

Article

An Assessment of Forest Fires and CO₂ Gross Primary Production from 1991 to 2019 in Mação (Portugal)

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Abstract: Forest-fire rates have increased in Southern European landscapes. These fires damage forest ecosystems and alter their development. During the last few decades, an increase in fast-growing and highly fuel-bearing plant species such as bush, *Eucalyptus globulus* Labill., and *Pinus pinaster* Ait. has been observable in the interior of Portugal. This study aims to verify this assumption by the quantification of the biomass carbon sink in the forests of the Mação municipality. Maps of fire severity and forest biomass evolution after a wildfire event were produced for the period of 1991 to 2019. To quantify carbon retention in this region, this evolution was correlated with gross primary production (GPP) on the basis of satellite imagery from Landsat 5, Landsat 8, and MODIS MYD17A2H. Results show that wildfires in Mação increased in area and severity with each passing decade due to the large accumulation of biomass promoted by the abandonment of rural areas. Before the large fires of 2003, 2017, and 2019, carbon rates reached a daily maximum of 5.4, 5.3, and 4.7 gC/m²/day, respectively, showing a trend of forest-biomass accumulation in the Mação municipality.

Keywords: wildfire; forest; GPP; satellite image; Mação



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1. Introduction

The increase in greenhouse gases (GHG) in the atmosphere and consequential global climate change are major concerns for today's society. According to Knorr et al. [1], and Guo et al. [2], forest fires release a very large amount of CO₂ (corresponding to approximately 2 to 3 PgC/year), significantly contributing to the concentration of GHG in the atmosphere. Several studies based on remote sensing were carried out to assess the severity of wildfires and to monitor postfire dynamics of forest ecosystems [3–6] or to quantify gross primary production (GPP) [7,8]. GPP is the amount of carbon fixed by vegetation through photosynthesis and is the key element in the carbon balance between biosphere and atmosphere [9]. After extreme weather events or anthropogenic disturbances, for example, forest fires, GPP suffers variations that could significantly impact the net carbon exchange of the ecosystem (net ecosystem exchange (NEE)) [10,11]. Therefore, changes in GPP before and after a wildfire event are a way to assess its severity.

In the Mediterranean region, over the last few decades, forest fires have become larger in area and of higher severity [2,12]. In Southern Europe, wildfires are becoming a frequent occurrence, compromising the development of forest ecosystems. Socioeconomic

changes that occurred in the second half of the last century are reflected both in land use and population lifestyle. The migration of inhabitants of rural areas to larger cities, a consequence of the abovementioned socioeconomic changes, resulted in the increased neglect of agricultural land and forestry, and consequently the accumulation of biomass over the years, leading to large-scale and intense fires. Another important contributing factor for the occurrence of these fires is the increase in highly combustible, easily cultivated, and fast-growing plant species stands, such as *Eucalyptus globulus* Labill. [13–17].

Prior to the 1980s, forest fires in Portugal never exceeded 10,000 ha of burnt area in a single occurrence [17]. The Portuguese Institute for Conservation of Nature and Forests (ICNF) regularly publishes statistics of large wildfires over 10,000 ha [18], which are the fires discussed in this study. The first major forest fire over 10,000 ha that had occurred in Portugal was on 13 July 1986 in the municipality of Vila de Rei (district of Castelo Branco), with 10,032 ha of burnt area. On 6 August 1992, Arganil was hit with a large fire that destroyed 12,814 ha; after that, there was a pause of 11 years without any other occurrence affecting more than 10,000 ha. The year 2003 was ominous, with large wildfires burning areas over 20,000 ha, and affecting many municipalities in the Central and Alto Alentejo regions, namely, the municipalities of Chamusca, Proença-a-Nova, Oleiros, Sertã, Vila de Rei, Mação, Gavião, Nisa, Ponte de Sor, Alter do Chão, and Crato. In the same year, the Algarve region faced the great fire of Monchique with more than 66,000 ha of burnt area, striking the municipalities of Silves, Aljezur, Portimão, Monchique, and Odemira, the latter in the Lower Alentejo region.

The year 2017 was the worst year in terms of loss of human lives, housing, and forests caused by several major forest fires. On 31 October 2017, a total of 412,781 ha was burnt [19], with 112 fatalities and more than 500 homes destroyed by the fires [20,21]. The centre of Portugal was the most affected area of mainland Portugal during the 2017 fires. The Pedrógão Grande (Leiria district) fire that broke out on 17 June destroyed 27,364 ha [19] and killed 64 people [20]. This fire merged with the Góis fire (Coimbra district) that burnt 17,521 ha [19]. The fire of Sertã (Castelo Branco district) on 23 July 2017 consumed 29,758 ha. In the same year, the worst month was October, with fires that burnt 16,610 ha in Figueira da Foz and 35,806 ha in Lousã (Coimbra district), 30,142 ha in Sertã (Castelo Branco district), 57,534 ha in Seia (Guarda district), and 15,687 ha in Alcobaça (Leiria district) [19].

At the end of July 2019, the centre of Portugal was again struck by major fires. The municipalities of Vila de Rei (Castelo Branco district) and Mação (Santarém district) were particularly affected by the fire of 20 July 2019, destroying 9249 ha of forest [22]. This burnt area bordered with Sertã (Castelo Branco district), where a big wildfire occurred on 23 July 2017. Table 1 summarizes the largest and most severe wildfires that occurred in mainland Portugal from 1986 to 2019.

Table 1. List of major wildfires in mainland Portugal from 1986 to 2019.

Date of Wildfire	Burnt Area [ha]	Municipality (DISTRICT)	Source of Data
July, 1986	10,032	Vila de Rei (CASTELO BRANCO)	[18]
Spetember, 1987	10,013	Arganil, Oliveira do Hospital (COIMBRA)	[18]
August, 1992	12,814	Arganil (COIMBRA)	[18]
August, 2003	>20,000	Oleiros, Proença-a-Nova, Sertã, Vila de Rei (CASTELO BRANCO); Alter do Chão, Crato, Gavião, Nisa, Ponte de Sor (PORTALEGRE); Chamusca, Mação (SANTARÉM)	[18]
August, 2003	≈66,000	Odemira (BEJA); Aljezur, Monchique, Portimão, Silves (FARO)	[18]
July, 2004	27,452	Almodôvar (BEJA); Loulé, Tavira, São Brás de Alportel (FARO)	[18]
July, 2005	15,837	Arganil, Oliveira do Hospital, Pampilhosa da Serra (COIMBRA); Seia (GUARDA); Covilhã, Fundão (CASTELO BRANCO)	[18]
August, 2005	>11,000	Arouca, Vale de Cambra (AVEIRO)	[18]
August, 2005	≈12,000	Pombal (LEIRIA); Ourém (SANTARÉM)	[18]
August, 2005	≈12,000	Pampilhosa da Serra (COIMBRA)	[18]

Table 1. Cont.

Date of Wildfire	Burnt Area [ha]	Municipality (DISTRICT)	Source of Data
August, 2005	>13,000	Coimbra, Lousã, Miranda do Corvo, Penacova, Penela, Vila Nova de Poiares (COIMBRA)	[18]
August, 2005	≈12,000	Abrantes, Chamusca, Ourém (SANTARÉM)	[18]
August, 2005	>11,000	Caminha, Paredes de Coura, Ponte de Lima, Viana do Castelo, Vila Nova da Cerveira (VIANA DO CASTELO)	[18]
July, 2012	24,843	Tavira (FARO)	[18]
July, 2013	13,706	Alfândega da Fé (BRAGANÇA)	[23]
August, 2016	21,910	Arouca (AVEIRO)	[24]
June, 2017	27,364	Pedrógão Grande (LEIRIA)	[19]
June, 2017	17,521	Góis (COIMBRA)	[19]
July, 2017	29,758	Sertã (CASTELO BRANCO)	[19]
October, 2017	16,610	Figueira da Foz, Lousã (COIMBRA)	[19]
October, 2017	35,806	Lousã (COIMBRA)	[19]
October, 2017	30,142	Sertã (CASTELO BRANCO)	[19]
October, 2017	57,534	Seia (GUARDA)	[19]
October, 2017	15,687	Alcobaça (LEIRIA)	[19]
August, 2018	26,763	Monchique (FARO)	[25]
July, 2019	9,249	Vila de Rei (CASTELO BRANCO); Mação (SANTARÉM)	[22]

The 2019 wildfire in Mação basically burnt the entire remaining unaffected forested area. According to the map presented by the European Forest Fire Information System (EFFIS), and with information provided by the ICNF [19,22], approximately 90% of the Mação municipality burnt between 2017 and 2019. Municipalities in deeper central Portugal, but particularly the municipality of Mação, have suffered from major fires in the last three decades. This reflects drastic changes in landscape caused by the collapse of the agrosilvopastoral system [26]. In the 1950s, this territory was characterized by the intensive use of viable lands for agriculture and herding. There was also intensive use of shrubbery to fertilize the land, and as flooring material for cattle pens. Basically, only hilly areas were left for forestry. Since then, new generations from deep central Portugal sought different forms of economic subsistence. As they moved to the large cities of Portugal or emigrated, those agricultural lands gave way to highly combustible forest species, such as *Eucalyptus globulus* Labill. and *Pinus pinaster* Ait. [14,26]. This has contributed to the strong susceptibility of those territories to large wildfires.

Mação is important for its archaeological heritage, ecological, economic, and therapeutic value. In the Ocreza River valley, southwest of the municipality, an outdoor rock art complex of engravings from between the Palaeolithic and the Bronze Age can be found [27]. The high temperatures caused by the wildfires severely affect some of the rock figures, causing cracks and detachments [28]. Mação is also crossed by the Tejo River, and both rivers are habitat of the Iberian Barbel (*Luciobarbus bocagei*), which is particularly affected by ash transported to rivers [29]. The hydromineral system of Ladeira de Envendos, located in the parish of Envendos (Mação), is a source of mineral water (bottled and supplied nationwide), and a thermal installation for thermal–therapeutic purposes (thermal baths with hydrotherapy). Wildfires negatively impact the runoff, infiltration, and groundwater-recharge processes, thereby affecting the chemical composition of surface water and groundwater [30]. Having this in mind, and on the basis of remote-sensing techniques, this study quantifies the severity of wildfires in the municipality of Mação and the consequent changes in gross primary production (GPP). According to Gough [31], GPP can be defined as “the total amount of carbon dioxide ‘fixed’ by land plants per unit time through the photosynthetic reduction of CO₂ into organic compounds”. Techniques based on remote sensing, GPP (MODIS product), and indices such as CO₂ flux were applied to some studies to monitor the deforestation of the Maiombe forest in Cabinda (Angola) [32], to update the boundaries between the Amazonia and Cerrado biomes in Brazil caused

by anthropic actions [33], and to evaluate the postwildfire recovery process in Gangwon province (South Korea) [8].

The period under analysis ranges from 1991 to 2019, i.e., comprising the major forest fires that affected Mação. In the last three decades, there has been an increase in burnt area and fire severity. The lack of proper land management creates conditions for major forest fires to occur every 10 years, as it corresponds to the recovery time of the vegetation and its ground accumulation. This study contributes to better forecasting future fires and to helping stakeholders to manage the territory, preventing and mitigating the harmful effects of fires to the inhabitants and environment of the region of Mação. This is of particular significance for a region that has lost population, and struggles to become more capable of attracting investment through forestry and tourism.

2. Materials and Methods

The Mação municipality (Santarém district, Portugal) has an area of approximately 40,000 ha (Figure 1). The climate of Mação is warm and temperate (according to the Köppen–Geiger classification), with a rainy winter, and a hot and dry summer. Yearly average temperature is 15.9 °C and total annual rainfall average is about 840 mm. The highest precipitation occurs in January with an average of 122 mm, while July is the driest month with an average of 7 mm. January is the coldest month with an average temperature of 9.3 °C, while the warmest is August with an average temperature of 23.6 °C [34]. The altitude in the Mação municipality ranges from 30 to 640 m, with steep slopes (over 30%) in many areas. The forested area of Mação is mainly occupied by highly combustible species, for example, *Eucalyptus globulus* Labill., *Pinus pinaster* Ait., and bush.

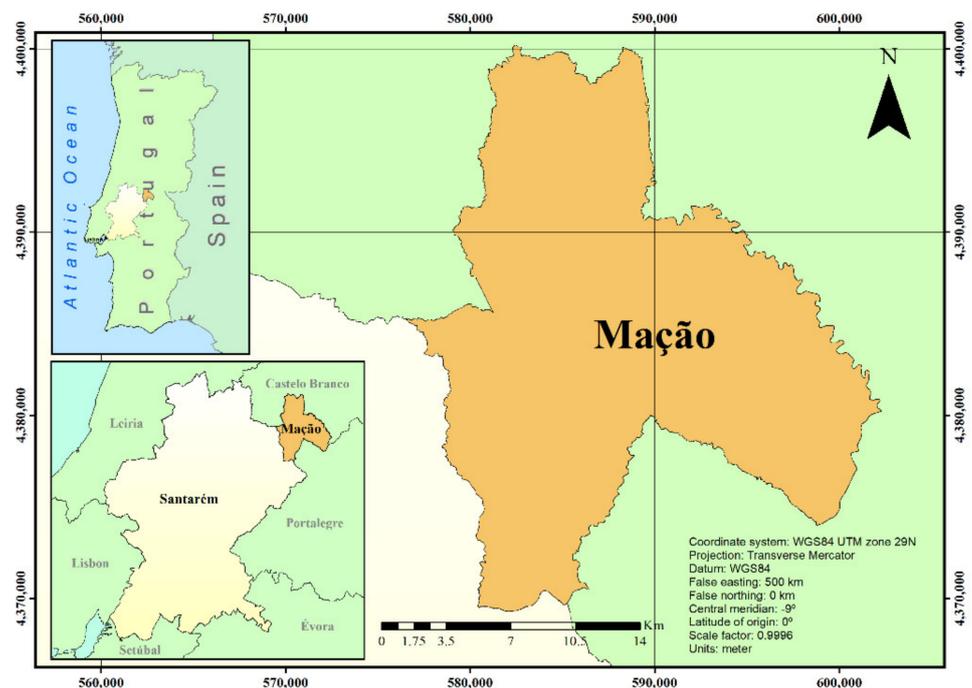


Figure 1. Location of study area. (light brown) Santarém district; (dark brown) Mação municipality.

Landsat 5 and 8 (NASA), and MODIS Terra (NASA) used in this study were obtained from the United States Geological Survey (USGS) Earth Explorer [35]. Images were acquired in 1991, 2003, 2017 and 2019, the years with major wildfires in the region: (i) on 24 and 26 June, 17 July, and 13 August 1991; (ii) on 25 June, 19 July, and 2 August 2003; and (iii) on 1 and 23 July, 16 August, and 23 September 2017. A short wildfire that occurred on 20 July 2019 was also included in this study because it affected areas unburned in 2017. Table 2 identifies imagery used to characterize the area burnt by these wildfires obtained from the

USGS Earth Explorer [35]. Only images with less than 20% of cloud coverage were selected for this study.

Table 2. Date of imagery used for wildfire characterization.

Satellite	Before Wildfires	After Wildfires
Landsat 5	02 September 1990	26 December 1991
	01 July 2002	12 August 2003
Landsat 8	15 June 2017	05 October 2017
	29 May 2019	01 August 2019
MODIS	26 June 2002 to 03 July 2002	13 August 2003 to 20 August 2003
	02 June 2017 to 09 June 2017	30 September 2017 to 07 October 2017
	25 May 2019 to 01 June 2019	28 July 2019 to 04 August 2019

Table 3 summarizes basic information on the sensors and the spatial resolution of the bands for each satellite used in this study obtained from the USGS website [36,37].

Table 3. Summary of satellites, sensors, products, and spatial resolution.

Satellite	Sensor	Bands (μm)/Product	Spatial Resolution (m)
Landsat 5	TM (Thematic Mapper)	Blue (0.45–0.52) Green (0.52–0.60) Red (0.63–0.69) NIR (0.76–0.90) Mid-IR (2.08–2.35)	30
Landsat 8	OLI (Operational Land Imager)	Blue (0.45–0.51) Green (0.53–0.59) Red (0.64–0.67) NIR (0.85–0.88) SWIR (2.11–2.29)	30
MODIS	Aqua	MYD17A2 (gross primary production)	500

Table 4 summarizes burnt areas in the wildfires of 1991, 2002, 2017, and 2019. The areas were calculated through intersecting the boundaries of the municipality of Mação with wildfire patches, the latter available in [18].

Table 4. Years of wildfire and burnt area.

Wildfire (Year)	Burnt Area (km^2)
1991	131.03
2003	193.50
2017	265.96
2019	56.31

During the studied period, the evolution of the vegetation cover was defined by the normalized difference vegetation index (NDVI). According to Rouse et al. [38], this index is calculated from the relation between the reflectance values of the red (ρ_{RED}) and near-infrared (ρ_{NIR}) bands (Equation (1)).

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{RED}}) / (\rho_{\text{NIR}} + \rho_{\text{RED}}) \quad (1)$$

The NDVI value range is between -1 (absence of vegetation) and 1 (maximal vegetation coverage). Most common values of NDVI for healthy vegetation are within the range of 0.2 and 0.8 [39]. Values close to 0 show the presence of bare soil. By means of field work and in situ recognition (visual observation) of the land occupation within the study

area, NDVI values were reclassified into four classes (Table 5). This reclassification is an adaptation from the studies of Weier and Herring [40], and Dalezios et al. [41].

Table 5. Classification of normalized difference vegetation index (NDVI) and definition of vegetation cover.

NDVI	Classification	Land Cover
[0.5; 1.0]	High	Dense vegetation (Pinus and eucalyptus)
[0.2; 0.5]	Moderate	Moderate vegetation (Pinus and eucalyptus)
[0.1; 0.2]	Low	Sparse vegetation (shrubs and grassland)
≤ 0.1	None	Bare soil, urban areas, and water bodies

The severity of the fires was quantified on the basis of the normalized burn ratio (NBR). According to Key and Benson [42], this ratio relates the near-infrared (ρ_{NIR}) with the medium-infrared (ρ_{MIR}) bands and is calculated for pre- and postfire scenarios (Equation (2)). The severity of the fire (dNBR; Equation (3)) can be given by the difference between NBR_{BF} and NRB_{AF} before and after the fire.

$$\text{NBR} = (\rho_{\text{NIR}} - \rho_{\text{MIR}}) / (\rho_{\text{NIR}} + \rho_{\text{MIR}}) \quad (2)$$

$$\text{dNBR} = \text{NBR}_{\text{BF}} - \text{NRB}_{\text{AF}} \quad (3)$$

The severity of the fire was then classified from an adaptation of the study of Key and Benson (Table 6) [42].

Table 6. Classification of fire severity based on dNBR.

dNBR	Severity
>0.66	High
[0.44; 0.66]	Moderate-high
[0.27; 0.44]	Moderate-low
<0.27	Low

Carbon sequestration was quantified on the basis of the CO_2 flux index (Equation (4)) [43], where sPRI is the photochemical reflectance index (PRI) [44], reclassified from 0 to 1 (Equation (5)).

$$\text{CO}_2\text{flux} = \text{NDVI} \times \text{sPRI} \quad (4)$$

$$\text{sPRI} = (\text{PRI} + 1) / 2 \quad (5)$$

PRI shows the relationship between the blue (ρ_{Blue}) and green (ρ_{Green}) bands (Equation (6)). PRI allows for establishing the relationship between photosynthesis and the efficient use of radiation. Therefore, it is a good indicator of the photosynthetic function of plants, at both the leaf- and the canopy-level scales [45].

$$\text{PRI} = (\rho_{\text{Blue}} - \rho_{\text{Green}}) / (\rho_{\text{Blue}} + \rho_{\text{Green}}) \quad (6)$$

The CO_2 flux index was validated on the basis of the obtained GPP from one of the products of Terra/MODIS (MOD17A2H) [37]. This product is available with data aggregated over 8 days, a spatial resolution of 500 m, and a scale factor of 0.0001. GPP is based on the concept of efficiency of solar radiation used by vegetation, and the daily GPP can be obtained through Equation (7). IPAR is the active photosynthetic radiation incident on the surface of the vegetation (MJ/m^2). FPAR is the fraction absorbed by the vegetation (dimensionless). ϵ is the light-use efficiency of the vegetation (gC/MJ). GPP is thus expressed in gC/m^2 .

$$\text{GPP} = \text{IPAR} \times \text{FPAR} \times \epsilon \quad (7)$$

CO₂ flux average values were calculated per GPP pixel for pre- and postfire scenarios immediately before and after the wildfires of 2003, 2007, and 2019. The 1991 wildfires were not included in the statistical analysis, as MODIS Aqua only started to operate from 2002. Linear regressions were established (Equation (8)), where m is the slope and b is intersect $X = 0$. The p value, R^2 of the model, and the four assumptions of the residuals (normality, homogeneity of variance, independence, and Cook's distance) were analysed for a confidence level of 95%.

$$\text{GPP} = m \times \text{Mean CO}_2\text{flux} + b \quad (8)$$

These linear-regression equations allowed for creating 8 days of accumulated GPP maps with 30 m resolution for the pre- and postfire scenarios in 2003, 2017, and 2019.

3. Results and Discussion

Figure 2 shows the spatial distribution of the NDVI classes before and after the wildfires. Figure 3 summarizes these results by presenting the relative weight of each class of NDVI before and after the great wildfires of 1991, 2003, 2017, and 2019.

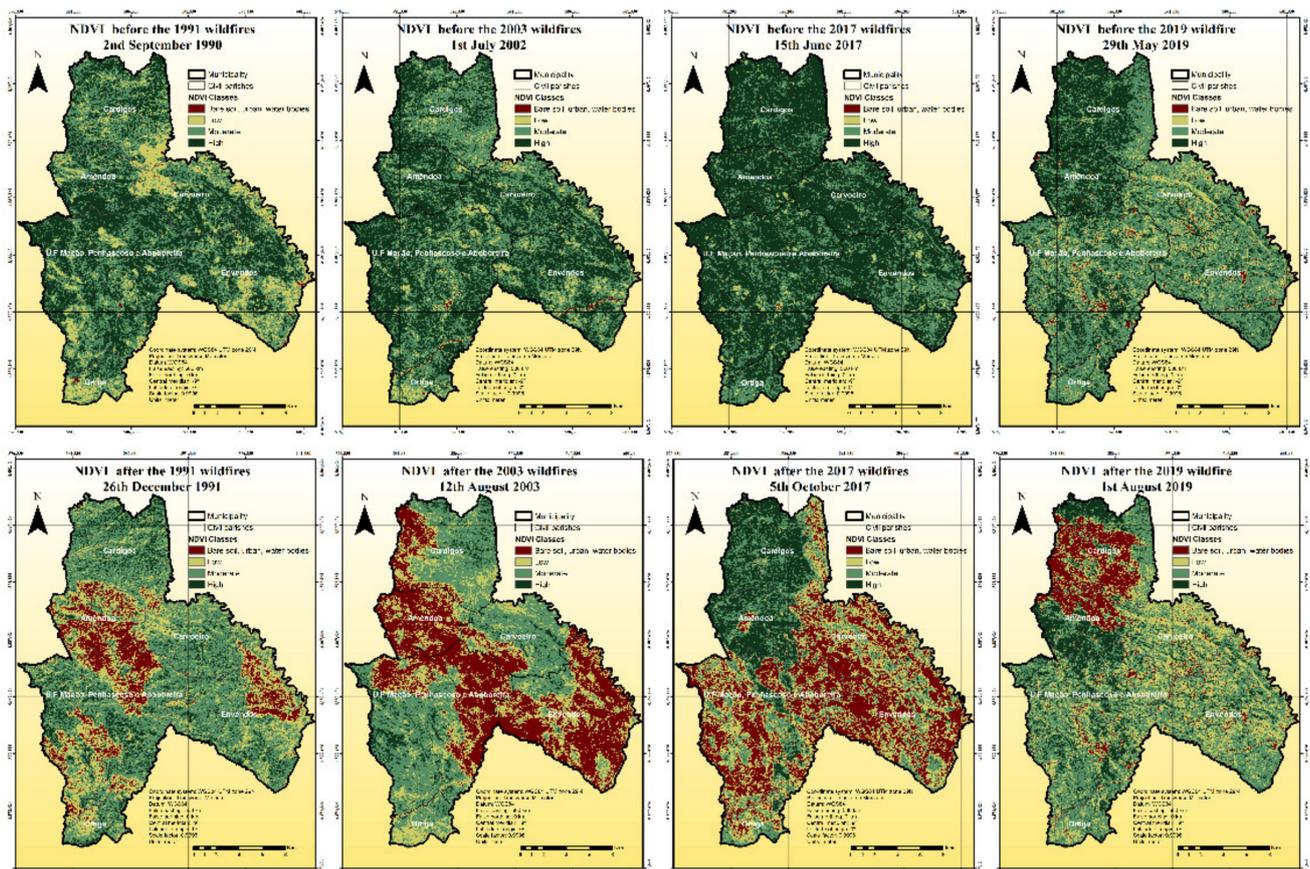


Figure 2. Spatial distribution of NDVI classes before and after the 1991, 2003, 2017, and 2019 wildfires.

Before the 1991 fires, the most represented NDVI classes in the study area were high and moderate. These areas correspond to agriculture and forestry (*Pinus pinaster* Ait.). According to Silva et al. [46], they were the main land occupation in 1990, with 49% and 19% of the Mação municipality area, respectively. After the 1991 wildfires, the high class suffered an important decrease, and the remaining classes consequently increased, particularly the low and bare soil/water/urban (which was null before the fires) classes.

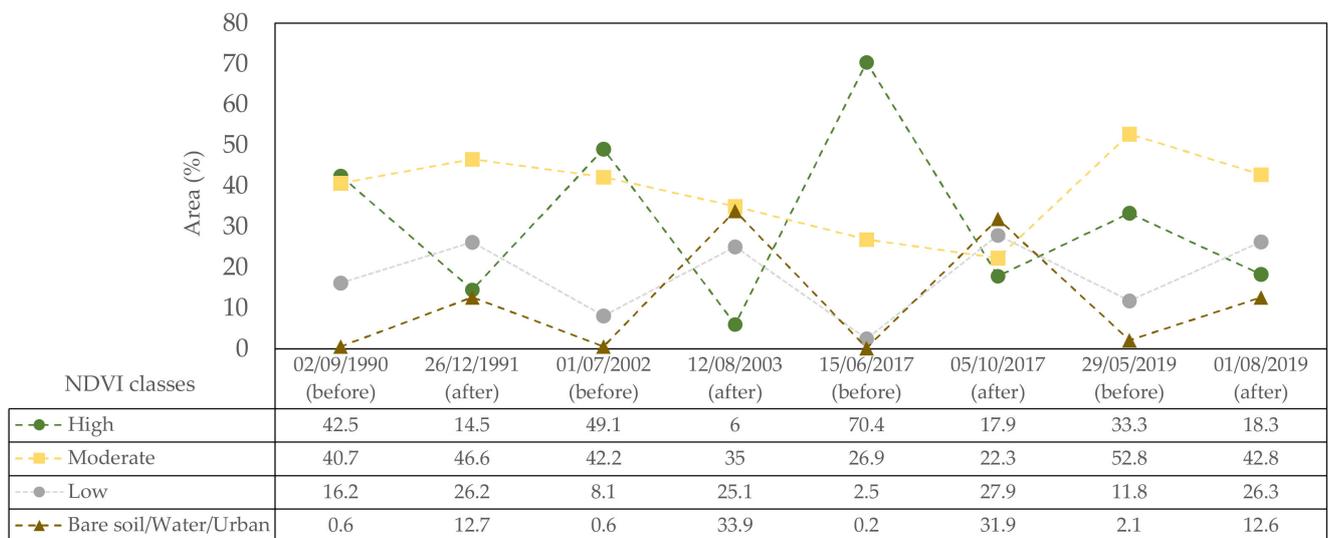


Figure 3. Evolution of occupation of the NDVI classes before and after the wildfires of 1991, 2003, 2017, and 2019.

A decade later, in 2002, the biomass had recovered. The high class increased to 49.1%, values nearly above the pre-1991 fires, while the remaining classes also recovered to pre-1991 values (with a decrease of approximately 15% in the low class). After the 2003 fires, a slight decrease in the moderate class (35.0%) and a sharp decrease in the high class (6.0%) were observed. The low class (25.1%) increased to an equivalent level to that of the post-1991 fires. The bare soil/water/urban class (33.9%) underwent a sharp increase, becoming almost equal to the moderate class in terms of area.

After 14 years, in 2017, biomass had markedly increased with about 70% of the Mação municipality area within the high NDVI class. The remaining classes had decreased, particularly the bare soil/water/urban (0.2%) and low (2.5%) classes. After 2017, the moderate class (22.3%) continued to decline, and the high class suffered a sharp reduction, with a reduction of more than 50% of the total area of the municipality. The low (27.9%) and bare soil/water/urban (31.9%) classes increased to values very close to those of the post-2003 fires. In October 2017, the entire area of Mação presented an even distribution of NDVI classes. Two years after the wildfires of 2017, the high (33.3%) and moderate (52.8%) classes partially recovered, with a very strong increase in the latter. The low (11.8%) and bare soil/water/urban (2.1%) classes decreased to prewildfire values. In fact, before the fires, the latter class was always near null. After the 2019 wildfire, the moderate (42.8%) and high (18.3%) classes were decreased, but the moderate class continues to be the prevalent. The low (26.3%) and bare soil/water/urban (12.6%) classes consequently were increased.

Figure 4 maps the severity of the wildfires using the dNBR index. In the 1991 fires, of the 131.03 km² of burnt area, 33.8% is classified as of low severity, and 16.7% as of moderate–low severity. The moderate–high severity class was the most representative, with 45.8% of the burnt area, while only 3.6% was classified as of high severity. In 2003, when 193.50 km² burnt, the low class was augmented to 5.3% of the Mação municipality area. The moderate–low class maintained similar values as those before, with 16.3%.

The moderate–high and high severity classes increased considerably to 68.6% and 9.8%, respectively. In 2017, a year with a burnt area of 265.96 km², the high class showed the highest peak, with approximately 21.9%. The moderate–high and low classes dropped to 54.9% and 7.2%, respectively. The moderate–low class stayed almost unchanged with 16.0%. In 2019, with 56.31 km² of burnt area, the high class was of approximately 20.2%. The moderate–high class decreased to 33.5%, and the moderate–low and low classes increased to 22.3% and 23.4% of the Mação municipality area, respectively.

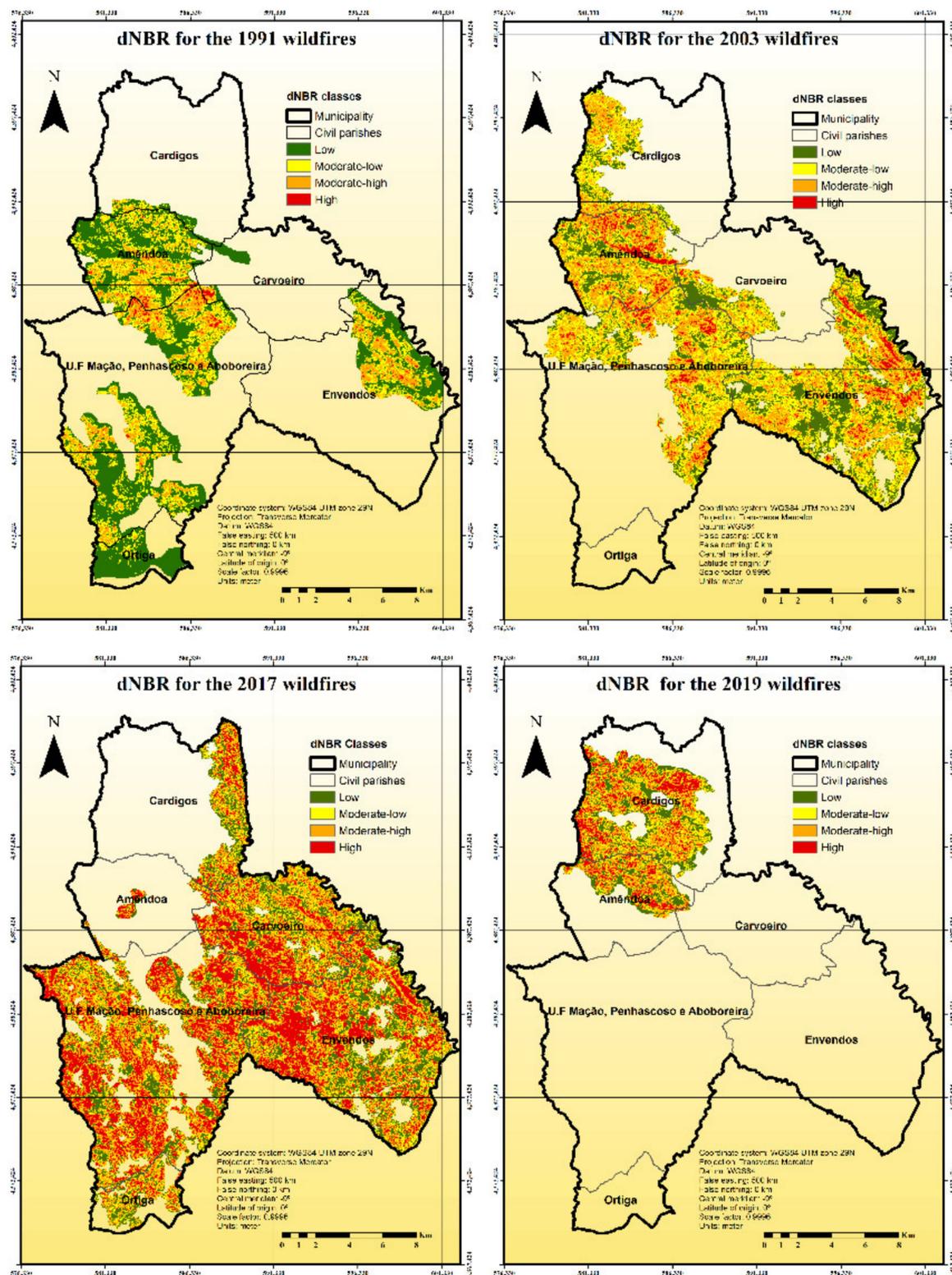


Figure 4. Spatial distribution of dNBR classes before and after the 1991, 2003, 2017, and 2019 wildfires.

Between 1991 and 2017, the municipality of Mação was plagued by wildfires that increased in terms of burnt area and severity, as is shown in Figure 4. This phenomenon occurs with an approximate periodicity of 10 years, which corresponds to the time of

vegetation recovery and biomass accumulation. The latter is caused by the lack of forestry and agricultural activities, derived from internal migrations from the inland rural areas to the cities near the coast of Portugal, as reported by Fernandes et al. [16]. These authors also stated that wildfires promote the homogeneity and continuity of vegetation coverage that could facilitate the occurrence of major fires.

Many of the areas once occupied by agriculture and conifers were replaced by scrub and mixed forests [46]. This helps to explain the strong recovery of biomass before the fires of 2002, 2017, and 2019, evidenced by the high NDVI values. According to Ferreira-Leite et al. [17], socioeconomic changes of the second half of last century were reflected in the abandonment of inland territories. Agricultural lands became landscapes prone to the occurrence of high-intensity fires due to the accumulation of biomass levels over the years. On the other hand, forestry was reshaped, and *Pinus pinaster* Ait., with slow growth but with a high capacity for the colonization of burnt areas [47], was largely replaced by other combustible species. The most common of these is *Eucalyptus globulus* Labill., of easy planting and rapid growth, which give it great economic importance [26,48]. The progressive increase in bare soil/water/urban areas (Figure 3) after the fires is explained by the fact that some of these areas are still in the bush stage. The regeneration of the forest is compromised by the inexistence of a seed bank, as plants may not reach reproductive maturity due to the short intervals between fires, especially in the case of coniferous forests (Silva et al. [46,47]).

In Portugal, the problem of biomass accumulation, particularly shrubs, has been addressed by different means. Portuguese laws and regulations [49–52] are now more demanding regarding, e.g., the obligation of municipalities and landlords to remove accumulated biomass, with penalties when failing to comply. A large part of Portugal, including the centre of the country, is characterised by small land parcels of different landlords. This makes the proper management of the territory difficult. To overcome this issue, forest intervention areas (ZIF) were created by Decree-Law 127/2005 [53] with the aim of promoting sustainable forest management, mitigating hindrances to forest intervention, and developing structural measures against wildfires [54]. In the specific case of Mação, five ZIFs were constituted [55], towards promoting ecosystem services (e.g., hunting, tourism, and biomass valorisation), proper reforestation (by replacing softwood with hardwood species, and increasing cork oak areas), fostering pastoral areas to reduce herbaceous and shrubs, promoting traditional agriculture, and improving and maintaining forest defence infrastructures (e.g., firebreaks, water reservoirs).

Figure 5 shows the relation between GPP and CO₂ flux before and after the 2003, 2017, and 2019 fires. The interval between wildfire events and satellite images was 10 (2003) and 12 (2017 and 2019) days, that is, within 1 month after the event. After the fires, the adjustment of the model was high, with R² ranging from 0.79 to 0.88. Before the fires, the adjustment was not so high, with R² between 0.49 and 0.69. This may be explained by the higher spatial autocorrelation of GPP after the fires, i.e., the lower and higher GPP values were grouped in larger and well-defined spatial clusters. For all periods under analysis, before and after the fires, regressions were statistically significant with a *p* value lower than 2.2×10^{-16} , for a 95% confidence interval.

Analysis of the residuals (see Figure S1) for the linear regressions was according to the following assumptions: homogeneity of variance, normality, independence, and Cook's distance. The four assumptions for residue validation were fulfilled. Homogeneity of variance and independence presented a random distribution. The Q–Q plot showed close to normal distribution residuals. Cook's distance was always <0.5; thus, no sample influenced the residuals.

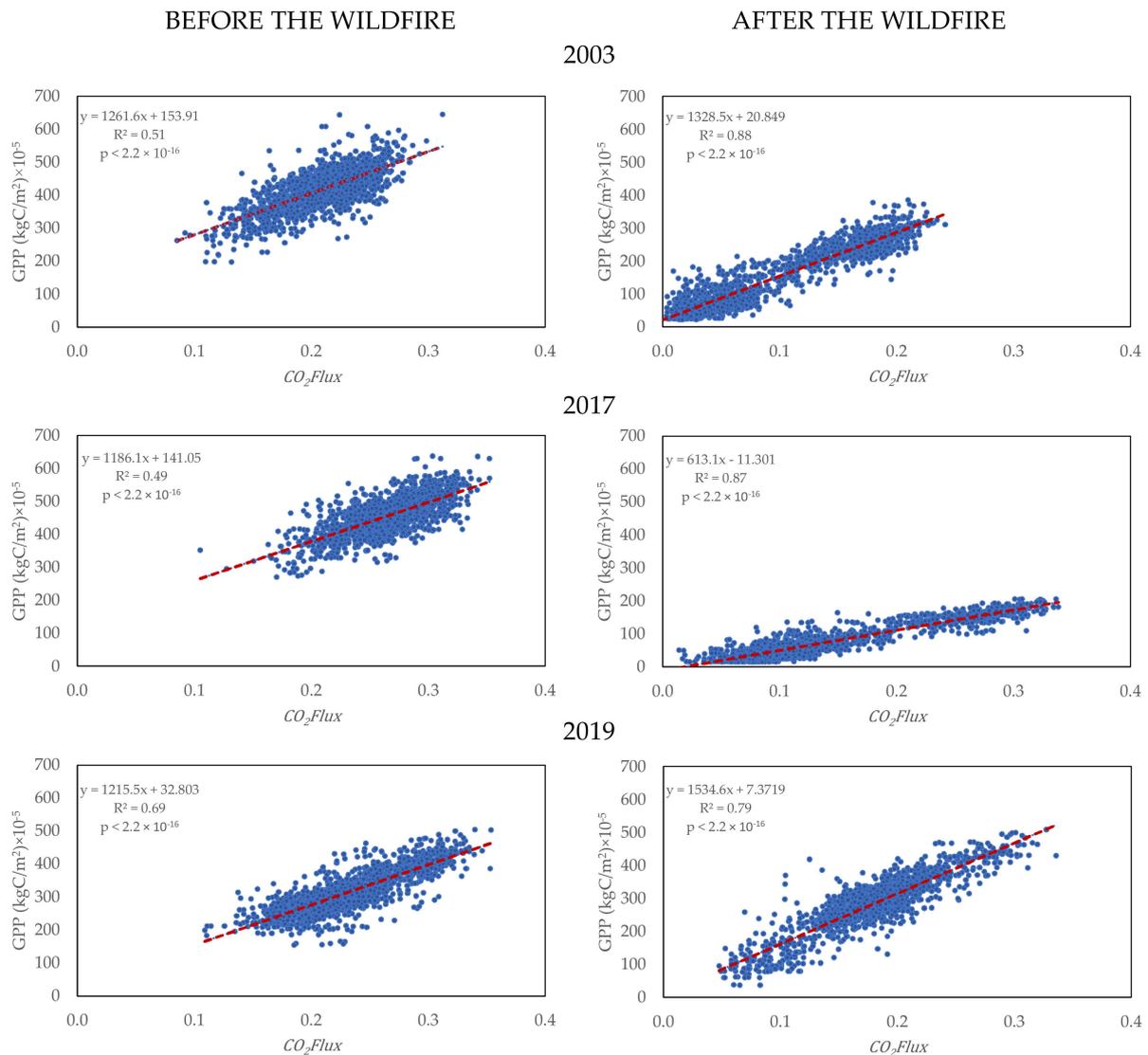


Figure 5. Linear regression between CO₂ flux and GPP in KgC/m² × 10⁻⁴ before and after the wildfires of 2003, 2017 and 2019.

Figure 6 shows the spatial distribution of GPP in the study area before and after the fires of 2003, 2017 and 2019. Before the fires, the study area mostly comprised a continuous patch, nonfragmented shrubs, *Eucalyptus globulus* Labill., and *Pinus pinaster* Ait. [28]. This area presented very high GPP values, with averages of 5.4 and 5.3 gC/m²/day in 1 July 2002 and 15 June 2017, respectively, thus showing good efficiency in the carbon-capture process. Before the 2019 fire (29 May 2019), the average GPP was 4.7 gC/m²/day, showing capacity for the rapid regeneration (in less than 2 years) of shrub and *Eucalyptus globulus* Labill. After the 2003 and 2017 wildfires, the affected areas presented an average GPP of 1.2 gC/m²/day, showing that nonindigenous forests were not very resilient to fires. Santana et al. [56] stated that forests that had burnt down are now more vulnerable to the loss of the organic carbon. This carbon, which is stored at the top 5 cm layer, can be easily mobilized by water erosion after the first rains.

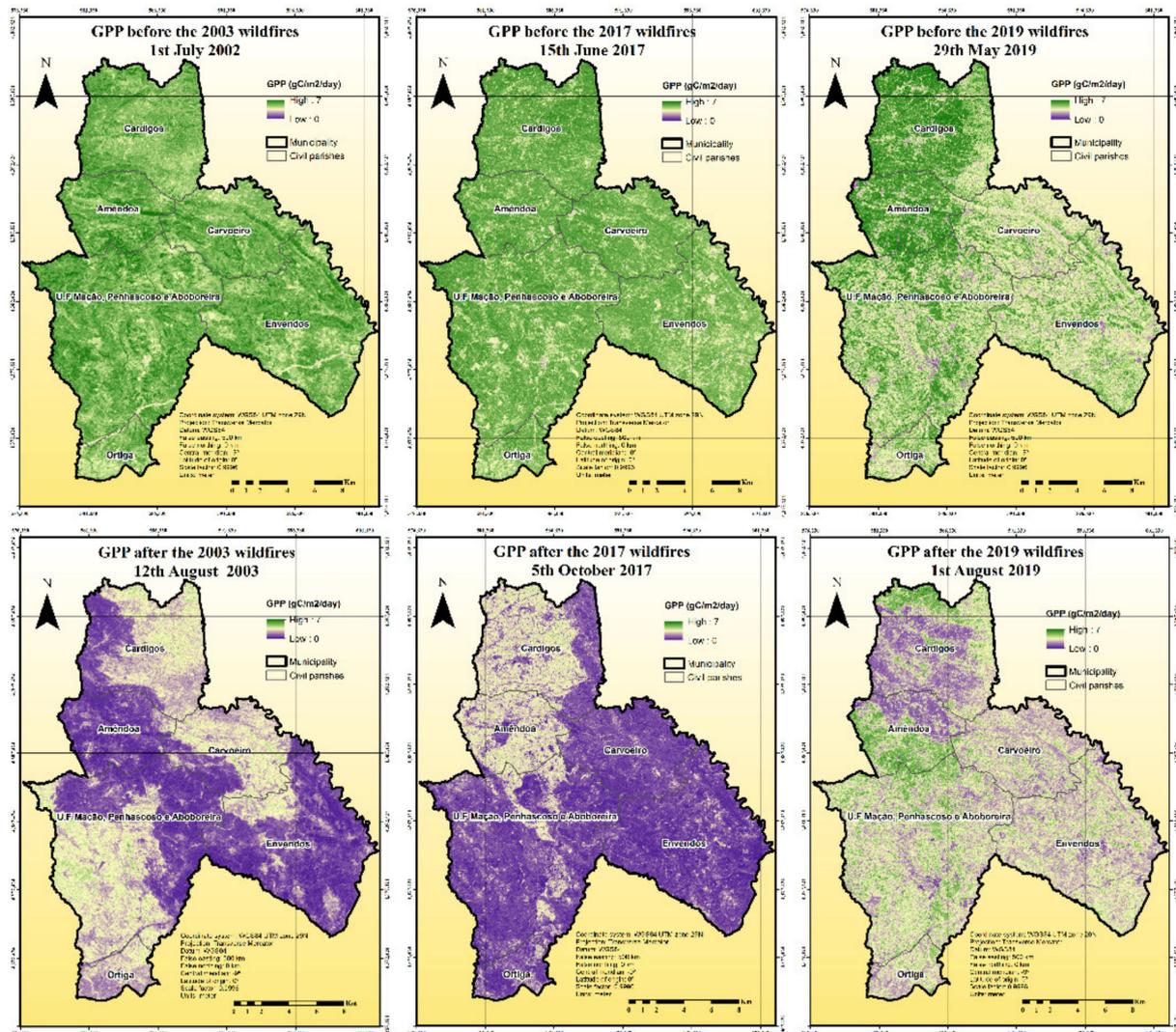


Figure 6. Spatial distribution of GPP before and after the wildfires of 2003, 2017, and 2019.

After the 2019 fire, the burnt area had an average GPP of $2.1 \text{ gC/m}^2/\text{day}$. This increase in GPP when compared to previous years can be explained by the fact that this area was unaffected by fires for a period of 30 years. So, this older forested area was more resilient to fire. GPP values before the fires were in accordance with the average value between April and December 2018 of 1.25 kgC/m^2 ($4.6 \text{ gC/m}^2/\text{day}$) estimated by the Satellite Application Facility on Land Surface Analysis (LSA SAF) of the European Organization for The Exploitation of Meteorological Satellites (EUMETSAT) [57]. Regarding the total area under study, GPP was reduced to 1.4, 1.5, and 0.6 GgC/day , respectively, for the wildfires of 2003, 2017, and 2019.

4. Conclusions

This study quantified the GPP rates in the forests of the Mação municipality and related them with the severity of wildfires for a period of nearly three decades. The high and moderate classes of NDVI, corresponding to about 80% of the area of Mação, before the fires of 1991, 2003, 2017 and 2019 revealed the existence of a high vegetation cover prior to the fires. In 1991, the cover was essentially *Pinus pinaster* Ait. After the fires, the vegetation cover recovered mainly in the form of shrubs and *Eucalyptus globulus* Labill.;

this was a consequence of the abandonment of forestry activities and management that followed the sharp decrease in population in the municipality.

Severity analysis showed that fires tend to be more severe and extensive when biomass is denser, i.e., with more combustible vegetation and with continuous spatial distribution. The wildfires of 2017 and 2019 together practically consumed the entire municipality.

The GPP models showed that, before the wildfires, the forested area of Mação was a large carbon sink, with average values of 5.4 and 5.3 gC/m²/day on 10 July 2002 and 14 June 2017, respectively. On 29 May 2019, GPP was slightly lower, reaching 4.7 gC/m²/day. After the fires of 2003 and 2017, GPP values in the burnt area reached an average value of 1.2 gC/m²/day, showing evidence of a nonautochthonous forested area with low resilience to fire. The 2019 fires burnt an area that had previously been unaffected by fire during the three decades under analysis. On 1 August 2019, this area had an average GPP of 2.1 gC/m²/day, again showing that an older forest has greater resilience to fire.

In the future, in the medium- and long-term, the regeneration capacity of the vegetation may be compromised in the case that fires become increasingly recurrent and intense, as there would be no time to restore the *Pinus pinaster* Ait. seed bank. Carbon sequestration in vegetation can also considerably decrease if the *Pinus pinaster* Ait. forest is extinguished and replaced by shrub or *Eucalyptus globulus* Labill.

The municipality of Mação faces the important challenge of attaining proper forest management and land-use planning to prevent and mitigate the consequences of wildfires. It is necessary to reduce biomass and disconnect forested areas rich in combustible plants, namely, shrubs, *Eucalyptus globulus* Labill., and *Pinus pinaster* Ait. Opting for pastoral practices and the planting of native trees, such as *Castanea sativa* Mill., *Quercus faginea* Lam., and *Quercus suber* L. can be an important aid to increase resilience to wildfires in this area of Portugal.

Regarding the economic value generated by forests, it is important to boost forestry associations. This would help to gather currently fragmented small properties in units of an adequate size to be properly managed. The introduction of recreational activities may also contribute to reaching the economic sustainability of forests that can be compatible with the conservation of biodiversity and the defence of forests against wildfires.

Future research in this theme will include analysis of the increase in GPP once the vegetation begins to recover. This will allow for gaining better insight on the relation between vegetation growth and GPP.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su13115816/s1>, Figure S1: Analysis of residuals according to (a) homogeneity of variance, (b) normality, (c) independence, and (d) Cook's distance, for the linear models before and after the wildfires of 2003, 2017 and 2019.

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