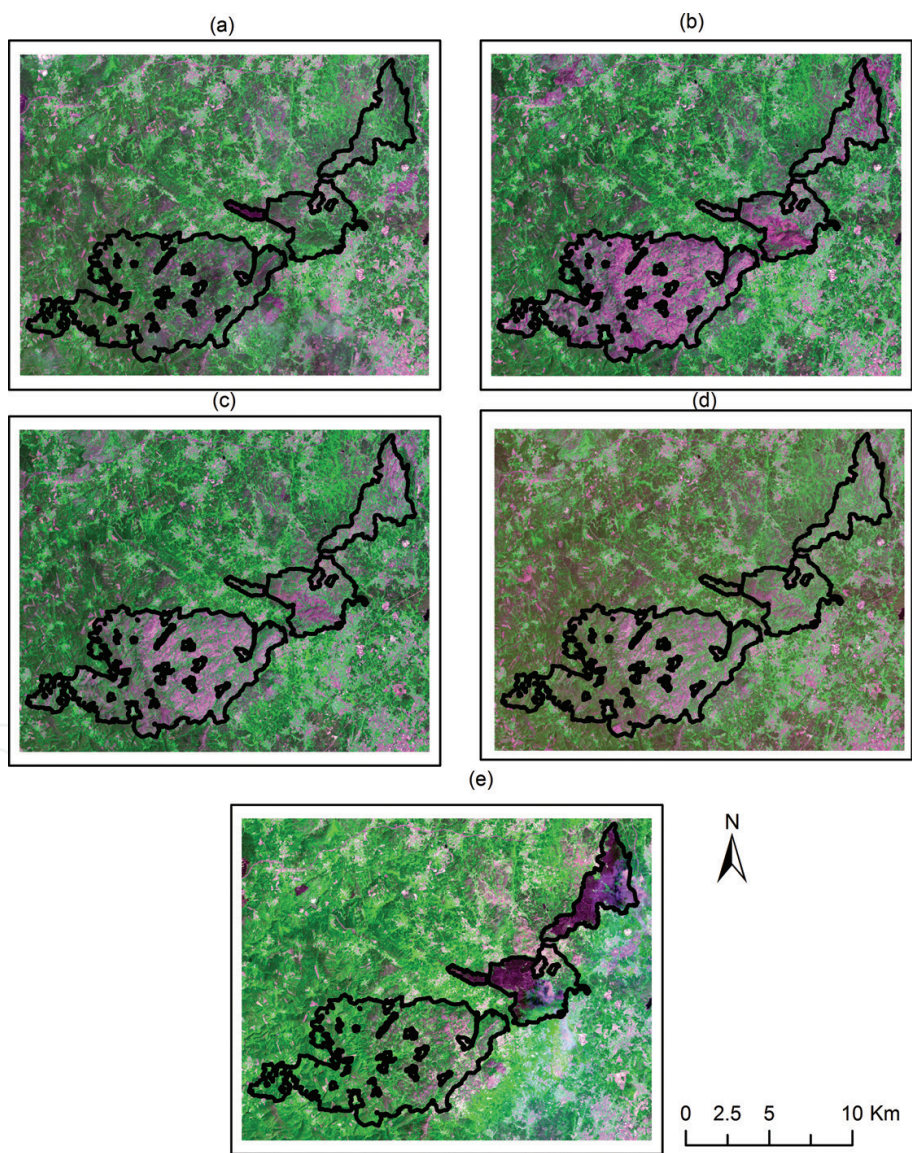

Figure 7. False-color composite Landsat 8 images (RGB—SWIR, NIR, Red) for 2013 (a), 2014 (b), 2015 (c), and 2016 (d) and an image with active Fire2 and Fire4 (e), including the burnt area perimeter (black line).

In this study, the NDVI was used to calculate on the basis of the normalized difference between NIR and RED bands (NDVI = ((NIR−RED)/(NIR+RED))). It was calculated both for pre- (NDVI$_{pre}$) and post-fire (NDVI$_{post}$) periods, as the mean value of NDVI before and after (for the 2014, 2015, and 2016 images) the fire event. The dates of satellite image acquisition were deliberately chosen to be a few days prior to the fire event and afterward annually in approximately the same dates, to eliminate the possible variations originated by the different vegetation phenological stage. The mean NDVI was obtained with the pixels located inside the selected burnt areas. The temporal vegetation variation was analyzed with the difference between the NDVI pre- and post-fire.

6.3. Post-fire analysis

In **Figure 7**, a strong decrease in NIR (green color tones) and increase in Red (rose color tones) reflectance within the fire perimeter from pre-fire image (**Figure 7a**) and the one acquired one year later (**Figure 7b**) for Fire1, Fire2, and Fire4 can be observed. For the two following years, 2015 (**Figure 7c**) and 2016 (**Figure 7d**), the fire scars are less evident. These changes are confirmed by the NDVI values (**Figure 8**), with the highest values of NDVI in the pre-fire image (2013) indicating the presence of dense vegetation and a relevant decrease in these values in the post-fire image (2014), where the fire scar is present. In the following two years, 2015 and 2016, an increase in the NDVI values can be observed, demonstrating a gradual recovery of vegetation, and even more accentuated in 2016. For Fire3 there is no pre-fire image, **Figure 8** shows a low NDVI value for 2013 (image acquired a few days after the fire event) and a gradual
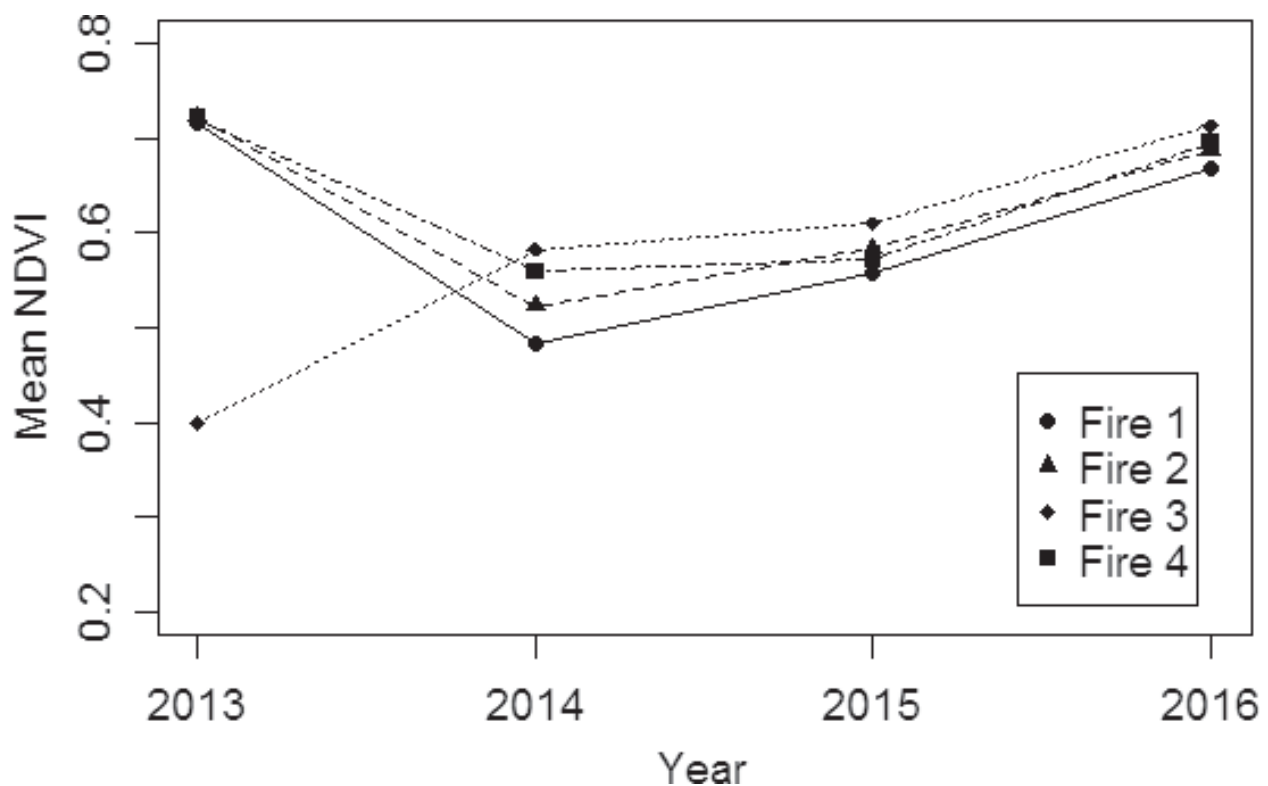

Figure 8. Evolution of mean NDVI values of the fire events from 2013 to 2016.

increase for next years in analysis. The increasing values of NDVI are indicative of the vegetation regeneration either by seed or by sprouts [4, 9, 94, 95], shortly after the fire [88–92, 96]. Nevertheless, for these fires, more than three years are necessary to achieve the pre-fire NDVI values, values, depending on several factors such as the pre-fire plant species composition [89–92], season of fire occurrence [93], and severity and intensity of fire [6]. The vegetation recovery will have also the advantage of reducing substantially the erosion risk [119–121, 125].

The interannual difference of the NDVI (**Figure 9**), the pre- and post-fire, shows also a gradual vegetation recovery, in the affected areas, by different land cover vegetation types. For all different land cover types the vegetation regeneration is similar. Differences of mean NDVI are between 0.2 and 0.25 for Fire1 and Fire2, and between 0.1 and 0.15 for Fire4. Lower mean NDVI points to lower severity, that is the maintenance of some vegetation or some live tree crowns after the fire event, which enables seed regeneration [9, 94, 95]. Therefore small positive differences were encountered for the *Pinus pinaster* and *Eucalyptus globulus* (Fire1), where the fire scar is accentuated one year after the fire event, as can be observed in **Figure 7**. The regeneration of these species is not sufficiently fast to increase the NDVI values.
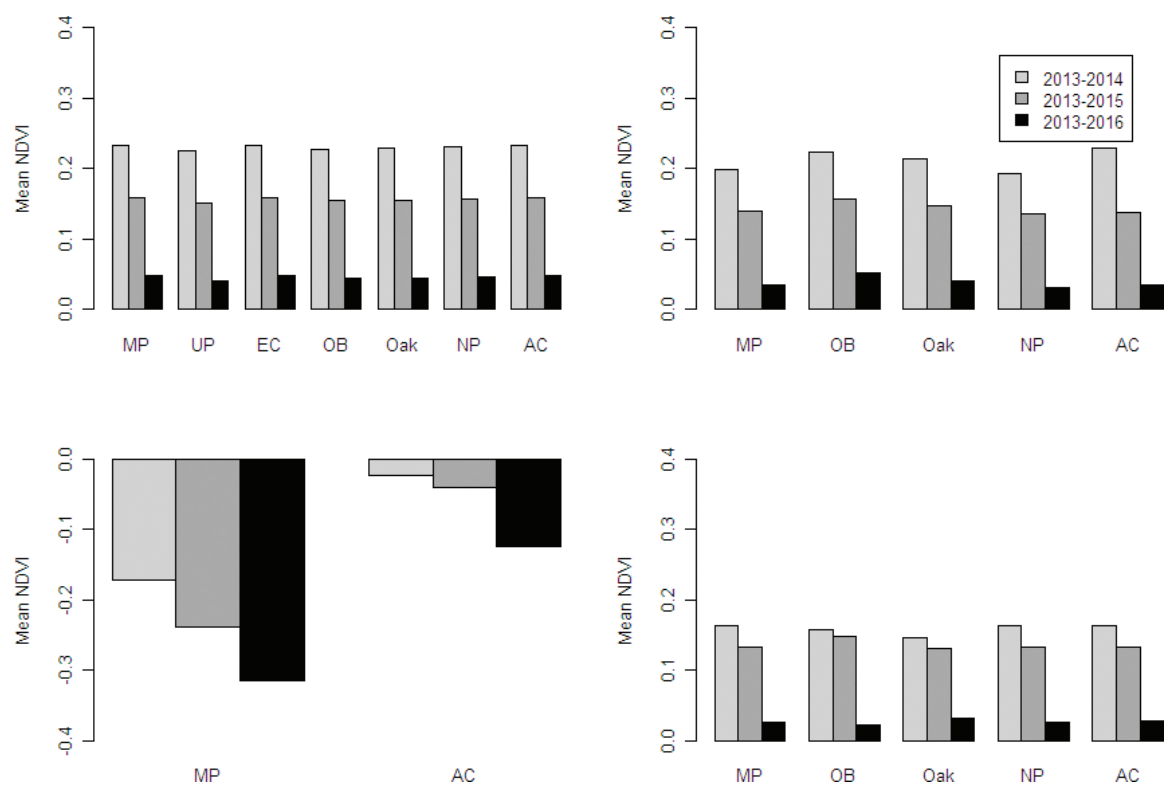

Figure 9. Difference of mean NDVI values per vegetation type (MP – Maritime pine, UP – Umbrella pine, EC – Tasmanian blue gum, OB – Other broadleaf species, Oak, NP – Natural pastures, AC – Annual culture).

7. Conclusions

Forest fires are a frequent feature in forest ecosystems. In the Mediterranean and, in particular in Portugal, they occur on regular annual basis. Nonetheless a wide range of variability, whether spatial or temporal, exists, partially explained by the type of forest system and the climate,

especially in relation to the high temperatures and low humidity. The most affected systems are those with high spatial, both vertical and horizontal continuity, and large fuel loads. In Portugal the most affected areas are those covered by *Pinus pinaster* and *Eucalyptus globulus*, which are also areas with larger burnt areas. The species characteristics, high flammability, as well as the large continuous areas when compared to other species, high stand density of trees and shrubs can explain, at least partially, the fire propagation. The spatial analysis detected regional differences. In northern and central Portugal, the number of fires and the burnt area as well as the frequency of fires were much larger than those in southern Portugal. This seems to be linked with vegetation type. While the forest areas of northern and central Portugal are predominantly of *Pinus pinaster* and *Eucalyptus globulus*, in the southern Portugal the evergreen oaks (*Quercus suber* and *Quercus rotundifolia*) dominate the forest landscape. The NDVI based on a time series Landsat 8 satellite images allows the monitoring and evaluation of post-fire vegetation regeneration. The interannual difference of NDVI enables better understanding of the temporal variability of the recovery vegetation after the fire event, and a reduction of the potential soil erosion risk in the Mediterranean ecosystems. The differences between fires and land cover types can be an indicator of the fire severity.

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