Chapter 6

Post-Fire Vegetation Recovery in Iberia Based on Remote-Sensing Information

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72594

Abstract

A previously developed procedure that aims at monitoring the process of vegetation recovery in areas affected by major fire episodes is revisited and assessed in terms of consistency and robustness. The procedure is based on 10-day fields of Maximum Value Composites of the Normalised Difference Vegetation Index (MVC-NDVI). The identification of fire scars is first achieved based on cluster analysis of persistent NDVI anomalies during the year following the fire event. Post-fire vegetation behaviour is then characterised based on maps of recovery rates as estimated by fitting a mono-parametric model of vegetation recovery to NDVI data over each burned scar. Results obtained indicate that reliable estimates of vegetation recovery times may be achieved using time series of NDVI of moderate length. It is also shown that consistent results are obtained when time series are derived either from 1-km spatial resolution data retrieved by the VEGETATION sensor on-board SPOT or from 250-m spatial resolution data from the MODIS instrument on-board Aqua and Terra. The regeneration model is also applied to estimate recovery rates in the case of recurrent fires. Overall results point out that the proposed methodology may play an important role in studying vegetation recovery and species succession after recurrent fires, namely when one vegetation type is replaced by another that regenerates faster, despite being more flammable and therefore increasing the risk of severe and large fires. The robustness of the proposed model highlights its adequacy to assess post-fire vegetation dynamics and therefore the procedure reveals as a promising tool for planning and implementing of better fire management practices before and after fire events.

Keywords: vegetation recovery, large fires, mono-parametric model, MODIS, NDVI

1. Introduction

Wildfires are a major disturbance striking most terrestrial ecosystems [1, 2], with important impacts on land degradation and desertification, vegetation composition, biomass loss [3, 4]

and changing the hydro-ecological regimes [5, 6]. Forest fires induce soil impoverishment due to the loss of nutrients during and after the fire, by runoff. The erosion processes may be accelerated due to the loss of soil cover; a minimum of 30% in soil cover is required to protect the soil against erosion [7], and the time needed to reach this protection level influences the erosion risk.

In Mediterranean regions, fire is frequent and plays an important role in controlling the evolution of ecosystems [4]. Despite being mostly of anthropogenic origin, the influence of the expected rise of temperature and evapotranspiration in the near future will contribute to increasing the frequency and severity of wildfires in the region [8, 9]. Other factors related with land-use management, namely rural abandonment and replacement of crops by grassland, also contribute to increasing fire frequency [10]. Although some plant species are able to recover and regenerate by means of either resprouting [11, 12] or germination of fire-protected seeds, stored in the soil or in the canopy [13, 14], not all plant species survive forest fires. Therefore, vegetation density and composition of Mediterranean ecosystems should be affected by recurrent fires [8, 13]. The replacement of pre-fire forest areas by shrubland or grassland after recurrent wildfires is mainly associated with the elimination of species that take long recovery times, such as *Pinus halepensis* Mill., that require almost two decades to fully recover [15]. Días-Delgado et al. [8] found that areas dominated by *Quercus* spp. were more resilient than forests in Central Portugal, dominated by *Pinus* spp. The regeneration in forests dominated by *P. pinaster* in Portugal was slower than in an area mainly populated by Eucalyptus that may quickly re-sprout from buds after fire [16]. Nevertheless, small intervals between fire occurrences may lead to plant species not reaching reproductive maturity, as happened to *P. pinaster* populations in Portugal [17]. Results from Tessler et al. [18] indicate that forest recovery after recurrent fires is more related with time within fires than with the number of previous fires.

During the process of recovery, vegetation may also be influenced by several environmental factors, such as fire severity/damage and climatological extreme events. Vegetation recovery depends on several climate factors, such as the occurrence of droughts, which may inhibit vegetation growth, but also on precipitation of high intensity, which contributes to nutrient loss and erosion by runoff [19]. In Portugal, fire damage has been identified as a main driving factor of vegetation recovery [20], but drought episodes occurring in post-fire conditions have also been shown to delay recovery times for several months [21].

Forest fires are recurrent in Portugal where the flammable material is high, and the moisture content is low, either due to climate conditions, to land-use change, or to a combination of the two. Wet and mild winters, together with dry and warm summers, favour the growth of the vegetation and its subsequent low moisture content, due to water stress [4], whereas the replacement of agricultural land by forest plantations or shrubland increases the available fuel [13, 22]. Large fires are promoted by the occurrence of high temperatures and drought episodes [23] that may lead to total burnt areas several times larger than the average, such as the burnt areas in 2003 and 2005, with amounts of 425,000 and 339,000 ha, respectively, that were until this year record breakings in the national history of fire events [24]. The fire season of 2017 in Portugal has been catastrophic by most accounts. The authorities reported more than 100 human fatalities, with about 500,000 ha of estimated burnt area which corresponds to the maximum record since 1980.

In the last decades, information from different sensors on-board several satellites has revealed to be a powerful tool to study and monitor vegetation dynamics, such as the influence of climate on vegetation [25, 26] including the effect of droughts [27, 28]. The Normalised Difference Vegetation Index (NDVI), as derived from SPOT-VEGETATION imagery, has been successfully used to identify large burnt areas in Portugal, given that burnt scars present very low values of NDVI anomalies following the fire [16].

Monitoring vegetation recovery is a very challenging and expensive task, and remote-sensing information has also been successfully used to monitor post-fire vegetation recovery [29–33]. Gouveia et al. [16] presented a procedure that allows monitoring the vegetation regeneration in the years following the 2003 fire season using 10-day fields of Maximum Value Composites of NDVI at 1-km x 1-km spatial resolution derived from the VEGETATION instrument. They selected two large burned scars located in Central and South-western Portugal and they showed that the post-fire vegetation dynamics in those areas could be characterized by fitting a mono-parametric model of vegetation recovery to NDVI over each burned scar. The patterns of recovery time over the two regions highlighted the different regeneration processes of different forest types, the region located in Southwestern Portugal presenting a faster recovery, which could be associated with a dominance of Eucalyptus. However, the dataset from VEGETATION available at the time was restricted to 1998–2006, a period not long enough to allow assessing the accuracy of the model's estimates. Later, Bastos et al. [20] provided a preliminary assessment of the model accuracy by comparing the regeneration rates obtained by the application of the model described to the same two regions analysed in Gouveia et al. [16] but using both the original 8-year dataset (1998–2006) and an updated one, extended to 11 years (1998–2009). They also successfully applied the technique to seven other burned areas of fire seasons from 2003 to 2005.

NDVI has also been used to assess the impacts of drought conditions on vegetation recovery [20, 21]. For instance, the occurrence of a severe drought event in 2004–2005 led to a decrease in recovery rates in the case of the burned scars of the 2003 fire season, delaying the regeneration process. When a severe drought event is observed in regions affected by fires in the following one or 2 years, water-stress conditions will limit photosynthetic activity and net primary production, thus reducing vegetation growth and regeneration.

The recent availability of several long-term remote-sensing datasets for monitoring vegetation conditions opens the opportunity to use them in areas where fire occurrence is high or when less in situ information about vegetation is available. Therefore, studies to assess the robustness of present techniques and their adaption to new indices and sensors are crucial. In this respect, the overall consistency of obtained results with the mono-parametric model of vegetation recovery [16, 20], together with the model simplicity in terms of formulation, anticipates that it may be quite easily adapted to other low-resolution satellite data, as well as to other types of vegetation indices. In the present chapter, an assessment will be made on the portability of the mono-parametric model originally developed using NDVI data from the VEGETATION sensor on-board SPOT [16] with 1 km of resolution by applying the model to NDVI data at 250 m of spatial resolution from the MODIS instrument on-board Aqua and Terra satellites.

2. Data and methods

2.1. Data

The NDVI time series were retrieved from the MODIS Terra V6 product, covering the period February 2000 to June 2017 over a region extending from 36.8910° to 42.3276° N and from 9.8280° to −6.1938° W. The time series used corresponds to the MODIS 16-day (MOD13Q1) product with a spatial resolution of 250 m, supplied on a sinusoidal projection. The pixel reliability index provided with the data was used to eliminate values that did not present the highest reliability level. Monthly composites were obtained using the Maximum Value Composite method [34] and the missing values were linearly interpolated.

Information about land cover was based on the Corine Land Cover (CLC) map, available on a 250-m spatial resolution for Europe and respecting to the years of 2000 and 2006 (http://land.copernicus.eu/pan-european/corine-land-cover/). The CLC classification offers an inventory of surface, with 44 classes of land cover. The thematic maps were resampled to the NDVI-MODIS projection.

2.2. Identification of burnt areas

In the present work, the fire seasons of 2003, 2005 and 2012 were analysed. The identification of burnt areas followed the procedure proposed by Gouveia et al. [16] and Bastos et al. [20]. Burned areas are identified by means of unsupervised clustering of the NDVI monthly anomalies, based on the K-means method [35, 36]. Due to the short number of years of the time series, and in order to mitigate the lever effects of extreme values, monthly anomalies were computed as departures from monthly medians instead of monthly means. Considering that the fire occurrences provoke a very sharp reduction in the NDVI values that persists on the following months [16], the clustering analysis was performed on the following hydrological year, which starts in September [27].

Burnt areas appear associated to the cluster whose centroid presents persistent negative anomalies during the entire vegetation cycle. The number of clusters required to adequately separate between burnt and non-burnt areas is not fixed and depends on several factors, such as the occurrence of a drought episode, which can also reduce NDVI [20]. In this work, four clusters were required in 2012, and three clusters in the remaining years analysed. Burnt areas may present low anomalies of NDVI that persist for more than 1 year after the fire [20], and for this reason burnt pixels from the two previous years were previously identified and removed from the analysis. Results obtained from the cluster analysis were visually compared with the maps of yearly burnt area made available from the National Institute of Nature and Forest Conservation (ICNF), and a very good agreement was found in the case of large burnt scars. **Figure 1** shows the burnt area and the centroids obtained by cluster analysis for the fire season of 2012.

2.3. Model of vegetation recovery

The model of vegetation recovery used in the present work is the mono-parametric model proposed by Gouveia et al. [16] and based on NDVI. The model is given by

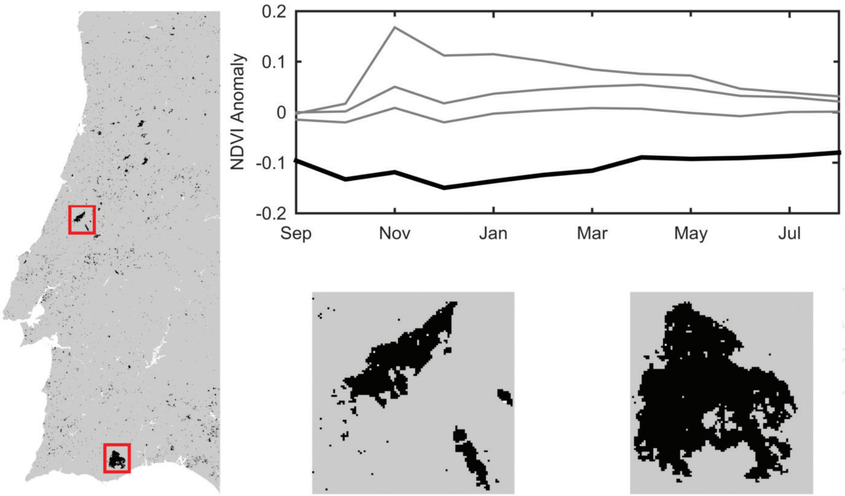

Figure 1. Left panel: Burned areas in continental Portugal during the fire season of 2012 (black pixels in the left panel) as identified by means of cluster analysis and annual cycles of monthly MVC-NDVI anomalies; top-right panel: centroids of the four identified clusters; centroid associated with burned areas is presented in black; bottom-right panel: burned areas selected to apply the recovery model.

$$y(t) = ae^{-bt} \tag{1}$$

where y is the so-called lack of greenness, defined as the departure of NDVI from the so-called Gorgeous Year (GY) that is defined as a hypothetic annual vegetative cycle associated to an ideally healthy state of vegetation. Parameter b in Eq. (1) characterises the recovery time and parameter a characterises the lack of greenness at the time of the occurrence of the fire event, being therefore viewed as an indicator of fire damage. The use of departures of NDVI from GY aims at minimising the impact of the inter-annual variability of NDVI. The monthly values of GY are computed by selecting the maximum value of NDVI in the pre-fire period for each month. Noting that

$$\frac{y(t)}{a} = \frac{NDVI(t) - GY(t)}{NDVI(t = 0) - GY(t = 0)} \tag{2}$$

the value of b is estimated by means of regression analysis performed on the following linear model:

$$ln\left[\frac{y(t)}{a}\right] = -bt \tag{3}$$

The mono-parametric model allows estimating the vegetation recovery time (tR), defined as the period elapsed from $t = 0$ (when the fire took place) up to the time when the modelled curve of y crosses the threshold defined as 90% of the median value in time of the spatially averaged lack of greenness over the pre-fire period.

In this work, the methodology described earlier was adapted to the MODIS Terra V6 product with a spatial resolution of 250 m from 2000 to 2016. The methodology will be applied to NDVI monthly composites for several large burnt areas detected in 2003, 2005 and 2012. Results obtained for 2003 and 2005 will then be compared with the findings

by Gouveia et al. [16] and Bastos et al. [20] allowing to assess whether the methodology may also be successfully applied to sensors with a resolution different from the one of SPOT-VEGETATION.

The fire seasons of 2003 and 2005 in Portugal were outstanding, with annual amounts of burnt area substantially larger than the 1980–2002 mean. The exceptional fire season of 2005 further coincided with the 2004/2005 drought, one of the most severe episodes since the early twentieth century [21, 27]. During the hydrological year of 2011/2012, Iberia was hit by another severe drought event. The events of 2004/2005 and 2011/2012 correspond to two of the worst drought episodes, in both magnitude and spatial extent, ever recorded in this semi-arid region [37, 38]. During the hydrological years of 2004/2005 and 2011/2012, drought episodes caused negative anomalies of NDVI over large sectors of Iberia for up to 7 months (out of 11) of the vegetative cycle. While in the case of the drought episode of 2005, the impact on vegetation covered roughly two-thirds of the Iberian Peninsula [21]; in the recent episode of 2012 the *deficit* in greenness affected a more restrictive area located in central Iberia. The effect of drought on post-fire vegetation is reflected by a delay in the regeneration rates, whereas the influence on pre-fire vegetation may be related with the dryness of fuel and on fire damage and severity [21]. The important role of drought on pre- and post-fire behaviour of vegetation strongly suggests also applying the methodology to monitor burnt scars and vegetation regeneration rates to the larger burned areas of 2012 fire season.

3. Results

3.1. Modelling vegetation recovery using NDVI-MODIS and comparison with NDVI-SPOT for 2003 and 2005 fire seasons

The original mono-parametric model to estimate vegetation regeneration times after large fire events relied on 10-day values of Maximum Value Composites of Normalised Difference Vegetation Index at 1-km spatial resolution as obtained from the VEGETATION sensor. In the present work, NDVI monthly values were computed by means of the maximum composite performed using MODIS 16-day (MOD13Q1) with a spatial resolution of 250 m.

After burned scars were identified by means of a cluster analysis on NDVI monthly anomalies (see Section 2.2), the regions to be studied in this chapter were chosen among the ones already selected by the authors in previous works [16, 20] for the 2003 and 2005 fire seasons over Portugal. The burnt scars chosen were the so-called regions I and II by Gouveia et al. [16] from the 2003 fire season (hereafter named R1 and R2, respectively) and the so-called regions RVII and RVIII [20] from the 2005 fire season (hereafter named R4 and R3, respectively). **Figure 2** shows both the location of the four chosen burned areas (left panel) and the corresponding land-cover types, as obtained from CLC2000 (right panel). The fractions of the main land-cover types in the selected burned areas are presented in **Table 1**.

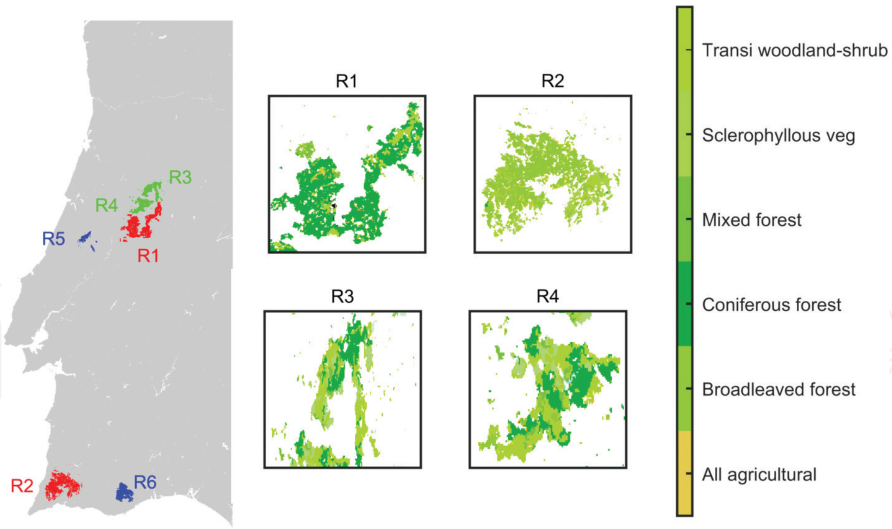

Figure 2. Burnt areas in Continental Portugal in 2003 (R1 and R2) 2005 (R3 and R4) and 2012 (R5 and R6) as obtained by cluster analysis of NDVI anomalies over the year following each fire season (left panel). Selected areas for the present work and respective nomenclature are identified by the rectangular frames labelled from R1 to R6. Corine Land-cover 2000 map for burned areas of 2003 and 2005 at 250 m spatial resolution (right panel).

The comparison of the obtained burnt areas using cluster analysis over NDVI anomalies as obtained using the MODIS dataset with previous results based on NDVI anomalies retrieved from SPOT [16, 20, 21] reveals very similar shapes on both cases, despite the different period of the available NDVI datasets, highlighting the robustness of the methodology used. The slight differences observed may be related with the different spatial resolution and projection of NDVI-MODIS.

It may be noted that, due to the different projection used in MODIS dataset, regions R3 and R4 include some pixels from other regions (i.e. pixels from R3 (R4) in R4 (R3)). **Figure 2** (right panel) and **Table 1** show, as expected, that R1 is mainly occupied by coniferous forest (76%, *P. pinaster*) and R2 by broadleaved forest (59%, Eucalyptus) (**Table 1**). In the cases of R3 and R4, they are mainly occupied by transitional woodland-shrub (around 40% in both cases) and coniferous forest (around 30%) (**Table 1**).

The mono-parametric model was then adjusted to the NDVI-MODIS time series spatially averaged over the four considered regions (**Figure 3**). The vegetative cycle that characterises the

	All agricultural	Broadleaved forest	Coniferous forest	Mixed forest	Sclerophyllous vegetation	Transitional woodland-shrub
R1	4.82	1.42	76.41	3.13	0.00	13.24
R2	3.06	59.18	0.25	0.28	19.96	17.13
R3	3.29	0.48	30.83	3.61	0.00	43.10
R4	1.98	3.41	33.12	5.93	0.00	44.44

Table 1. Main land-cover types, as obtained using Corine Land Cover 2000 classification, that are present in the burned scars selected: R1 and R3 from 2003 and R4 and R5 from 2005.

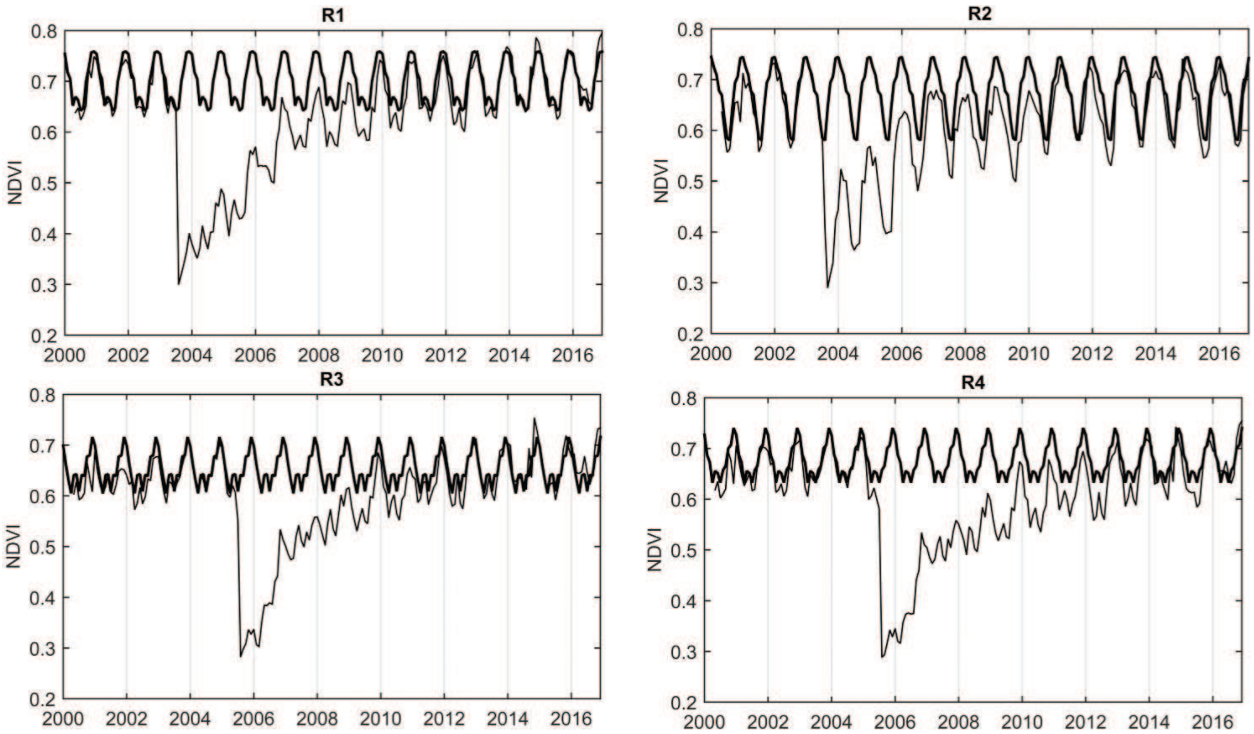

Figure 3. Time series of NDVI (grey curves) spatially averaged over the four considered burned scars: R1 and R2 for 2003 (top panel) and R3 and R4 for 2005 (bottom panel) fire season. Black curves represent the Gorgeous Years (GY) of vegetation, given by the annual cycles of maximum NDVI for each month over the considered period.

dominant vegetation type within the burned area is also shown in **Figure 3**. As expected, the vegetative cycle of vegetation over the R2 region presents a higher inter-annual variability than over R1, which is consistent with the broadleaved dominance in R2. The sharp decay in NDVI time series during the fire season of 2003 (**Figure 3**, top panel) and 2005 (**Figure 3**, bottom panel) corresponds to the loss of vegetation over the considered scars that resulted from the fires.

As described in the previous section, the time required for vegetation recovery (tR) is counted up to the month when the modelled curve of y intercepts the line defined as 80% of the median values of y during the pre-fire period (**Figure 4**). Obtained recovery times (averaged values over each burnt scar) are presented in **Table 2**. When compared with corresponding recovery times obtained in the previous works, estimates obtained with NDVI-MODIS data for scars R1 and R2 fall inside the 95% confidence interval of the previous estimates with NDVI-VEGETATION, whereas for scars R3 and R4 the estimated recovery times are 3 months longer than the upper bound of the 95% confidence interval. However, it should be noted that regions R3 and R4 of the present work include parts of external burn scars not included in RIII and RII of the previous study [20], respectively, and this may contribute to increasing the recovery rates obtained with NDVI-MODIS. On the other hand, the shorter ranges of the 95% confidence intervals obtained for the estimates with NDVI-MODIS are worth being emphasised. This could be associated with the larger post-fire period of available information which allows a better adjustment of the regeneration curve.

It may be noted that Gouveia et al. [16] and Bastos et al. [20] have used 90% of the median (instead of 80%) as the threshold. However, in the present work, when using the MODIS dataset

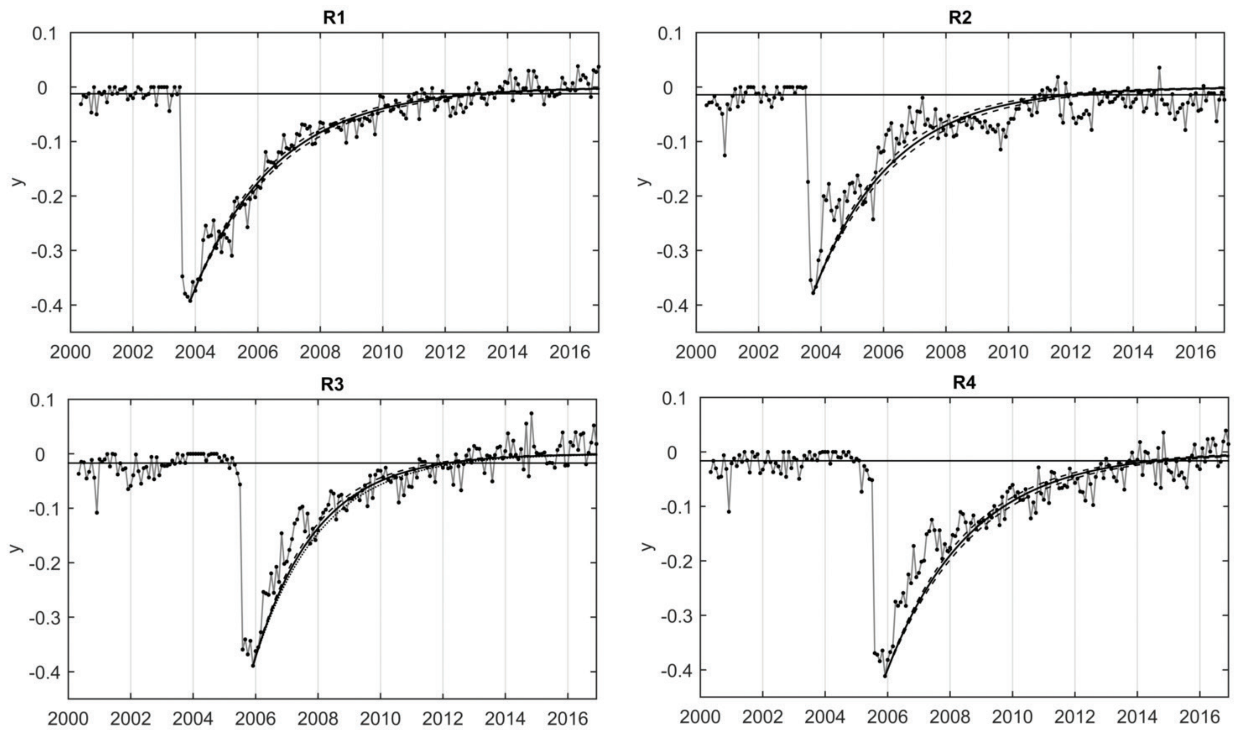

Figure 4. Time series of monthly lack of greenness, y (black line with asterisks) and modelled curve (solid line) of vegetation recovery, spatially averaged over R1 and R2 from 2003 (bottom left panel) and R3 and R4 from 2005 fire seasons (bottom right panel). Dashed lines indicate the 95% confidence limits of the regressed curve.

there is an increase in spatial resolution from 1km to 250m and therefore NDVI values present a less smooth behaviour inside the considered pixel. An additional feature is related with the differences observed for RED and NIR channels for the two sensors (i.e. RED: 0.62–0.67 and NIR: 0.841–0.876 μm for MODIS versus RED: 0.61–0.68 and NIR: 0.78–0.89 μm for SPOT).

Figure 5 presents the spatial distribution of recovery times over R1 and R2 from 2003 (bottom-left panel) and R3 and R4 from 2005 fire seasons (bottom-right panel). A visual inspection reveals a very good agreement between the spatial patterns of vegetation recovery obtained using NDVI-MODIS with the ones obtained in previous works (**Figures 6** and **7** from [1, 2]), when using NDVI-SPOT. Despite the obvious differences in spatial resolution, the spatial patterns of higher (lower)-recovery time values (tR) are located in the same regions.

Despite the different periods covered by the available NDVI datasets, the differences associated with spatial resolution and projection and the slight differences in spectral channels used

	R1	R2	R3	R4
tR (months)	49 [52]	45 [43]	35 [30]	48 [42]
I95(tR) (months)	46–51 [45–59]	42–48 [38–49]	33–37 [28–32]	45–50 [40–45]

Results from [16] in the case of R1 and R2 and from [20] in the case of R3 and R4 are also shown in brackets for comparison.

Table 2. Estimates (tR) and 95% confidence intervals (I95(tR)) of recovery time respecting to the fit by linear regression of the mono-parametric model of vegetation recover on y dataset from NDVI-MODIS for R1 and R2 for 2003 and R3 and R4 for 2005 fire seasons.

to compute NDVI, which contribute to slight differences of NDVI between the two products, the recovery rates estimated when using NDVI retrieved from MODIS dataset with NDVI obtained from SPOT [16, 20, 21] reveal very similar recovery patterns, highlighting the robustness of the methodology used and their applicability to other indices and sensors.

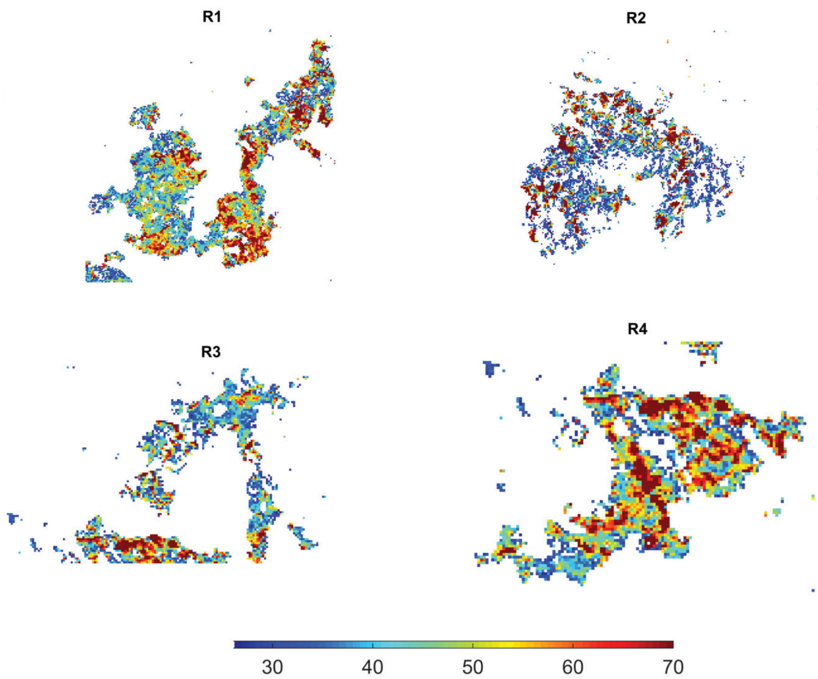

Figure 5. Spatial distribution of recovery times, in months, over R1 and R2 from 2003 (bottom-left panel) and R3 and R4 from 2005 fire seasons (bottom-right panel).

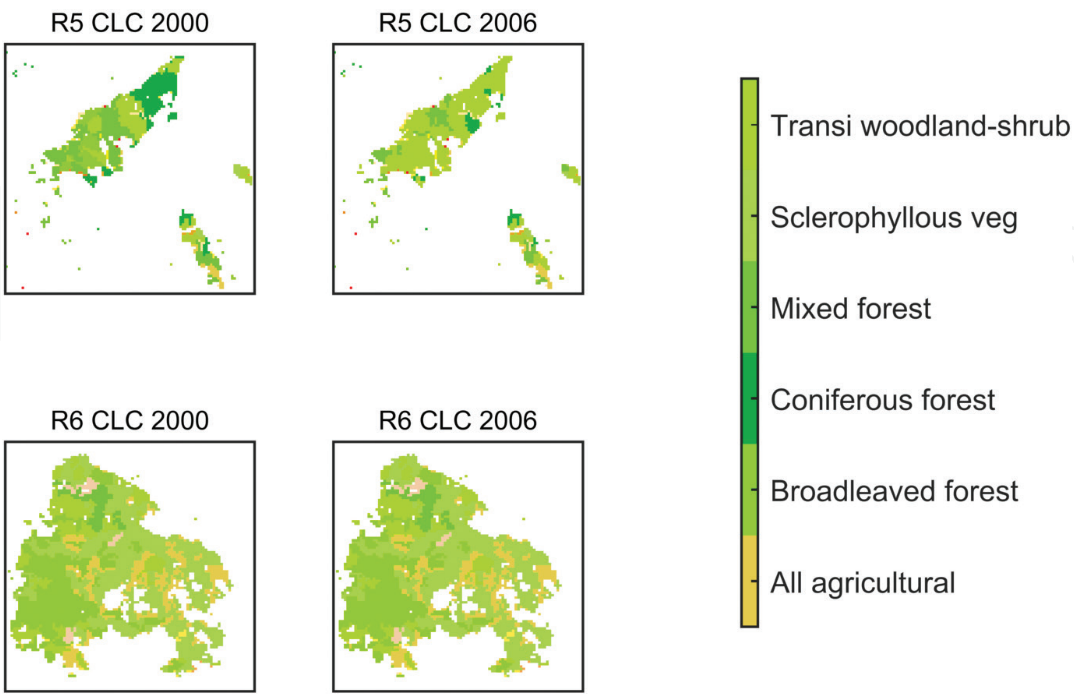

Figure 6. Corine Land Cover 2000 (left panel) and 2006 (right panel) map for burned areas R5 (top panel) and R6 (bottom panel) for 2012 fire season.

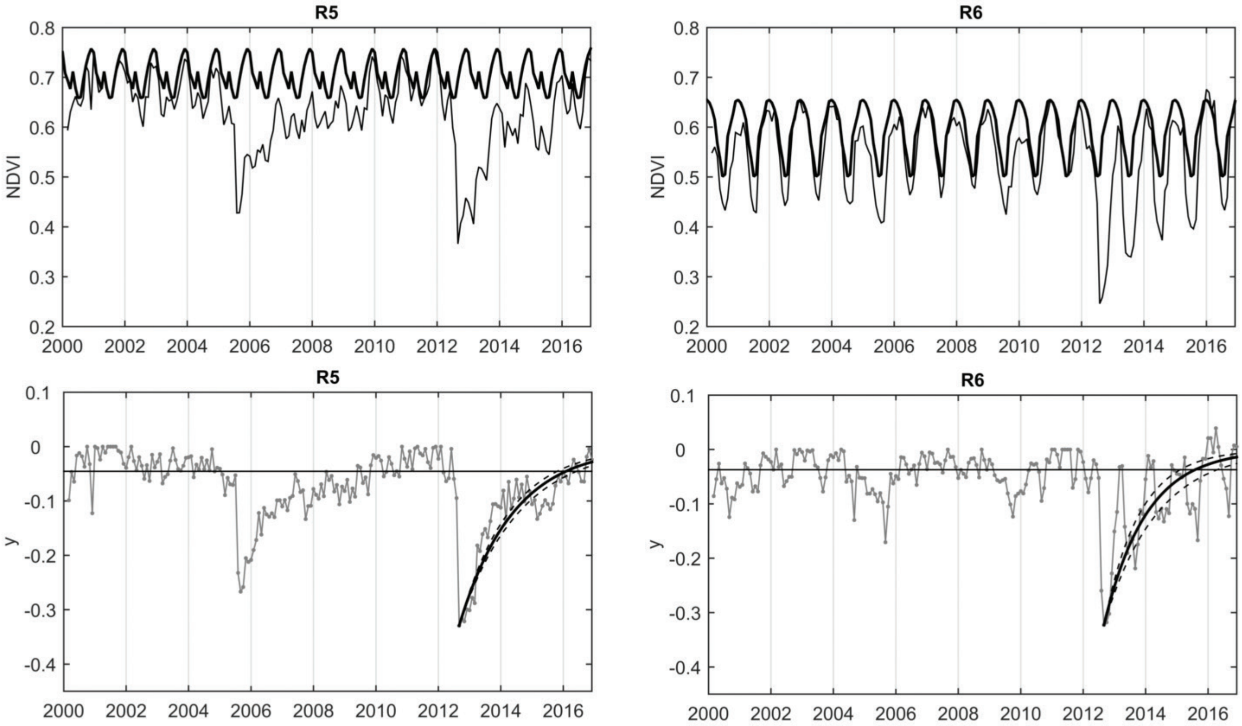

Figure 7. Time series of NDVI (grey curves) spatially averaged over the two considered burned scars: R5 and R6 for 2012 (top panel) fire season. Black curves represent the Gorgeous Years (GY) of vegetation, given by the annual cycles of maximum NDVI for each month over the considered period. Time series of monthly lack of greenness, *y* (black line with asterisks) and modelled curve (solid line) of vegetation recovery, spatially averaged over R5 and R5 for 2012 (bottom panel). Dashed lines indicate the 95% confidence limits of the regressed curve.

3.2. Vegetation recovery after 2012 fire season

The two largest burnt scars obtained by the clustering technique applied to NDVI anomalies of the 2012 hydrological year are presented in **Figure 1**. These two regions are named R5 and R6 (**Figure 2**). Choice of the scars was also motivated by the associated land-cover types, as they are mainly occupied by transitional woodland-shrub type in the case of R5 (around 70%) and by Sclerophyllous vegetation in the case of R6 (around 40%) (**Table 3**). In the region located in the South of Portugal, a considerable number of pixels corresponding to broad-leaved forest (21%), transitional woodland-shrub (21%) and agricultural practices (16%) are also found (**Table 3**). It is the first time that the mono-parametric model is used to study the recovery process in burnt scars mainly occupied by this type of Mediterranean vegetation (Sclerophyllous vegetation).

The mono-parametric model was accordingly adjusted to the NDVI-MODIS time series spatially averaged over the two considered regions (**Figure 7**, top panel). The vegetative cycle that characterises the dominant vegetation type within R6 presents a higher inter-annual variability than for R5, although showing smaller values of NDVI. This feature is in agreement with the dominant types of vegetation that show a very marked vegetative cycle (broad-leaved, grassland and agriculture), but also present less greenness and density typical of the Mediterranean vegetation. The decrease of NDVI values during 2005 in R6 is also worth noting, being consistent with the impact of the 2004/2005 drought event on the vegetation.

		All agricultural	Broadleaved forest	Coniferous forest	Mixed forest	Sclerophyllous vegetation	Transitional woodland-shrub
R5	2000	8.49	10.90	22.29	31.61	1.93	24.43
	2006	8.49	0.21	6.35	14.15	1.38	69.01
R6	2000	15.49	24.17	0.00	3.60	43.07	13.68
	2006	15.14	21.06	1.21	3.25	37.89	21.45

Table 3. Main land-cover types, as obtained using CLC2000 and CLC2006 classifications, that are present in the burned scars selected: R5 and R6 for 2012 fire season.

The sharp decay in NDVI time series during the fire season of 2012 (**Figure 7**, top panel) corresponds to the loss of vegetation over the considered scar that resulted from the fire. However, in the case of R5 a second decrease moment of NDVI is obvious. This feature is a clear indicator that the pixels (or at least some pixels) inside the burnt scar of 2012 have also burned in 2005.

Figure 7 (bottom panel) shows the time series of deviation of NDVI from the GY (y) and the respective modelled curves. The time of recovery is lower in R6 (tR = 20 months, I95[tR] = [17, 25]) than in R5 (tR = 24 months, I95[tR] = [22, 26]). Recovery rates in these two regions are lower than the ones obtained in 2003 and 2005 for regions dominated by forests. However, they are higher than the regeneration rates obtained for burnt areas of 2004 in South of Portugal, also dominated by agricultural and grassland practices [20]. The 95% confidence interval is higher in the case of R6, due to the high variability observed in the time series of y that could be associated to the different vegetative cycles of the several land-cover types that are found in the large area defined as R6. Additionally, as mentioned in Section 2, the definition of vegetation recovery obtained by the adjustment of the mono-parametric model does not assume the regeneration of the same type of vegetation. In the case of R6, the vegetation that recovers from the 2012 fire seasons seems to have different phenological characteristics than in the pre-fire vegetation, which could be associated with the potential enlargement of the transitional woodland-shrub or the replacement of crops by grassland, a typical feature observed after large fires in semi-arid regions [10].

Figure 8 shows the spatial distribution of recovery times over R5 (left panel) and R6 (right panel) of the 2012 fire season. As expected, the recovery time obtained for the majority of the pixels over both regions is about 20 months. However, small spots of recovery rates of about 40 months are observed in both regions and a very few number of values of about 60 months are also present in the R6 region. By visual inspection, pixels presenting high recovery rates were found to be associated with forest (**Figure 6**), where it is common to find such regeneration rates.

Forest fires are recurrent in Portugal due to the accumulation of flammable material and water stress, usually associated with either climate extremes or land-use change [4]. Although well adapted to fire, the vegetation density and composition should be affected by severe fire episodes [8, 13, 18]. The vegetation cycle observed in **Figure 7** over R5, where the occurrence of two fire episodes is conspicuous, one in 2005 and another in 2012, turns this region into a very interesting case study in the framework of recurrent-fires analysis. Therefore, the burnt area classification obtained through cluster analysis for 2005 and 2012 was overlapped and R5 region was analysed in detail. **Figure 9** (top panel) presents the burned areas over the R5 region for 2005 in light grey, for 2012 in dark grey and the overlapped region in black. In **Figure 9** (bottom, left panel), the

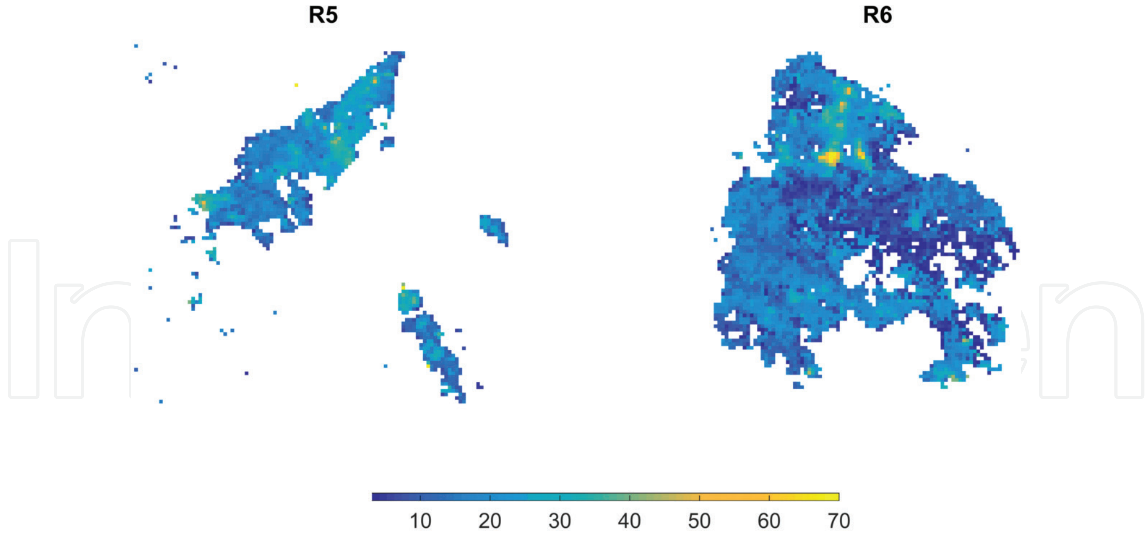

Figure 8. Recovery time in months for the regions R5 and R6.

NDVI (grey curve) represents the spatially averaged values over the area in black (i.e. the area that burned in both 2005 and 2012). The Gorgeous Year, as obtained considering the period until the fire season of 2012, and the time series of the monthly lack of greenness, spatially averaged over the area in black of R5, are also presented. The modelled curves (solid line) of vegetation recovery for the fire season of 2005 and 2012 are represented in red in **Figure 9** (bottom, right panel).

Regeneration rates were also computed for both fire seasons, being longer in the case of the fire season of 2005 (tR = 34 months, I95[tR] = [32, 35]) than in the case of 2012 (tR = 29 months,

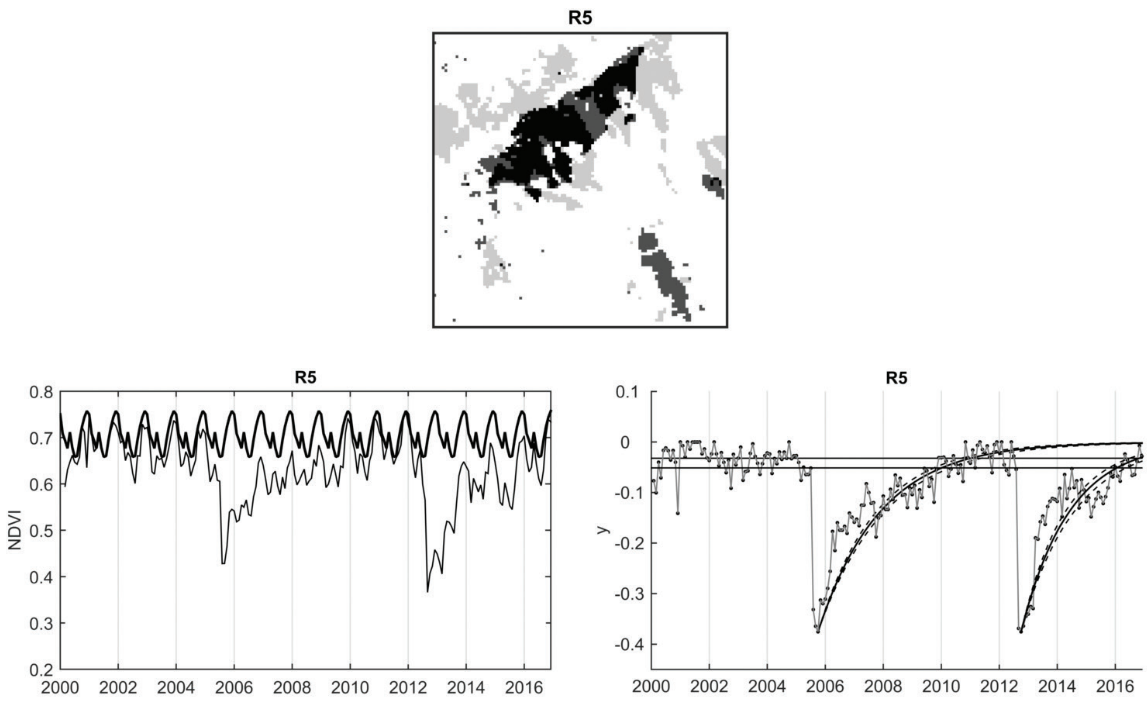

Figure 9. Top: Burned areas obtained through cluster analysis for 2005 (in light grey) and 2012 (in dark grey) over R5 region and overlapped region (in black); bottom: As in **Figure 7** but for the pixels simultaneously burned in 2005 and 2012.

I95[tR] = [27, 32]). As already mentioned, vegetation recovering from the 2005 fire season seems to have different phenological characteristics when compared to the pre-fire vegetation, which are related with the replacement of the existing forest before the fire season of 2005 which occupied around two-thirds of the burnt scar (Broadleaved—11%, Coniferous—22% and Mixed Forest—32%, **Table 3** and **Figure 6**) by transitional woodland-shrub, occupying an area that went from 24% in CLC2000 up to 69% in CLC2006 (**Table 3** and **Figure 6**). This new predominant vegetation type is prone to become dry, namely in the case of the severe drought that occurred in 2012 [4, 21], becoming flammable fuel [22] and contributing to increase the severity of fires and to larger burned areas [39].

4. Conclusions

A mono-parametric model of vegetation recovery in areas affected by large wild fires was assessed in terms of consistency and robustness. For this purpose, vegetation recovery is here modelled based on time series of NDVI from the MODIS instrument (MODIS Terra V6) and results compared against previously obtained ones using data from the VEGETATION sensor [16]. The pre-fire period covered by NDVI-MODIS is 2 years shorter than the one by NDVI-VEGETATION, but a long period of data after the fires of 2003 and 2005 is available, allowing to compare the results obtained with both datasets. In addition, the 250-m spatial resolution of NDVI-MODIS is substantially higher than the 1-km resolution of NDVI-VEGETATION, which may allow to better model the vegetation dynamics and its recovery after a fire episode.

Burnt scars were identified by means of cluster analysis performed on monthly anomalies of NDVI and four previously studied regions, two from the 2003 [16] and two from the 2005 fire seasons [20], were selected to be studied. The fit of the mono-parametric model allowed estimating the time required for vegetation recovery (tR). Despite differences in terms of used datasets, obtained recovery rates when using the NDVI-MODIS dataset presents very similar patterns to the ones obtained with the NDVI-VEGETATION dataset [16, 20, 21] highlighting the robustness of the methodology used and its applicability to other indices and sensors.

The important role of drought on pre- and post-fire behaviour of vegetation has motivated the application of the developed methodology to monitor burnt scars and vegetation regeneration rates to two large burned areas of the 2012 fire season. The regeneration rates obtained through the application of the vegetation recovery model to both burnt scars are lower (around 20 months) than the ones obtained in previous works for regions dominated by forest, but are higher than the recovery rates obtained in regions dominated by agricultural and grassland practices [16, 20]. A detailed analysis of the spatial patterns of recovery times over both regions reveals a large majority of pixels presenting recovery times around 20 months, with some hotspots of pixels presenting 40 and 60 months that are found in regions dominated by forest [20].

One of the studied areas was successively affected by two large fires, one in 2005 and the other in 2012. The regeneration model when applied to the subset of pixels that burned in both 2005 and 2012 pointed to a higher-recovery time for the pixels burned during the 2005 fire than in 2012, although both being around 30 months. The definition of vegetation recovery used in the present work (and proposed in [16]) is based on NVDI and therefore does not assume

the regeneration of the same type of vegetation. It was found that the pre-fire forest, which occupied around 65% of the burnt scar, was indeed replaced by transitional woodland-shrub, which in post-fire has increased from 24% in CLC2000 to 69% in CLC2006. The predominance of a more flammable vegetation type [22], as well as more sensitive to extreme drought events, will increase the risk of more severe and large fires [39].

The development of reliable techniques to assess post-fire vegetation recovery features in conditions of recurrent fires is crucial for a better understanding of vegetation behaviour and species succession in the Mediterranean region, namely in Portugal, which is recurrently affected by severe fire seasons. The recent SENTINEL program, developed by ESA on behalf of the joint ESA/European Commission initiative GMES (Global Monitoring for Environment and Security), will allow the development of new vegetation products at high spatial resolution (Sentinel-2) that will offer an excellent opportunity for better understanding, monitoring and consequently developing new strategies when dealing with pre- and post-fire events.

The application of the proposed procedure based on a simple mono-parametric model of vegetation recovery in regions prone to extreme climate events such as droughts and where land-use practices have changed significantly will allow the development and implementation of better strategies for fire prevention, management and mitigation before and after recurrent fires, namely fuel hazard assessment, prescribed burning, choice of plant species for reforestation, among others [31, 40].

Acknowledgements

This research is supported by FAPESP/FCT Project Brazilian Fire-Land-Atmosphere System (BrFLAS) (2015/01389-4 and FAPESP/1389/2014).

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