Chapter

New Remote Sensing Technologies Applied to the Prediction of Spontaneous Forest Fires

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Abstract

One of the causes of a forest fire is a combination of environmental variables such as temperature and relative humidity, as well as wind speed. When environmental conditions are favorable, chemical reactions occur at the forest mass level, resulting in pre-ignition. A big-data analysis of three spontaneous forest fires that occurred in Spain between 2015 and 2019 was performed to determine the chemical compound from which the forest fire starts. After analyzing satellite data, it was discovered that the critical temperature at which a fire starts spontaneously is 51.27°C, a value that coincides with the maximum limit of decrease in environmental sulfur dioxide concentration ([SO_2]), presumably due to sulfur capture by part of the wood, an element that is released into the environment after the fire occurs. The Spontaneous Forest Fire Process (SFFP) and fAPAR have a close relationship because pre-ignition occurs when the critical temperature determined by environmental conditions is reached.

Keywords: sulfur dioxide, thermal plugging, Broglie Law, Iberian Peninsula, remote sensing technologies

1. Introduction

Hitherto, when a forest fire occurs, the habitat is destroyed, without it being possible to avoid the devastation of the environment when the fire is due to natural causes.

According to Government of Spain [1], Spanish forest ecosystems occupy just over 26 million hectares (26,280.281 ha), of which almost 15 million (14,717.898 ha) are wooded and some 12 (11,562.382 ha) treeless, which respectively represent 29 and 23% of the national territory. The coniferous forests have a similar extension than the hardwood ones (5.7 and 5.2 million hectares, respectively) while the mixed ones have a somewhat smaller population (3.9 million hectares).

In another vein, and based on the latest study published by [2], it is of great interest to take into account the deforestation linked to international trade, especially since Spain causes the deforestation of 32,900 hectares of forest each year (the production and consumption of soybeans, palm oil and beef are the main items that explain this situation). However, at the national level, a notable increase in the area of wooded mountains has been detected at the cost of a decrease in the cultivated area, as well as that corresponding to land without forest mass [1]. In general terms, the Government of Spain has action policies to control both deforestation and forest conversion to other uses through the sustainable use of its resources. In this regard, and although deforestation occurs as a result of the mutual interaction of various factors, the problem of a forest fire, as an independent variable, should not be ignored, since as consequence of the destruction of areas of both biological and ecological interest, it is difficult to adapt the damaged ecosystem to the situation prior to the fire.

In relation to the above, the trend that climate-change represents in the medium term is of enormous importance, since the increase in temperatures as well as the increase in the incidence of prolonged and intense drought periods will result in a decrease in relative humidity. in the atmosphere close to the forest mass, and therefore the appearance of suitable conditions for spontaneous forest fires to take place much more often than at present [3].

Likewise, it is important to take into account the relationship between the dynamics of the lower atmosphere and the movement of air resulting in large fires that favor the development of enormous plumes, generating a series of processes that give rise to a vertical transfer of matter and energy in turbulent movements and rapid [4]. On the other hand, it is interesting to know that, during a forest fire, high-risk situations are frequently generated when specific fire sources are created, associated or not, with sudden changes in direction or speed of the wind. It is evident that, when temperature, relative humidity and local wind speed take place together, the forest fire expansion danger increases, making extinction work difficult [5].

The importance of the type of fuel existing in the forest mass should not be forgotten. For this reason, it should be noted that in Spain the predominant hardwood species are *Quercus ilex*, followed by *Quercus pyrenaica, Quercus pubescens, Eucalyptus spp., Quercus suber, Fagus sylvatica, Quercus faginea, Quercus canariensis, Quercus robur, Quercus petraea and Castanea sativa*. Regarding conifers, *Pinus halepensis, Pinus pinaster, Pinus sylvestris, Pinus nigra* and *Pinus radiata* stand out. The great richness in scrub, bush and grass species existing in Spanish forests should not be forgotten, mainly due to the amount of dry matter that they can contribute to the fire.

According to [6], in this country, around 5% of fires are due to natural causes (adequate relationship between relative humidity and temperature, lightning, etc.), being the cause of the remaining 95% very varied, highlighting among them accidents or negligences, intentional fire and unknown reasons.

In another vein, and as a result of the technological advances that have occurred in recent decades, it is evident that remote sensing can be a tool of greater interest, than it is currently, in the evaluation and monitoring of forest fires. To date, satellite sensors collect data about the location of the fire, as well as those characteristics of the forest mass that may influence its duration and/or its extension [7]. As it is known, there are several satellites that inform us in almost real time of forest fires. One of the best known is NASA's MODIS (Moderate-Resolution Imaging Spectroradiometer), which is a scientific instrument on board both the Terra satellite and the Aqua satellite. Another of them is the VIIRS (Visible Infrared Imaging Radiometer Suite) also from NASA, a sensor on board of Suomi National Polar-orbiting (Suomi NPP) and NOAA-20, and which together with the MODIS provide data on forest fires within the NASA program, Fire Information for Resource Management System, dedicated exclusively to giving us timely and very precise information in near real time (NRT) of forest fires, within 3 hours after the passage of the satellite. The Sentinel satellites of the Copernicus program cannot be forgotten, a great help in this field of study carried out jointly by the European Space Agency (ESA) and by the European Union through the European Environment Agency. ESA is currently developing seven missions, and has five underway, of which, each Sentinel mission is made up of two satellites to ensure total coverage in each mission.

As is well known, in many parts of the world most forest monitoring is still carried out using traditional methods, no existing information on the advantages of new and accurate remote sensing techniques. For this reason, it is very important to point out that there is currently no procedure, based on environmental information, capable of predicting those areas with a high probability of occurrence of a forest fire with time enough for the firefighting services can intervene before a major disaster occurs. Based on the comments, this study focuses on obtaining an algorithm, based on environmental information obtained through remote sensing, capable of predicting the moment in which the pre-ignition of a spontaneous forest fire occurs. The resulting algorithm can be useful for decision making, as well as preventing spontaneous forest fires.

2. Study area

The municipality of Lújar (36°47′16″N; 3°24′10″W), Grenada (Spain), is located at south of the Iberian Peninsula (**Figure 1**). In general, the study area has a temperate and warm climate, with rainfall concentrated mainly in winter. According to the Köppen-Geiger classification, Lújar is located in the Csa climatic zone, with an

Figure 1.
Location of the study area.

average annual temperature of 16.8°C, while its annual rainfall amounts to an average of 416 mm.

Of a total of 36.83 km2 (3683 ha) of surface that Lújar has, on July 30, 2015, as a result of a spontaneous fire, 1034.96 ha (28.1%) were burned (**Table 1**).

Lújar is located in the Sierra of Lújar, one of the most outstanding natural spaces in the region of the Grenada tropical coast. The affected area is made up of deep and steep ravines distributed in all geographical orientations and has a vegetation that, although it has been greatly damaged in large part by fires in the last 30 years, preserves remnants of the original natural formations. It must be emphasized, as a result of its fauna and flora characteristics, that the Sierra of Lújar is entirely a hunting ground, most of it managed by local hunting societies and some areas by the owners of the farms.

As a result of the above, over time there has been a process of renewal of the traditional landscape, characterized by the mining and agricultural sectors as the main drivers of the municipal economy, in which the maintenance of natural vegetation stands out, resulting in an improvement in the quality of the landscape, and therefore, in an increase of the ecological value of the study area. This aspect has been of great importance for the existing sustainable rural tourism in the municipality of Lújar, although after the fire that occurred it was radically damaged, causing a terrible impact at all levels.

On the other hand, according to [8], the study area is characterized by soils with a pH close to neutrality (mean value of 7.15), with a Base Saturation Percentage (BSP) of 77.80%, a Cation Exchange Capacity (CEC) of 8.58 meq·$100g^{-1}$, with an average value in Active Limestone (AL) of 0.179% and, an Organic Matter (OM) value of 2.766%.

Land uses	**Value (€)**	**Burned area (ha)**
Cork oak	2,733,155.04	138.01
Irrigated almond tree	75,767.88	12.79
Non-irrigated almond tree	1,002,130.83	171.77
Subtropical fruit trees	30,894.42	0.70
Irrigated fruit tree	21,364.36	0.67
Intensive farmland	171,583.18	3.88
Non-productive farmland	14,418.64	8.99
Horticultural greenhouse	292,915.52	6.62
Dry lands	45,496.84	5.61
Shrubs	480,809.30	299.76
Non-irrigated olive grove	1,039,887.76	28.32
Irrigated olive grove	43,288.80	1.07
Pastureland	497,723.32	310.30
Timber pine forest	878,343.08	44.50
Non-irrigated vineyard	42,442.75	1.98
Total sum →	**7,370,221.73**	**1034.96**

Table 1.
Affected area by the spontaneous forest fire, and their economic value.

With regard to the species, or type of canopy, affected by the fire, it should be noted that, before the disaster occurred, there were different typology of agricultural crops, noble Mediterranean scrub, vegetation classified as other Mediterranean scrub, a mixture of *Pinus* and *Quercus* in a similar proportion, cork oak and areas with scarce vegetation.

One of the main economic bastions of the municipality of Lújar is natural or green tourism. In general, this type of tourism refers to those activities that tourists can develop in a completely natural environment, such as hunting tourism (one of those mainly affected by the fire), ecotourism, ornithological tourism, agro-tourism and rural tourism. To a greater or lesser extent, and to date, the recovery of these activities has been supervised by a series of active policies, resulting in both an economic and social resurgence of the affected area, and therefore in a possibility that the Sierra of Lújar is declared a protected natural area.

3. Materials and methods

To carry out this study, a total of 503 images were downloaded from the Earth Explorer archive, belonging to the U.S. Geological Service (USGS), which covered the period between January 2015 and December 2020, both inclusive. In order to adequately characterize the affected area by the fire, from an environmental point of view, each one of the images was examined and classified in one of three determined periods of time (January 1, 2015-July 29, 2015; July 30, 2015- August 31, 2015; September 1, 2015-December 31, 2020) depending on how the study area was (before, immediately after, and after the spontaneous forest fire). All images (Path 200 Row 34 and 35 "WRS") were acquired during January 2021. Subsequently, and with the use of the Geographic Information System (GIS) Ilwis, all the images (Sentinel-2 L2A, Sentinel-2 L1C both of them with 10 m spatial resolution and Landsat 8-C "LC8" Operational Land Imager "OLI", with a spatial resolution of 30 m, and Thermal Infrared Sensor "TIRS" of 100 m spatial resolution rescaled by cubic convolution to 30 m in order to match the multispectral bands of the OLI sensor) were improved. In order to keep the original brightness of the pixel values unchanged, the nearest neighbor algorithm was used.

As a result of the existence of a process of assimilation, and dis-assimilation, of sulfur by the wood of forest mass [9, 10], as well as the need for the existence of sulfur, in trace amounts, in wood for spontaneous combustion, an extensive search for sulfur isotopologues was carried out for the purpose of finding out the proper wavelength at which sulfur can be found in the atmosphere, and for this reason, to be able to select the appropriate satellite to analyze the possible variation of said element in the atmosphere near the forest mass.

For that reason, and as a result of the fact that when a forest fire occurs, the sulfur dioxide concentration ($[SO_2]$) in the atmosphere immediately in contact with the forest mass increases, data on this pollutant were downloaded from [11] between January 2015 and December 2019. Subsequently, 50 images were downloaded from the Sentinel-5P satellite (7×3.5 km spatial resolution) from May 6, 2018 to December 31, 2020 to correlate [11] data with satellite data using multiple triangulation. The objective of this correlation was to find out which of the three specified pollutants is related to the pre-ignition of spontaneous forest fires, based on the conditions of temperature (greater than 30°C) and relative humidity (less than 30%) that must occur during the days prior to the fire.

From the analysis of data obtained from satellite images, as well as those downloaded from [11], a linear model was obtained that allows obtaining, in any forest area and through remote sensing, the moment in which the pre-ignition of forest mass occurs.

In order to adequately contrast the obtained algorithm, a bibliographical review was carried out to determine the possible existence of a temporary record of climatic data (temperature and precipitation) of the affected area by the spontaneous fire, which is broad and significant enough to be able to obtain results, discussions and conclusions consistent with this research. In this regard, the information provided by the Global Climate Monitor (University of Seville, Spain) was of great importance, as it provided a temporal record of data, with significance ≤0.05, between 1901 and 2020 (120 years).

Last but not least, it was decided to test the algorithm obtained, as well as the results of this study, in two other spontaneous fires that occurred in Spain (1.- Doñana Natural Park "Matalascañas, Huelva" on June 24, 2017; 2.- Municipality of La Torre de l'Espanyol "Catalonia" on June 26, 2019), obtaining results consistent with those achieved in the study area.

4. Results and discussion

As has been confirmed in this study, remote sensing plays a fundamental role in the prevention of spontaneous forest fires. For this reason, the historical climatic variables of the study area (mean, maximum and minimum temperatures, as well as precipitation) should not be ignored, since when they exist in significant quantity they can help explain certain reflectivity characteristics produced at the pixel level [12].

In this type of study, the atmospheric contaminant amount in the study area is also of great importance, which will affect the optical depth of the atmosphere, and therefore the luminance of the analyzed pixel.

Therefore, in the analysis carried out using satellite images, it has been taken into account that the amount of radiation reflected by each object, and receiving by the satellite sensor, will result in a different reading per pixel than the one that would be in the case of atmosphere clean. This is an aspect of great interest, in addition to the relationship between the radiation reflected by the object in question, and the increase in atmosphere temperature, since when there are extremely reflective surfaces, a Thermal Plugging (TP) is caused in the atmosphere that leads to a decrease in Photosynthetically Active Radiation (fAPAR) in the study area [13], and therefore, a pronounced decrease in both Forest Mass Production (FMP) and Dry Matter Productivity (DMP).

As a result of the fact that in a forest fire the concentration of carbon monoxide (CO), carbon dioxide (CO_2) and sulfur dioxide (SO_2) increases in the affected area, it is logical to think that the temperature also increases, and therefore the fAPAR radiation is affected [14]. This fact is due to the fact that at higher atmospheric temperatures, a TP is generated (as long as there is wind speed ≥5 m/s that causes a situation of turbulent regime, and therefore, a mixture of the different air layers), thanks to which the fAPAR radiation, a consequence of the mixture of air layers, will be reflected or refracted, resulting in a lower amount of photosynthetically active radiation that will reach the surface of the plant canopy. The relationship between fAPAR radiation and the Average Environmental Temperature (AET), in Celsius degrees, is presented in the following equation (Eq. (1)):

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$$fAPAR = 0.564 - 0.011 \cdot AET \; (r = 0.83; R^2 = 0.7; p \le 0.001) \tag{1}$$

If the Eq. (1) is analyzed based on the TP, the critical temperature for a spontaneous pre-ignition to take place coincides with the moment in which the TP is maximum. At this time, and as a result of the increase in [SO_2] in the atmosphere immediately close to the forest mass, the air particules movement amount (Broglie's Law) increases, giving rise to successive collisions between these particules up to a point where, due to the elastic collision at high speed, an air particules coupling is produced that causes a wave front that prevents the fAPAR radiation reaches the plant canopy, since it is reflected towards the outside of the atmosphere close to the forest mass. This fact causes the successive heating of the air layers towards the surface, implying a successive decrease in the environmental Relative Humidity (RH in %), and as a final consequence another increase in [SO_2]. According to what was mentioned above, the fAPAR radiation decreases to zero, and therefore the accumulated temperature necessary for a spontaneous pre-ignition process to start is 51.27°C according to Eq. (1).

It is evident that the sulfur dioxide concentration depends on the Forest Mass Production (FMP), mainly due to the fact that the quantity and type of forest mass existing in the fire area is what gives rise, after its ignition, to certain levels of environmental [SO_2], in $mol \cdot m^{-2}$, or others. In this sense, a linear relationship has been found between [SO_2] and the FMP (variable dimensionless spectral index between 0 "zero Forest Mass Production" and 1 "maximum Forest Mass Production"), which is presented below (Eq. (2)):

$$[SO_2] = 2.84 \cdot 10^{-5} + FMP \cdot 4.35 \cdot 10^{-4} \; (r = 0.92; R^2 = 0.873; p \le 0.001) \tag{2}$$

In order to facilitate, as far as possible, obtaining the FMP, it is important to comment that a direct relationship has been found with the Normalized Difference Humidity Index (NDMI), which is logical if one takes into account that greater forest mass humidity, greater will be the probability that this mass will be more productive (see Eqs. (3) and (4)):

$$NDMI = -0.353 + 0.791 \cdot FMP \; (r = 0.913; R^2 = 0.833; p \le 0.001) \tag{3}$$

$$NDMI = \frac{NIR - SWIR}{NIR + SWIR} \tag{4}$$

where:

NIR = Near Infrared spectral band.

SWIR = Short wave infrared spectral band.

Likewise, a relationship has been found to be able to obtain, in kg per hectare, the Dry Matter Productivity (DMP) (see Eqs. (5) and (6)):

$$DMP = -636.35 + 276.32 \cdot NDMI + 3798.18 \cdot GNDVI \; (r = 0.89; R^2 = 0.79; p \le 0.001) \tag{5}$$

$$GNDVI = \frac{NIR - Green}{NIR + Green} \tag{6}$$

where:

GNDVI = Green Normalized Difference Vegetation Index.

NIR = Near Infrared spectral band.

Green = Green spectral band.

However, apart from the above, after analyzing the data obtained, it has been possible to verify the decrease, from the 9th day before the spontaneous fire occurred (**Figure 2**), in [SO_2]. This fact is the key to being able to predict whether or not the conditions that give rise to a spontaneous forest fire will occur. As can be inferred from **Figure 2**, during the summer months mainly, seems to be a variation in sulfur dioxide concentration levels in the atmosphere immediately close to the forest mass, which begins to be more pronounced 9 days prior to spontaneous fire. This decrease in [SO_2] will be more (**Figure 2a** and **c**) or less (**Figure 2b**) visible depending on the predominant type of vegetation in the affected area. However, it must be taken into account that 2 or 3 days before the spontaneous fire occurs, the decrease in [SO_2] is more pronounced, which may be due to the existence of a process of rapid assimilation of environmental sulfur by forest mass similar to that described by [9, 10]. Logically, and as a result of the decrease in fAPAR radiation, the increase in environmental temperature, as well as the decrease in relative humidity, favors the appearance of a process, which will be called Spontaneous Forest Fire Process (SFFP) (Eq. (7)). Thanks to this process, and according to [15], the sulfur dioxide concentration plays an extremely important role, since when the mean value of the concentrations corresponding to the 9 days prior to the fire ([SO_2]$_{\text{mean value 9 days before}}$) is greater, positive difference, than the estimated value of the day of the fire ([SO_2]$_{\text{estimated value}}$), a spontaneous fire will take place. Otherwise, negative difference, the spontaneous fire will not occur (**Table 2**).

$$SFFP = [SO_2]_{mean\ value\ nine\ days\ before} - [SO_2]_{estimated\ value} \quad (7)$$

It is evident that the assumption of the SFFP is of great importance when it comes to monitoring the possible potential risk of spontaneous forest fires occurrence, and

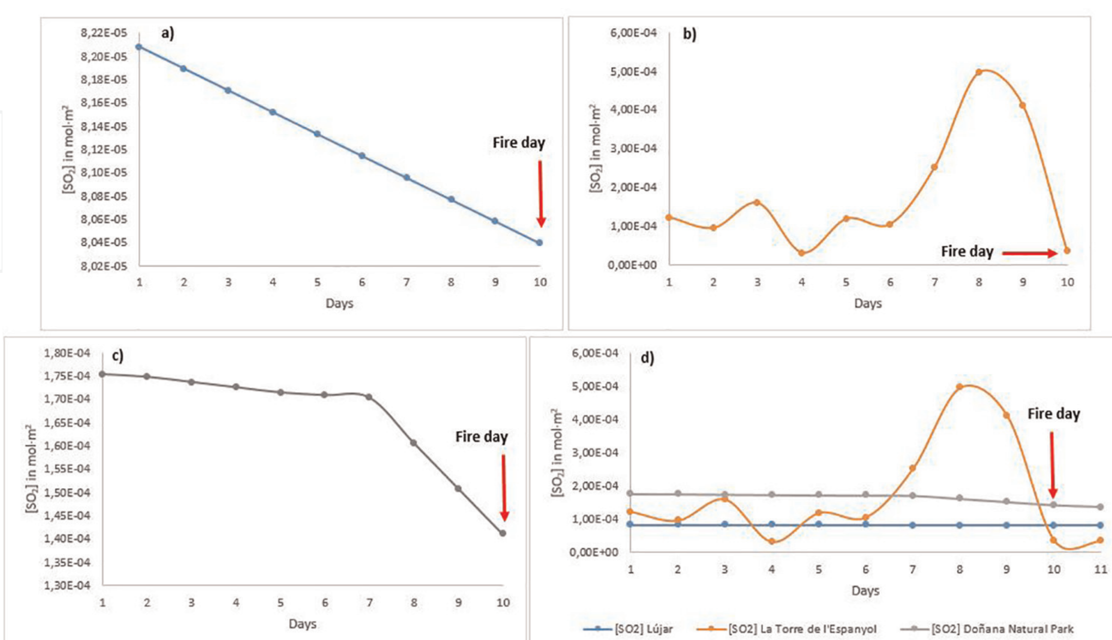

Figure 2.
Variation of sulfur dioxide concentration in Lújar "(a)", La Torre de l'Espanyol "(b)" and Doñana Natural Park "(c)" during the 9 days prior to the spontaneous fire. Picture "(d)" shows the comparison of the previous three.

	[SO_2] Lújar	[SO_2] La Torre de l'Espanyol	[SO_2] Doñana Natural Park
Mean value days 1 to 9 ($mol \cdot m^{-2}$)	8.13×10^{-5}	1.98×10^{-4}	1.69×10^{-4}
Fire day value ($mol \cdot m^{-2}$)	8.04×10^{-5}	3.44×10^{-5}	1.41×10^{-4}
Percentage difference	1.15	82.67	16.51
Difference type	Positive	Positive	Positive
SFFP	Occurs	Occurs	Occurs

Table 2.
Occurrence of the spontaneous forest fire process (SFFP).

therefore, of great interest for the sustainable environmental maintenance of all forests. From the point of view of land use planning, control, evaluation and environmental development of forests around the world, it is of great interest to alleviate the effects of climate change, whose relationship with the effect of Thermal Capping (TP), as well as with the decrease in fAPAR, must be taken into account.

There is no doubt that the incorporation of the proposed methodology to determine the spontaneous forest fire occurrence is simple, as well as easy to implement in any type of airborne or satellite platform.

5. Conclusions

Methodology proposed in this study provides a useful tool to carry out summer monitoring of environmental sulfur dioxide concentration, through satellite images, in any forest area. Likewise, the finding called Spontaneous Forest Fire Process (SFFP) should be highlighted, since it allows a better understanding of what happens in the atmosphere immediately close to the forest mass before the spontaneous fire takes place. It should not be forgotten that, associated with SFFP, there is a decrease in fAPAR radiation which has as a consequence, when it becomes equal to zero, the appearance of a critical temperature (51.27°C) at which the pre-ignition of the spontaneous forest fire occurs. It is necessary to emphasize the importance of Relative Humidity (RH), which decreases in relation to the increase in environmental temperature. Without this decrease in RH, it is difficult for SFFP to take place.

In another vein, it may be of great interest to take into account the cumulative effect of temperature on the soil-forest mass-atmosphere system, as well as its relationship with the assimilation, and dis-assimilation, of sulfur by the forest mass. However, the time dimension in which climatic variables can be forecast is still too short. For this reason, continuous monitoring of them is of vital importance, especially in forest areas where access is difficult in order to avoid natural disasters.

Regarding the affected area, Lújar, it is evident that both the environmental and landscape deterioration to which it was doomed after the fire, whose consequences may be the result of climate change [16].

However, as can be seen in **Figure 3**, the sulfur dioxide concentration before the fire (June 30, 2015) is related, on the surface, to the type of existing vegetation. On the other hand, this concentration varies completely once the fire has been controlled (August 1, 2015), giving rise to a situation very similar to what occurs in a desert area, that is, due to thermal accumulation, or thermal inertia, existing sulfur dioxide levels

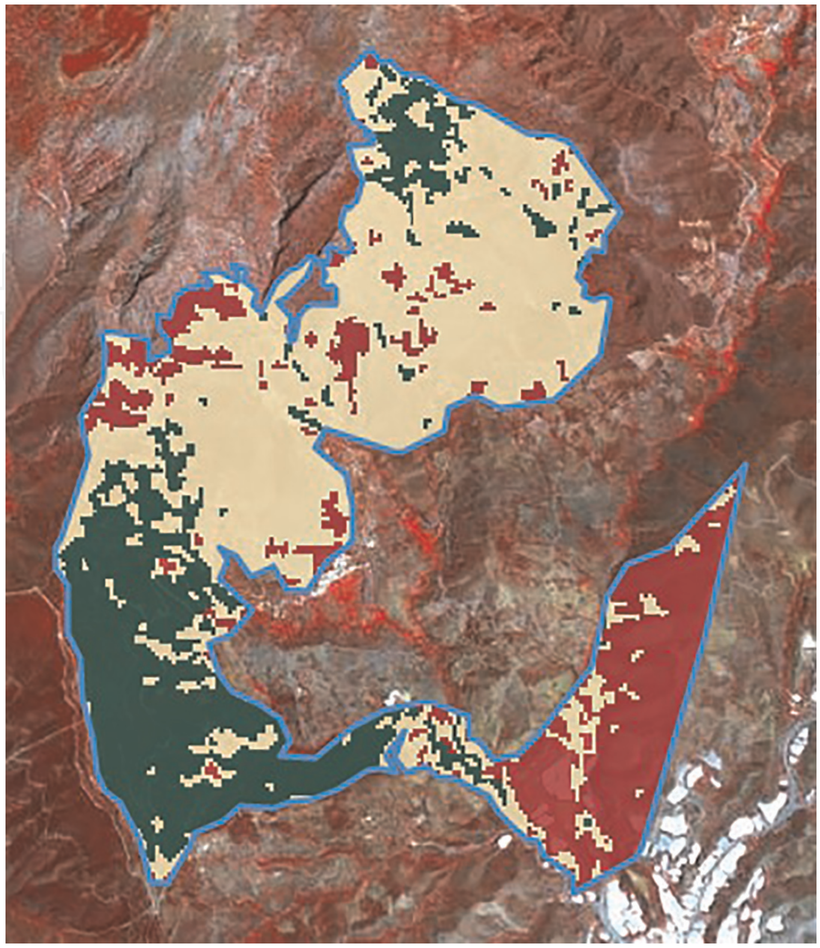

Figure 3.
Environmental SO_2 concentration, in Lújar, 1 month before (June 30, 2015) of the spontaneous fire. The red color is equivalent to 0 mol · m^{-2}, the area in yellow has values $<1.25 \times \cdot 10^{-3}$ mol · m^{-2}, while the area in green has values $>1.25 \times \cdot 10^{-3}$ mol · m^{-2}.

drop in those areas without vegetation due to thermal plugging (**Figure 4**). Over time, and as a result of the restoration policies carried out by the municipal government, the affected area has been recovering its initial status, giving rise to a situation (**Figure 5**), on August 14, 2020, similar to the one shown in **Figure 3**.

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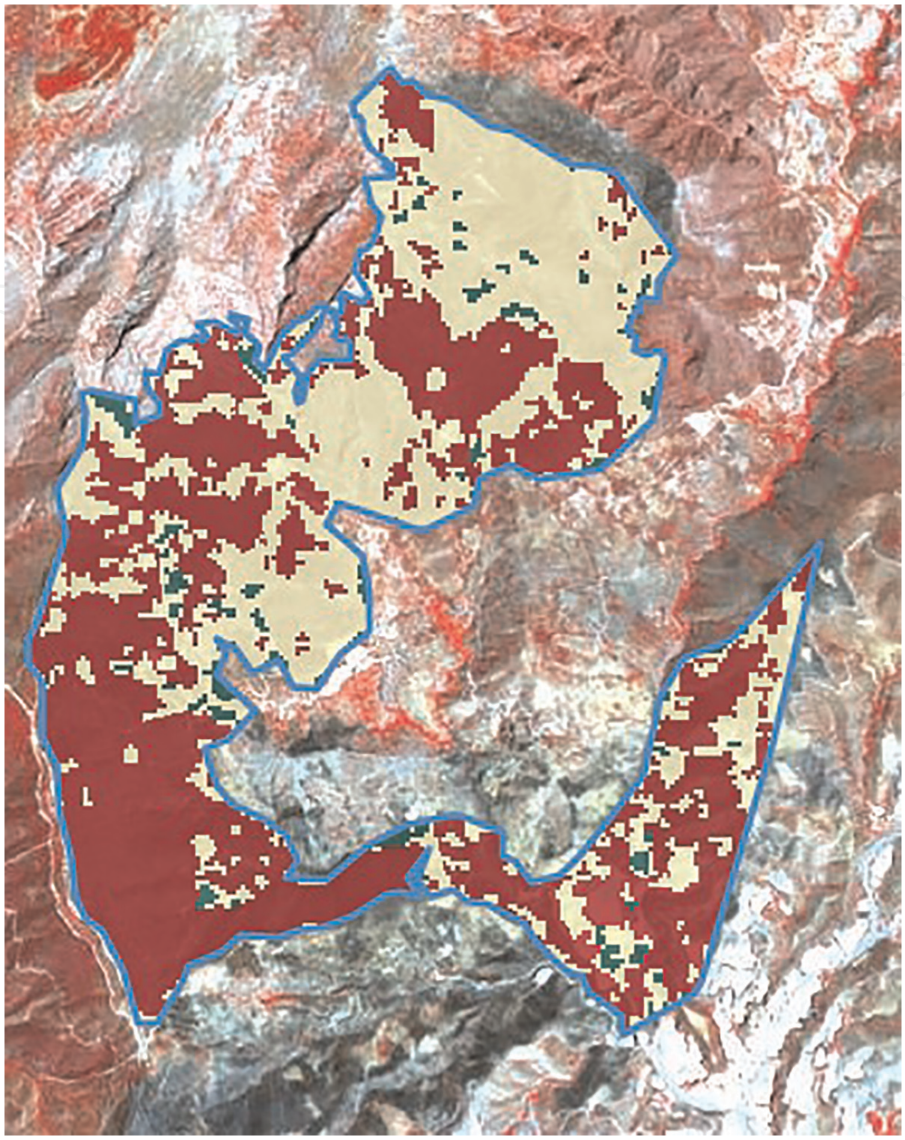

Figure 4.
Environmental SO_2 concentration, in Lújar, when the fire was controlled (August 1, 2015). The red color is equivalent to 0 mol · m^{-2}, the area in yellow has values <1.25 × ·10^{-3} mol · m^{-2}, while the area in green has values >1.25 × ·10^{-3} mol · m^{-2}.

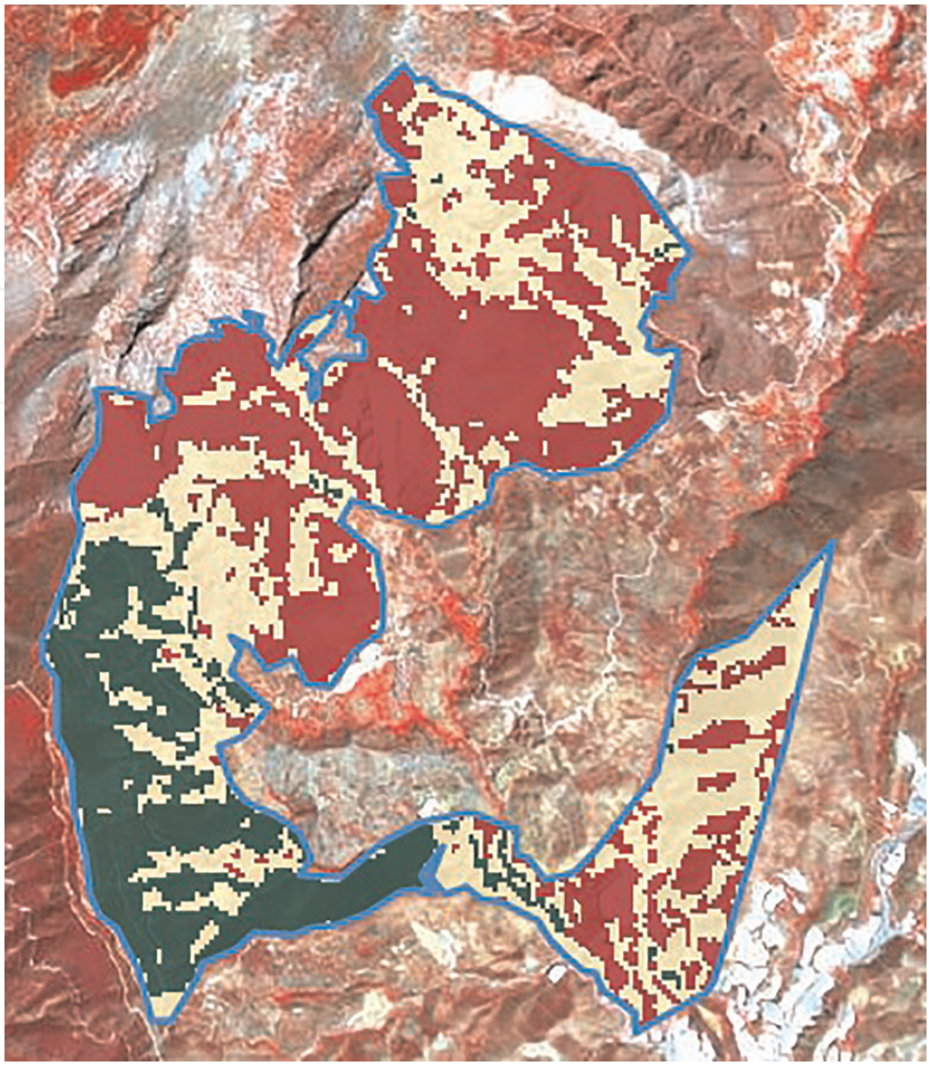

Figure 5.
Environmental SO_2 concentration, in Lújar, on August 14, 2020. The red color is equivalent to 0 mol · m^{-2}, the area in yellow has values <1.25 × ·10^{-3} mol · m^{-2}, while the area in green has values >1.25 × ·10^{-3} mol · m^{-2}.

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Conflict of interest

The authors declare no conflict of interest.

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