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RESEARCH

A remote sensing assessment of oak forest recovery after postfire restoration

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Abstract
Mediterranean Europe is experiencing a rise in severe wildfires, resulting in growing socioeconomic and ecological impacts. Postfire restoration has become a crucial approach to mitigate these impacts and promote ecosystem recovery. However, the ecological effects of such interventions are still not well understood. We employed remote sensing techniques to evaluate the impact of postfire emergency stabilization on the recovery of deciduous oak forests in Portugal. Our study encompassed 3013 sampling points located in areas with and without postfire interventions. We chose the Normalized Difference Vegetation Index (NDVI) as an indicator of oak forest recovery over a four-year period following wildfires that took place in 2016 and 2017. We used a Generalized Additive Mixed Model (GAMM) to assess how NDVI changed over time as a function of postfire restoration, fire characteristics, topography, and postfire drought events. We found that postfire restoration had a significant positive effect on NDVI recovery over time, although this effect was small. Severe drought and fire recurrence up to six fires had a negative effect on the recovery of NDVI. Conversely, severe wetness and either low or high burn severities had a positive effect on recovery. Our study emphasizes the importance of monitoring postfire restoration effects on forest recovery to guide restoration planning and improve forest management in burned areas. This becomes even more relevant under increased wildfire severity predicted for the Mediterranean region interacting with other climate-driven disturbances, which will further negatively affect forest recovery.

Keywords Postfire restoration · Remote sensing · Vegetation recovery · Wildfires · Vegetation indices · Deciduous oaks

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Background

In the last decades, global changes have led to a change in wildfire regimes across the world, with an increase in extreme wildfire events and great socioeconomic and ecological impacts (Rogers et al. 2020; Pausas and Keeley 2021). In Europe, wildfire seasons have become longer and with a trend to be more severe, particularly in the Mediterranean region (Duane et al. 2021; Fernandez-Anez et al. 2021; San-Miguel-Ayanz et al. 2022). Larger and more severe wildfires have caused significant changes in Mediterranean forests such as the homogenization of forest landscapes and the conversion of forests into shrublands in a self-reinforcing feedback loop (Duane et al. 2021; Rego et al. 2021).

The natural pattern of forest recovery after a wildfire (without human intervention) depends on various factors, such as fire regime and fire characteristics, composition of burned forests, biophysical and weather conditions. High fire frequency can prevent the establishment of tree seedlings and saplings, and high burn severity may limit

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postfire regeneration of vegetation due to great impacts on the burned vegetation and soil, and decreased seed availability and germination (Tepley et al. 2018; McLauchlan et al. 2020; Castro Rego et al. 2021). The recovery of ground cover after fire is faster in forests dominated by resprouting species, which regenerate vegetatively after fire, in comparison with seeders (Pausas 1999a, b; Lamont et al. 2011). Biophysical conditions (e.g. slope and aspect) influence the microclimate of forest natural regeneration, and slope enhances fire spread, which increases burn severity indirectly (Hawbaker et al. 2013; Fernandes et al. 2016). The rate of postfire forest recovery is also influenced by postfire weather conditions (Pausas 1999a; McLauchlan et al. 2020), especially precipitation and temperature (Díaz-Delgado et al. 2002; Torres et al. 2018).

Postfire restoration is a common strategy to facilitate the recovery of burned forests (Vallejo et al. 2012). The first stage of postfire restoration (named as emergency stabilization) is extremely important to stabilize the burned area and avoid soil loss, particularly when the risk of soil erosion is high and plant regeneration is slow (Vallejo et al. 2012; Vega et al. 2013). Emergency stabilization measures should be implemented shortly after the wildfire and, if possible, before the first autumn rains, in order to prevent further degradation, mitigate risks to people and assets, and minimize the significant loss of ashes and soil that typically occurs within the initial four months after the fire (Vallejo et al. 2012; Ferreira et al. 2015).

The restoration of forest ecosystems affected by wildfires has been increasingly integrated into European Union (EU) policies in the past decades (Faivre et al. 2018). However, monitoring of vegetation recovery after postfire restoration is seldom done in Europe (Ribeiro et al. 2020), and there is a large knowledge gap on the ecological effects of postfire restoration, with very few studies available (e.g. Robichaud et al. 2009; Bontrager et al. 2019). Portugal is the southern European country most affected by wildfires, with large burned areas resulting from a small number of fire events, with extraordinary negative environmental, social, and economic impacts (Mateus and Fernandes 2014; Tonini et al. 2017). In Portugal, postfire restoration is mostly implemented with public funding subsidized by EU funds (Pinho 2017; Ribeiro et al. 2018). However, postfire restoration in Portugal is often ineffective and carried out beyond the optimal timeframe (Lopes et al. 2022). Furthermore, the lack of a systematic monitoring constrains the optimization of treatments (Observatório Técnico Independente 2019; Ribeiro et al. 2020). In particular, little is known about postfire restoration effects on the regeneration of Mediterranean deciduous oaks (Espelta et al. 2012).

Deciduous oaks were once the native dominant forest vegetation of north and central Portugal, but have decreased gradually over time due to anthropogenic disturbances (Fletcher et al. 2007; Reboredo and Pais 2014) and are today restricted to small fragmented patches (Silva 2007; ICNF 2019). Oak species are resprouters, with the ability to regenerate after major disturbances such as wildfires, even at young ages (Alves et al. 2018; Marañón et al. 2020), and with a fast recovery of the forest canopy in a few years after fire, although canopy recovery depends largely on top kill, which in turn depends on fire severity (Calvo et al. 1999; Catry et al. 2013, for *Quercus pyrenaica*). Such postfire regeneration capacity, in association with wetter understory environments commonly found in mature oak stands (Dimitrakopoulos and Papaioannou 2001; Fernandes 2009), makes these forests fire-resilient (Díaz-Delgado et al. 2002; Botequim et al. 2017). This is particularly relevant for postfire forest restoration in the northern and central regions of Portugal where wildfires predominate (Pereira et al. 2006; Tonini et al. 2017).

In this study, we analysed the effects of postfire emergency stabilization on deciduous oak forest recovery in Portugal. Forest recovery was defined as the increase in vegetation greenness quantified with spectral indices through remote sensing (Gitas et al. 2012; Meneses 2021; Pérez-Cabello et al. 2021; White et al. 2022). Remote sensing techniques have been widely used to assess different types of restoration (e.g. Chen et al. 2014) and particularly postfire restoration (Vo and Kinoshita 2020; Carrari et al. 2022), providing biophysical measurements in a time-efficient and less costly manner, in comparison with fieldwork (Szpakowski and Jensen 2019; Pérez-Cabello et al. 2021). Spectral indices, such as the Normalized Difference Vegetation Index (NDVI), have also been increasingly used in fire ecology (Gitas et al. 2012; Szpakowski and Jensen 2019).

We analysed oak forest recovery for a period of four years after fire, for fire events that occurred in 2016 and 2017, by comparing recovery between burned areas with and without postfire emergency stabilization interventions. We asked the questions: (i) did postfire emergency stabilization has a positive impact on the recovery of oak forests? And (ii) how did fire characteristics, topography, and postfire drought events affected oak forest recovery? Assessing the effects of postfire restoration on forest recovery will contribute to improve knowledge on the effectiveness of implemented practices and optimize postfire forest management, particularly under increased wildfire severity predicted for the Mediterranean region (Dupuy et al. 2020; Rogers et al. 2020).

Methods

Study area

Mainland Portugal (latitude 37°–42°N, longitude 6°–10°W) is positioned in the extreme southwest of continental Europe, on the Iberian Peninsula. The Portuguese climate is Mediterranean, with a north–south temperature and precipitation gradients (Mora and Vieira 2020). There are considerable physiographic differences between northern and southern regions, with the northern half having a more rugged topography, a denser river network, and the majority of forests and semi-natural areas (Tonini et al. 2017). In 2015, Portugal was predominantly covered by forests (36%), shrublands and pastures (31%), and agricultural land (23%) (ICNF 2019). The main forest species in the country are blue gum eucalypt (*Eucalyptus globulus*), cork oak (*Quercus suber*), and maritime pine (*Pinus pinaster*), with 26.2%, 22.3%, and 22.1% of total forest area, respectively. Deciduous oaks account for only 2.5% of total forest area, mainly distributed across north and central Portugal (ICNF 2019).

Selection of spatial sampling units

We collected all the projects with postfire emergency stabilization interventions after the fires of 2016 and 2017, which were approved and funded by the Portuguese Rural Development Programme. The expenses eligible by this funding programme include not only emergency stabilization interventions such as mulching, erosion barriers, shredding of organic/forest residues but also sowing or planting (normally considered as intermediate-stage interventions) (Ministério da Agricultura e do Mar 2015). Each project may include any of these interventions implemented at one or several parcels. Available data do not allow distinguishing specific interventions, and therefore, they were analysed as a unique group. Project data and parcel identification numbers were provided by the Financing Institute for Agriculture and Fisheries (IFAP), and parcel spatial location was obtained from IFAP online services, which shows the parcel coordinates based on its identification.

Spatial data on oak land cover were extracted from the 2015 National Land Use and Land Cover (LULC) Map (hereafter COS2015, Cartografia de Ocupação do Solo 2015, Direção-Geral do Território 2022). We selected "oak forests" land cover class from COS2015, which includes three main species, namely, Pyrenean oak *(Quercus pyrenaica* (Willd.)), Portuguese oak (*Quercus faginea* (Lam.)), and Pedunculate oak (*Quercus robur* (L.)), since map categories do not distinguish the deciduous oak species. This class is dominated by *Q. pyrenaica*, including pure or mixed stands (with other broadleaves) (Carvalho 2007).

Areas burned between 2016 and 2017 were collected from the national database, which contains this information since 1975 (ICNF 2021).

We intersected the three spatial layers (in vector format), namely, (i) polygons (parcels) with postfire restoration projects, (ii) polygons dominated by deciduous oak forests, and (iii) burned areas, in order to obtain the final polygons for analysis, which corresponded to areas dominated by oak forest that burned in 2016–2017 where postfire restoration was implemented. Polygons with an area smaller than 1000 m^2 were excluded from further analysis, to ensure a large enough area to minimize edge effects whilst keeping a reasonable number of polygons for analysis.

We created a buffer area of 500 m around the perimeter of each final polygon. Contiguous buffers were aggregated to constitute unique spatial units (with a single identification number), in a total of 60 final units. Within each final buffer, we produced control polygons by selecting areas dominated by deciduous oak forests that burned in 2016–2017 but without postfire restoration interventions, and with at least 1000 m^2. Lastly, we created random points within the final polygons, with a minimum distance of 100 m between points. Random points were generated as circles of 15-m radius with zonal statistics (median value). This approach increases the sampling size, ensuring the diversity of intervention and control areas, and also homogenizing the spatial size of each observation. A total of 3013 random points were created, of which 43.6% ($n = 1314$) were located within polygons with postfire restoration projects and 56.4% ($n = 1699$) within control polygons (Fig. 1). Spatial analysis was performed in ArcGIS Pro (Esri Inc. 2022). Random points were used as the sampling units for data collection and analysis.

Data collection

For each sampling point, we collected remote sensing data using the Google Earth Engine (GEE) platform (Gorelick et al. 2017) and spatial data on fire characteristics and topography with GIS (Table 1). We used data from Sentinel-2 (MultiSpectral Instrument, Level-1C) and employed the QA (Quality Assurance) band to mask clouds, effectively excluding pixels associated with both opaque and cirrus clouds (Bit 10 and Bit 11) and ensuring clear conditions in the resulting images. Further details on the masking process can be found in ESA (2023).

We quantified two vegetation spectral indices: the Normalized Difference Vegetation Index (NDVI) and the Modified Soil Adjusted Vegetation Index 2 (MSAVI2). NDVI is widely used to analyse the state of recovery of burnt vegetation (Paci et al. 2017; Torres et al. 2018; Pérez-Cabello et al. 2021) and is the most robust vegetation index for vegetation recovery assessments (Veraverbeke et al. 2012; Szpakowski and Jensen 2019), showing a strong relationship with aboveground biomass for a wide range of ecosystems (Gitas et al. 2012). Since all vegetation indices have advantages and disadvantages, it is common to work simultaneously with more than one index (Wegmann et al. 2016). Therefore, we selected MSAVI2 since it minimizes the effect of bare soil of the Soil Adjusted Vegetation Index (SAVI), which is in turn used to rectify the effect of soil brightness in areas where

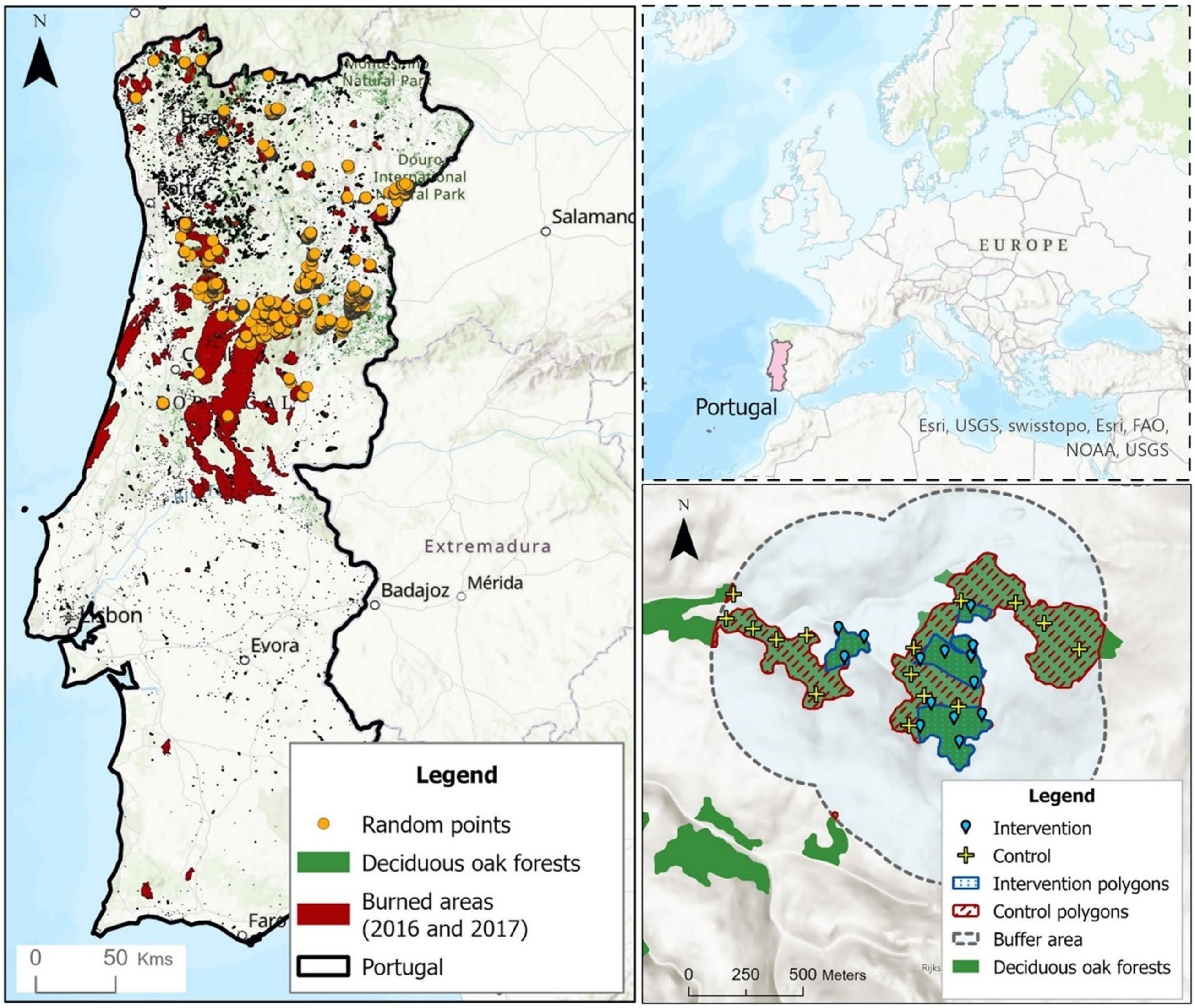

Fig. 1 Spatial location of random points, deciduous oak forests, and burned areas in 2016 and 2017 (left). Spatial location of Portugal in Europe (upper right). Representation of a buffer area of 500 m with intervention and control polygons, corresponding random points (intervention and control) and deciduous oak forest land cover (lower right)

vegetative cover is low (Qi et al. 1994). Both vegetation indices range from -1 to 1, with negative values indicating clouds and water, positive values near zero indicating bare soil, and higher positive values indicating denser vegetation (the closer to 1, the denser the vegetation). Postfire vegetation indices (NDVI and MSAVI2) were used as proxies of oak forest recovery and were calculated as monthly median values for the 48 months after the fire, for each random point. Monthly medians were computed to diminish the leverage effect of extreme values, which may arise from noise introduced by factors such as atmospheric conditions, shadows, sensor anomalies, or variations in vegetation phenology (Huang et al. 2021).

We also quantified the differenced Normalized Burn Ratio (dNBR) to estimate the burn severity for each random point. The index dNBR is important to discriminate different degrees of severity on surfaces affected by fire (Keeley 2009) and is commonly used for burn severity assessment (Szpakowski and Jensen 2019). To obtain the dNBR, we calculated the difference between the Normalized Burn Index (NBR) for prefire and postfire (NBR prefire—NBR postfire) and used the time interval of 21 days before the fire-start date and 21 days after the fire-end date. We chose this timeframe to increase the chances of obtaining high-quality images, since Sentinel-2 standard revisit interval is approximately five days. To ensure accurate assessment of burn severity, we calculated dNBR offset to account for temporal and seasonal differences between prefire and postfire satellite images. For that, we used a total of 1996 random points located outside the fire perimeter (> 1000 m) and within the same

Table 1 Data collected, respective time periods, resolution, and data sources

Group	Variable	Period*	Temporal resolution	Spatial resolution	Data source
Fire variables	Fire recurrence Time since the last fire	1975–2015 1975–2016	Minimum mapping area variable over time. Between 1975–1983 = 35 ha; 1984–2004 = 5 ha; since 2005 it is possible to detect smaller fires		National database of burned areas (ICNF 2021)
	Burn severity (dNBR)	2016–2020	Monthly	10 m	Sentinel-2 (Copernicus Sentinel 2022)
Postfire vegetation indices	NDVI MSAVI2	2017–2021			
Postfire drought	PDSI		Monthly	4638 m	TerraClimate (Abatzoglou et al. 2018)
Topography	Aspect Elevation Slope	–	–	30 m	NASA SRTM Digital Elevation (NASA JPL 2020)

*Depending on the fire year (2016 or 2017)

Spatial analysis was performed in ArcGIS Pro (Esri Inc. 2022).

vegetation type (deciduous oaks), obtaining a mean dNBR value of −16.9, which is within the dNBR offset acceptable range (−50 to 50) (Picotte et al. 2020). Burn severity levels employed correspond to those established by the United States Geological Survey (USGS) (Key and Benson 2006a). Sampling points with dNBR values < 100 (11.2%, $n = 338$), corresponding to the levels of "Unburned" and "Regrowth" (Key and Benson 2006b), were excluded from the analysis, since these points were likely located in unburned islands inside the burned areas (Kolden et al. 2012). Hence, 2675 points were retained for further analysis.

We collected additional variables for each random point, namely: (i) fire recurrence (number of fires occurred between 1975 and the analysed fire event, 2016 or 2017) and time (number of years) since the last fire (before 2016 or 2017), both collected from the national database of burned areas, which starts in 1975 (ICNF 2021); (ii) postfire monthly values of the Palmer Drought Severity Index (PDSI), which uses temperature and precipitation records to estimate relative dryness (values between −1 and −4 correspond to different drought levels) from TerraClimate (Abatzoglou et al. 2018); and (iii) topographic information (aspect, elevation, and slope) from the NASA DEM Digital Elevation Model (NASA JPL 2020).

Data collected to characterize the sampling points are shown in Table 1.

Data analysis

We used Generalized Additive Mixed Models (GAMM) to assess the effects of postfire restoration, fire characteristics, topography, and postfire drought events on the temporal changes of NDVI and MSAVI2, for a period of 48 months following the fire. We chose GAMM because we observed highly nonlinear relationships between the dependent and independent variables. To select the final set of covariates, we conducted pairwise correlation analysis and identified a subset of variables that exhibited a relationship with the dependent variable and a correlation coefficient lower than 0.50 (see Annex 1—Sect. 5.2). The final set of covariates used in the models included burn severity, time since the last fire, fire recurrence, PDSI (log transformed), aspect, elevation, and slope (see Table 1). The effect of postfire restoration was added to the model as a factorial variable called "Intervention" which takes the value 1 for restored areas and 0 for control areas. Since NDVI/MSAVI2 values present temporal correlation, we added a correlation structure of order 1 (corAR1) to the model's residuals (Zuur et al. 2009). We included the identification of each buffer as a random effect because projects located within the same buffer were more likely to have similarities, compared to those located outside the buffer. We validated the models by checking that the model's residuals followed an approximately normal distribution and that there were no patterns when the residuals were plotted against the covariates. We fitted the models using R 4.0.3 (R Core Team 2020) and the package "mgcv" (Wood 2022). We found that the MSAVI2 model performed very poorly, so we decided to exclude it from the analysis. The R code used to run the analysis is shown in Annex 1.

Results

Characterization of sampling points: fire characteristics, postfire drought, and topography

The different levels of burn severity showed a similar distribution between sampling points with and without (control) postfire interventions, with the moderate-high burn severity level being the most frequent (33.64%), followed by high

(26.13%), and moderate-low levels (24.07%) (Table 2). The points with values equivalent to "Unburned" and "Regrowth" (dNBR < 100) were removed from the model analysis, as already mentioned in the methods section (and are not included in Table 3).

Table 3 shows the descriptive statistics of the covariates used in the model. The altitude of random points locations ranged from 22 m to about 1300 m, and the majority of the sampling points were exposed to ESE (East–South–East, between 90° and 135°) or WNW (West–North–West, between 270° and 315°), with highly variable slopes. Fire recurrence ranged from 0 to a maximum of ten fire events in 1975–2016/2017, from which 24% of sampling points (650) never burned, 44% (1182 points) burned once or twice, and 32% (843 points) burned three or more times. Time since the last fire was also highly variable, ranging from one year until a maximum of 42 years (corresponding to points that did not burn during the studied period, although they might have burned before 1975), in accordance with the variability of fire recurrence. Burn severity, measured by dNBR, ranged from 100 (defined as minimum limit) to 1171.

Postfire drought (PDSI monthly values) showed similar seasonal patterns across sampling points over the two analysed periods (2016–2020 or 2017–2021, depending on the fire event) (Fig. 2). For the majority of sampling points, severe to extreme drought levels (PDSI < −3) were registered in the first 3–5 months after fire, followed by mild to moderate drought levels (−1 < PDSI < −3). Normal to moderate wet periods (3 < PDSI < 0) were mostly concentrated between the fifth and the 15th months after the start of both 2016 and 2017 fires. After the 15th month, the PDSI values decreased, ranging between normal to moderate dry levels (0 > PDSI > −3) until the end of the observation period. In contrast, the sampling points located within fires that started in September 2017 ($n = 14$) showed an unexpected and opposed pattern; these points belong to two spatially close buffers (1.7 km—distance), forming a cluster situated on a south-east facing hillside near a village, which may be subjected to specific microclimatic conditions.

Effects of postfire restoration, fire characteristics, and postfire drought events on oak forest recovery

The NDVI model was accounted for a moderate portion (26.4%) of the observed variance (see SM—Annex I). The postfire restoration intervention had a weakly positive but statistically significant effect ($\beta = 0.011$, $p < 0.001$). NDVI values in restored areas tended to be 1% higher compared to control areas. The smooth terms for all covariates were significant ($p < 0.001$).

Figure 3 shows the GAMM partial effects plots of smooth variables on NDVI recovery rate. The relationship between the Palmer Drought Severity Index (PDSI) and the Normalized Difference Vegetation Index (NDVI) was characterized by a highly nonlinear pattern. However, higher PDSI values (i.e. wetter conditions) were generally associated with higher NDVI values. The model also indicates a complex relationship between the NDVI and the covariate burn severity, represented by the differenced Normalized Burn Ratio (dNBR). For dNBR values lower than 270, the relationship with

Table 2 Contingency table of burn severity and postfire intervention

Burn severity levels	Regrowth	Unburned	Low	Moderate-low	Moderate-high	High	Total
dNBR values	−250 ≥ and < −100	−100 ≥ and < 100	100 ≥ and < 270	270 ≥ and < 440	440 ≥ and < 660	≥ 660	
Points with postfire Intervention	7 (0.2%)	140 (4.6%)	223 (7.4%)	287 (9.5%)	371 (12.3%)	286 (9.5%)	1314 (43.6%)
Control Points	2 (0.1%)	189 (6.3%)	209 (6.9%)	357 (11.8%)	529 (17.6%)	413 (13.7%)	1699 (56.4%)
Total	9 (0.3%)	432 (10.9%)	432 (14.3%)	644 (21.4%)	900 (29.9%)	699 (23.2%)	3013 (100%)

Table 3 Descriptive statistics of predictor variables

Group	Variable	Min	Mean	Max	SD
Fire characteristics	Fire recurrence	0	2	10	1.9
	Time since the last fire[a] (years)	1	15	42	9.3
	Burn severity (dNBR)	101	503	1171	218
Postfire drought	PDSI	−5.5	−1.8	3.4	2
Topography	Altitude (m)	22	652	1326	197
	Slope (°)	0	10	47	8

Aspect (°) was excluded from the table due to its 0–360 scale (refer to the text for further details)

[a]The values are limited by the temporal resolution, which only allows a maximum value of 42 years (1975–2017)

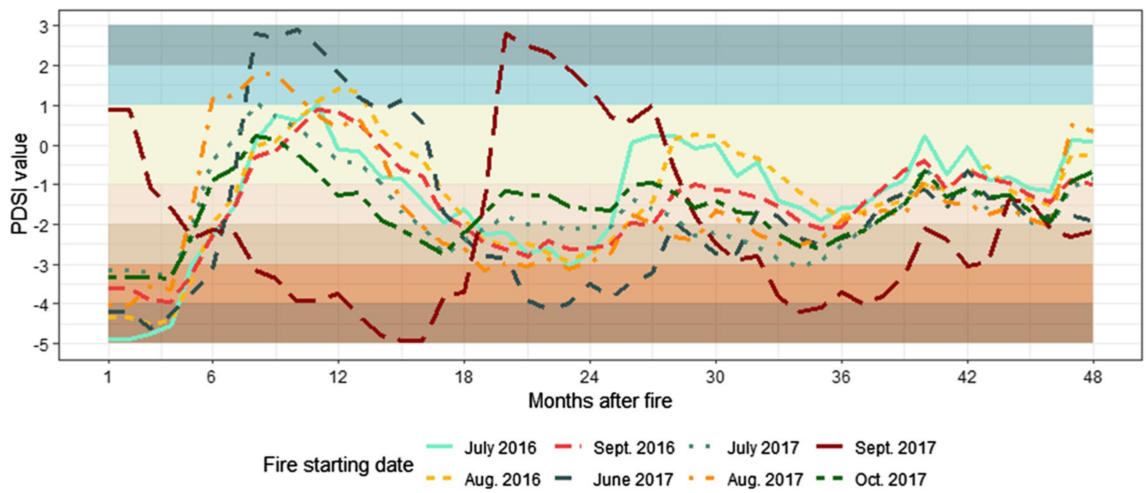

Fig. 2 Mean monthly PDSI values over the 48 months after fire, grouped by fire-starting date. Sampling points with the same fire-starting month are grouped with the same line colour, and years are differentiated by lighter (2016) or darker (2017) colours. Colour areas in the background indicate PDSI categories, as seen in (Pires 2003)

NDVI appeared to be negative. For dNBR values between 270 and 440, NDVI did not appear to change significantly. However, when dNBR values increased beyond 660, there was a strong positive relationship with NDVI. The relationship between fire recurrence and NDVI was also complex. Initially, as the number of fires increased from zero to six, NDVI values declined rapidly. However, as the number of fires continued to increase from six to ten, NDVI values began to grow. Finally, the NDVI values appeared to fluctuate over time in a cyclical pattern corresponding to each year´s seasons. Nevertheless, there was a noticeable overall upwards trend in NDVI values over time (Fig. 3).

Discussion

Effects of postfire restoration on oak forest recovery

We found a tendency for an increase in NDVI over time, which indicates a generalized postfire oak forest recovery in the study areas. NDVI maximum annual values increased during the spring meteorological season, which corresponds to the period between the start of the Mediterranean growing season (March) and the maximum of photosynthetic activity (June) (Piedallu et al. 2019). We also observed an increase in annual maximum NDVI values amidst the second and the third year. Such trends agree with other studies that show a gradual recovery of oak forest communities, dominated by the recovery of herbaceous species during the first two years, with the recovery of woody species (shrubs and trees) becoming stronger from the third year onwards (Calvo et al. 2002, 2003; Capitanio and Carcaillet 2008).

Postfire restoration interventions had a significant positive impact on oak forest recovery, however with a small model effect. The small effect observed may be the result of interventions executed outside the optimal timeframe, which is common in postfire emergency stabilization projects subsidized by public funding in Portugal, with a median time interval of about 88 days (three months) between fire extinction and the start of the project (Lopes et al. 2022). Delayed postfire emergency stabilization will not mitigate the loss of ashes and soil, which occurs mostly up to the first three months after fire, and hence will not efficiently protect the burned soil and facilitate vegetation recovery (Vallejo et al. 2012; Vega et al. 2013). Moreover, postfire emergency restoration projects analysed in this study may include different types of interventions, with distinct levels of effectiveness, which may have diminished the overall effects of postfire restoration. Other studies have shown distinct effectiveness depending on the postfire emergency treatments implemented (Robichaud et al. 2010; Gómez-Sánchez et al. 2019; Girona-García et al. 2021; Lucas-Borja et al. 2021). For example, distinct treatments may reduce postfire soil erosion but not postfire runoff, and may impact differently vegetation recovery (Lucas-Borja et al. 2019; Girona-García et al. 2021). In addition, unproperly implemented interventions, such as too thick mulching, may create a physical barrier that inhibits the establishment of native vegetation (Fernández and Vega 2016; Bontrager et al. 2019).

The marginal effect of postfire emergency stabilization on oak recovery (NDVI) can also be attributed to the natural capacity of oaks and coexisting understory shrubs to regenerate naturally following a fire, as previously mentioned, which could have led to small differences in vegetation greenness between areas with and without postfire

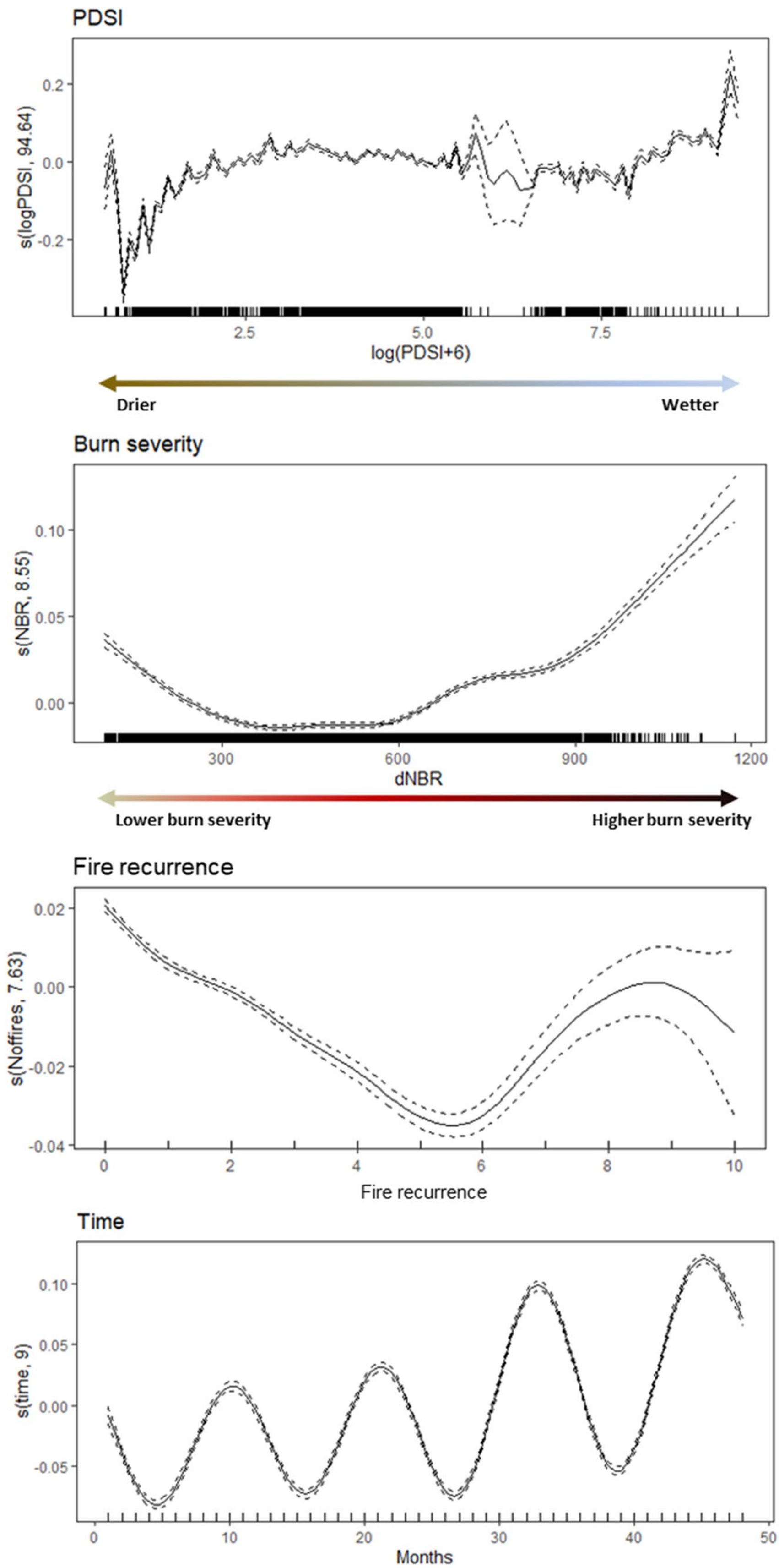

Fig. 3 GAMM partial effects plots of smooth variables on NDVI recovery rate. *X*-axis shows predictor variable values. The *y*-axis represents the effect of each variable, with y-axis values indicating the effective degrees of freedom (edf). Tick marks on the *x*-axis are observed data points. Dotted lines indicate the 95% confidence intervals

restoration. Other studies found small effects of postfire treatments on shrub vegetation recovery and a greater regeneration of woody species in non-treated areas for similar climatic conditions (Fernández and Vega 2014; Carrari et al. 2022). Nevertheless, the effects of postfire emergency treatments on the recovery of Mediterranean deciduous oak forests are still poorly investigated and hinder the discussion of the small effect observed in our study.

Effects of postfire drought events and fire characteristics on oak forest recovery

The drought index PDSI was the variable with the higher effect on the postfire recovery of NDVI. During the analysed period, PDSI monthly values were mostly negative (reflecting mild to extreme drought levels), with the most severe drought levels observed in the first months after the fire. In fact, the hydrological year 2016–2017 was the ninth driest year since 1931, and in 2017–2018, most of the mainland Portugal was under severe to extreme drought. In addition, this drought event was distinct from the former drought years since drought severity was aggravated in the autumn of 2017 (IPMA 2020). Our results showed that postfire recovery of NDVI was negatively affected by severe drought levels and positively affected by increased wetness, which seemed also to be influenced by local topography and microclimatic conditions. Indeed, several studies show that the initial stages of the oak life cycle are especially vulnerable to the reduction of precipitation (Montagnoli et al. 2016; Marañón et al. 2020), and severe droughts will likely affect postfire regeneration capacity of oak forests (Acácio et al. 2017; Marañón et al. 2020). A recent study also showed that precipitation deficits were associated with changes from deciduous oak forests to other land cover types in Portugal (Acácio et al. 2017). In general, postfire climatic conditions have been pointed out as one of the most important predictive factors for postfire vegetation recovery (Pausas et al. 1999; Torres et al. 2018; Nolan et al. 2021).

Regarding burn severity, our results showed that NDVI responded positively to both low and high burn severities, whilst intermediate severities showed a reduced effect on NDVI recovery rate. Although both extreme categories appear to have a similar outcome, the NDVI response can be justified by different reasons. On one hand, low-burn severity fires will generally provide beneficial consequences, since trees will not be top-killed, surface litter will be only partially consumed, and the soil organic layer will remain largely intact (Keeley 2009; Fernandes et al. 2010). This will result in availability of soil nutrients and faster habitat rejuvenation (Castro Rego et al. 2021), as shown in this study by the higher NDVI recovery rate in areas of low burn severity, where oak recovery is likely to be greater (Catry et al. 2013). On the other hand, higher burn severity levels will cause higher impacts on the soil and vegetation when compared to lower-severity fires (Viana-Soto et al. 2017; Castro Rego et al. 2021). High-severity fires (often crown fires) may lead to near-complete mortality of the above-ground vegetation, including a significant amount of postfire stem mortality in deciduous oak trees (Catry et al. 2010, 2013), and total consumption of the forest floor (Keeley 2009; Tepley et al. 2018). Nevertheless, the available literature also shows that Mediterranean species belonging to the genera *Cytisus* spp. and *Genista* spp. may regenerate vigorously in the short-term after severe fires (1–2 years, Trabaud 1992; Ojeda et al. 1996; Cruz et al. 2020). Such species are commonly found in deciduous oak forests of northern and central regions of Portugal, where understory vegetation is dominated by shrubs such as *Crataegus monogyna*, C*ytisus* spp., *Genista falcata,* and *Erica arborea* (ICNB 2000). In addition, and despite the existence of contradictory literature (Vega et al. 2005), *Q. pyrenaica* may also be highly resilient to high burn severities, as shown in a study in Spain, with *Q. pyrenaica* achieving a ground cover of 47%, two years after the fire and under high severity (oak recovery was even higher than under medium and low severities) (Huerta et al. 2022). Hence, NDVI increase under high burn severity in our study area may be partially explained by the fast recovery of the understory vegetation (Castro Rego et al. 2021). Such differences in the type of vegetation that recovers cannot be detected by NDVI measurements, which show vegetation greenness and do not guarantee that the same type of prefire vegetation is being regenerated (Gouveia et al. 2010; Meneses 2021). In agreement with our results, postfire NDVI values in pine forests mixed with oaks and other woody species under moderate/high burn severities increased quickly over time, achieving those of the lightly burned areas two years after the fire (Lee and Chow 2015).

Lastly, fire recurrence showed a small negative effect on NDVI recovery rate, up to a maximum frequency of six fires. Higher fire frequency may lead to a diminishing capacity of oaks to resprout (Frelich et al. 2015), and its effect seems to be increasingly negative on sapling density, with Pedunculate oak and Pyrenean oak saplings being especially sensitive (Monteiro-Henriques and Fernandes 2018). Hence, recurrent fires may alter the stand structure and lead to a decrease in oak dominance in favour of other tree species (Burton et al. 2010; Frelich et al. 2015). For example, repeated burning can transform an uneven-aged oak stand into an even-aged stand (Knapp et al. 2017). However, and as our results indicate, if fire frequency is above a certain threshold, it will lead to lower fuel loading and consequent lower burn severity, with lower impacts on the oak forest (Burton et al. 2010; Steel et al. 2015; Knapp et al. 2017).

Future research

Our study shows that remote sensing is a valuable tool to estimate the recovery of burned oak forests and the effectiveness of postfire restoration. Emergency stabilization interventions should be focussed on the restoration of areas with high burn severity, where soil is greatly damaged and lower oak recovery is expected, particularly in dry years, despite the fast recovery of understory shrubs in those areas, as suggested by our study. Therefore, postfire assessment and restoration in the short-term should prioritize areas for the implementation of emergency stabilization based on burn severity levels, which indicate qualitatively the fire effects on the forest ecosystem, in order to maximize restoration effectiveness and reduce overall costs. This procedure is commonly done in the USA by emergency response teams (Robichaud et al. 2009). However, public funding procedures for postfire emergency stabilization in Portugal do not make this distinction. In this regard, remote sensing techniques should be used by governmental agencies in Portugal as a complement to field evaluation to assess burn severity as part of the funding process for postfire restoration, allowing to minimize restoration costs and maximize its effectiveness.

After the implementation of treatments, remote sensing methods should be used in association with field assessments for the systematic monitoring of postfire restoration effectiveness, allowing to reduce the costs of field monitoring, and providing quick, continuous, and long-term information on postfire vegetation recovery and dynamics (Gitas et al. 2012; Pérez-Cabello et al. 2021). Furthermore, the recent developments in remote sensing, such as the increasing supply of medium to high resolution (< 100 m) observations, are leading to a transition from bitemporal to continuous approaches, allowing analysis of spectral trajectories across regular time series (Szpakowski and Jensen 2019; Woodcock et al. 2020; Pérez-Cabello et al. 2021).

Future changes in fire regimes are expected worldwide as a result of climate change, in particular for southern Europe (e.g. higher frequency and severity) (Dupuy et al. 2020). Although resprouting species such as oaks are likely the most resilient to changing fire regimes, postfire oak recruitment and forest recovery may be hindered by overlapping climate-driven stressors such as pest outbreaks, droughts, and heatwaves, which may significantly limit the capacity of vegetation to recover in the future (Nolan et al. 2021). It is therefore necessary to continue studying the impacts of postfire restoration interventions on forest recovery and integrate the possible ecological consequences of restoration into the decision-making process (Robichaud et al. 2009). Ultimately, a better understanding of the impacts of postfire restoration measures on vegetation dynamics will lead to better decisions regarding postfire forest management.

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Author contributions LFL and VA conceived and designed the analysis; LFL performed data collection; data analysis and interpretation were performed by LFL in collaboration with FSD, PMF, and VA; all authors participated in writing/edition of the manuscript.

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Data availability and materials The data set generated in the present study is available and can be found here: https://doi.org/10.6084/m9.figshare.22015970.

Code availability Information can be found in Supplementary Material—Annex I "R code for reproducing the analysis".

Declarations

Conflict of interest The authors declare that they have no competing interests.

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