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LETTER

Interactions between hot and dry fuel conditions and vegetation dynamics in the 2017 fire season in Portugal

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Abstract

Wildfires are a serious threat to ecosystems and human. In Portugal, during 2017, a catastrophic fire season burned more than 500 000 hectares and caused the death of more than 100 people. Previous studies have shown that hot and dry fuel conditions promoted widespread propagation of wildfires. However, burned area (BA) and mega-fires, such as the 2017 ones, depend not just on favourable meteorological conditions, but also on fuel accumulation and dryness. In this study, we will assess the influence of spring meteorological conditions on fire season BA, through their effects on fuel accumulation and dryness. Using satellite-based data, we show that the association of higher temperatures and water availability in spring can increase the risk of summer wildfires propagation, flammability and intensity through their influence on vegetation gross productivity. This study highlights the important role of fuel accumulation during the growing season in fire-prone regions like Portugal. Our results imply that fuel management may be an effective way to mitigate extreme fire seasons associated with warmer and drier conditions in the future.

1. Introduction

Mediterranean ecosystems are particularly prone to large fires (Salis *et al* 2014), burning on average 4500 km^2 every year (San-Miguel-Ayanz *et al* 2013, Rodrigues *et al* 2021), especially during summer season (Pereira *et al* 2005, Koutsias *et al* 2012, Turco *et al* 2017, Ruffault *et al* 2018). These events have impacts on vegetation carbon and nutrient cycling (Caon *et al* 2014, Pellegrini *et al* 2018, Jones *et al* 2020) and on CO$_2$ released towards the atmosphere (Lasslop *et al* 2019), but also result in major losses on the economy and human lives. In addition to direct human casualties, these episodes generate intense smoke plumes, which affect air quality, and consequently human health over wide regions (Shaposhnikov *et al* 2014, Cascio 2018, Tarín-Carrasco *et al* 2021).

Droughts and heatwaves have been shown to be closely linked to the ignition and propagation of wildfires (Urbieta *et al* 2015, Sutanto *et al* 2020). For instance, the summer heatwave in 2010 over western Russia contributed to widespread fire events (Shaposhnikov *et al* 2014), leading to large losses of vegetation gross productivity that reached $-1.8\ \mathrm{TgC\ yr^{-1}}$ (Bastos *et al* 2014, Flach *et al* 2018). In turn, the extreme climatic conditions experienced in 2003, 2005 and 2017 over western Europe and Iberian Peninsula were associated to remarkable wildfires, especially in Portugal, where more than 300 000 ha burned on each of those fire seasons (Trigo *et al* 2006, Gouveia *et al* 2012, Turco *et al* 2019, Oliveira *et al* 2020). This was also the case of extreme conditions experienced over Greece during the summers of 2007 and 2021, which led to catastrophic fires that resulted in burned areas (BAs) over 200 000 hectares each (Gouveia *et al* 2016, Evelpidou *et al* 2022, Giannaros *et al* 2022).

Over the Iberian Peninsula, the strong relationship between wildfire occurrence and summer hot and dry fuel conditions (Trigo *et al* 2016, Russo *et al* 2017) and the increasing occurrence of hot and dry days (Fonseca *et al* 2016) can exacerbate the fire hazard, lengthen of fire seasons and result in the increase of BA (Jolly *et al* 2015). Future climate projections in Mediterranean region suggest an increasing frequency and severity of heatwaves and droughts and the co-occurrence of these two events (Zscheischler *et al* 2018, Vogel *et al* 2021), which enhance the potential risk of wildfires (Flannigan *et al* 2013, Barbero *et al* 2015, Abatzoglou and Williams 2016, Ruffault *et al* 2018). For example, Amatulli *et al* (2013) projected an increment of 66%–140% in BAs over the European Mediterranean region until the end of the 21st century, according to different climate scenarios.

The availability of biomass and moisture content before the fire events, resulting from combined favourable weather conditions such as persistent dryness and hot summer situations, are broadly recognized as the main drivers of wildfires intensity and propagation (Gouveia *et al* 2012, Flannigan *et al* 2013, Barbero *et al* 2015, Vieira *et al* 2020). On one hand, Rodrigues *et al* (2020) and Vieira *et al* (2020) highlighted that high temperatures and low humidity are key conditions to trigger wildfires in several regions of the Iberian Peninsula. On the other hand, Gouveia *et al* (2012) found higher fire selectivity over the areas with more vegetative and water stress conditions during the 2003 and 2005 fire seasons in Portugal, but also pinpointed the critical role of accumulated fuel during spring months preceding the fires period. Therefore, climatic and ecological conditions before summer fire season strongly modulate the wildfires, both in terms of their intensity, flammability and propagation (Pausas and Paula 2012). The meteorological conditions on late winter and spring have an important role on the development of vegetation in Iberian Peninsula, as this period characterizes the growing season of many ecosystems. In turn, these conditions can mediate the amplification or reduction of potential fire risk in summer (Gouveia *et al* 2012).

Here, we explore the link between the pre-fire season vegetation productivity and the occurrence of fire events in conjunction with hot and dry conditions, relying on remotely sensed data. In this study, we focus on the worst fire season in Portugal, which occurred in 2017, and evaluate how hot and dry fuel conditions in conjunction with ecological stress contributed to the propagation of wildfires. We further compare the results with two other dramatic fire seasons in 2003 and 2005.

2. Data and methods

2.1. Remote sensing data

Vegetation productivity was assessed using the satellite-based gross primary production (GPP) from the MOD17A2 Collection 6 (Running and Zhao 2015). MOD17A2 GPP is calculated based on light use efficiency model (Monteith 1972, 1977), satellite-derived absorbed radiation (APAR), surface meteorological data and information related with specific biome-type radiation conversion efficiency (Zhao *et al* 2005). GPP is provided at 500 m as 8 d composites, expressed in kg C m^{-2}/8 d.

We detected BAs with 250 m of spatial resolution and monthly time step through the ESA Fire Climate Change Initiative version 5.1 satellite product (FireCCI51, (Lizundia-Loiola *et al* 2020)). FireCCI51 covers the period 2001–2019 and complements the previous version 5.0, by extending the temporal range and including several refinements on the algorithm (Lizundia-Loiola *et al* 2020). FireCCI51 merges two MODIS satellite products associated with surface reflectance (MOD09) and thermal surface information (MCD14) (Chuvieco *et al* 2018), which allows for improved BA detection.

FireCCI51 encompasses the date of detection (Julian Day, hereafter JD) to monitor the day when the fire was firstly detected, the level of confidence of the BA (confidence level, hereafter CL) and the land cover of the burned pixel (Land Cover, hereafter LC) retrieved from Climate Change Initiative Land Cover Collection, used to analyse the LC-type of burned pixels.

The JD and LC datasets were firstly resampled to a coarser resolution of 500 m, as used in MODIS GPP grid, by calculating the fraction of BA (figure S1). To increase the confidence of the BA detection, we selected only the pixels of the resampled grid which had 100% of BA. Nonetheless, it should be noted that the resampling to coarser resolution results in partial loss of information, especially over regions which were affected by small fires. The LC dataset describes the LC category of BAs before the fire occurrence and, in this work, we merged the classes into six different categories: broad leaved forest, needle leaved forest, mixed forest, shrubland, cropland and others. More details about the definition and grouping of LC classes can be found in table S1.

Land Surface Temperature (LST) was evaluated relying on MOD11A2 Collection 6 of TERRA satellite. The product consists of an 8 d average of daily daytime and night-time measurements, with a spatial resolution of 1 km (Wan 2014). LST fields were remapped to the finer resolution of GPP grid (500 m). The most recent version of LST MODIS includes several refinements on the split-window algorithm, leading to reduction on LST bias, which are lower than 1 °C in the range of -10 °C to 58 °C (Wan 2014).

The water availability on vegetation was assessed by the Normalised Difference Water Index (NDWI). This index, proposed initially by Gao (1996) combines information about Near-InfraRed (NIR) ($\sim$0.84 μm) and Short-Wave InfraRed (SWIR) ($\sim$1.24 μm), showing high suitability to monitor the vegetation water leaf content and the effects of drought severity on vegetation (Serrano *et al* 2019,

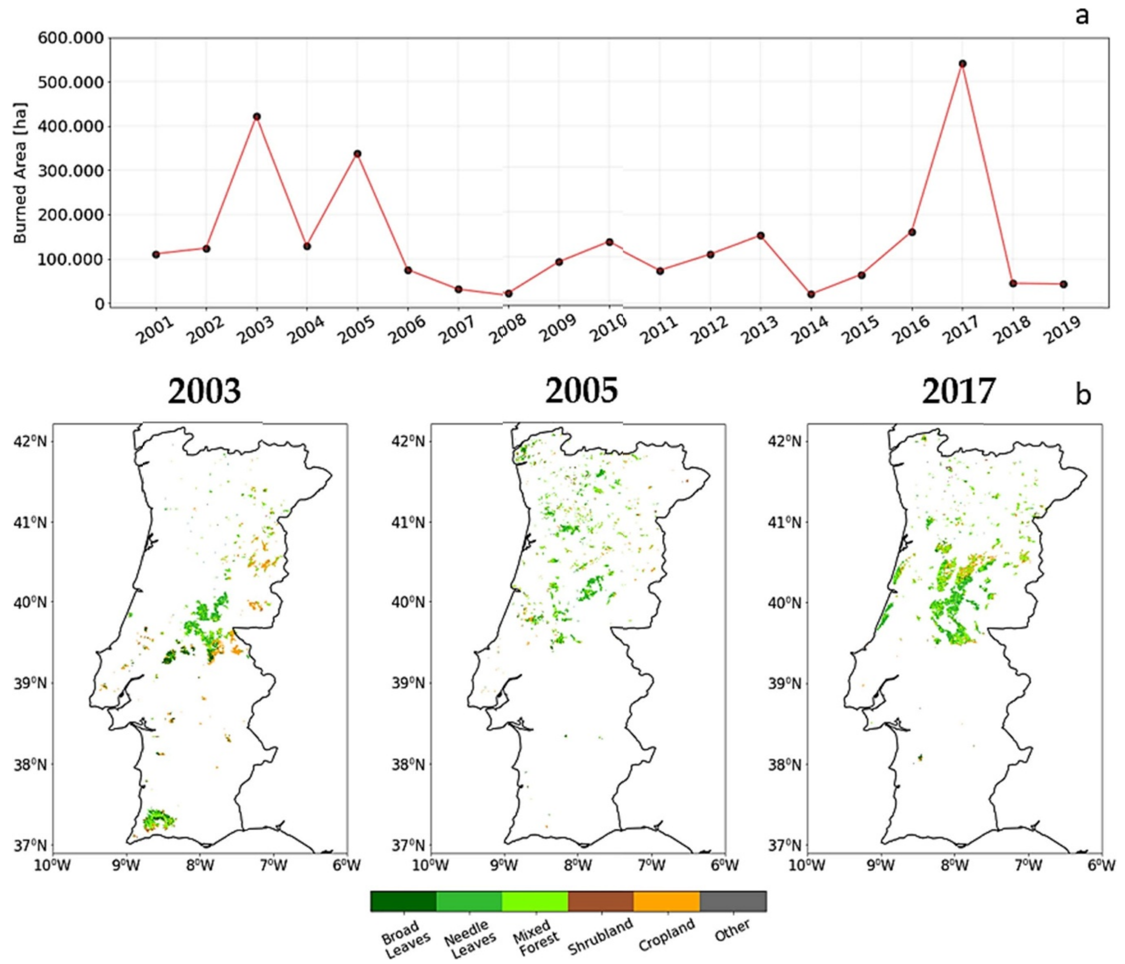

Figure 1. (a) Burned area extension in Portugal between 2001 and 2019. (b) Burned vegetation during the three worst fire seasons in Portugal: 2003 (left panel), 2005 (central panel) and 2017 (right panel).

Marusig *et al* 2020). The index was in turn adapted by Gond *et al* (2004) that used information of NIR (∼0.84 μm) and Medium-Wave InfraRed (MIR) (∼1.64 μm), since MIR showed a more robust correlation with water content. Therefore, NDWI can be defined according to the following equation (Gond *et al* 2004):

$$\mathrm{NDWI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{MIR}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{MIR}}}.$$

The NDWI is calculated from Bands 2 (ρ_{NIR}) and 6 (ρ_{MIR}) of the MOD09 Collection 6 dataset, at a 500 m of spatial resolution and 8 d time-steps (Vermote *et al* 1997).

2.2. Study area

Across the Mediterranean basin, Portugal is one of the most affected territories by wildfires and the country registers the highest percentage of BA in the last century (Mateus and Fernandes 2014, Turco *et al* 2019). The vegetation distribution in this region is highly heterogeneous and various studies have shown a recent decline of forest coverage, with reduction of areas with maritime pine and an increase of eucalyptus dominated regions (Meneses *et al* 2017, Fernandes *et al* 2019, Nunes *et al* 2019). These tree species are highly flammable and can potentiate the risk of fire severity. On the other hand, Barros and Pereira (2014) also showed strong preference of fire for shrubland areas with high fuel load. Therefore, appropriate land management policies and fire risk prevention are crucial to reduce the wildfires propagation (Meira Castro *et al* 2020), and fire management practices, such as prescribed burning and fuel management, are starting to be used in the region. However, the benefits of the application of these techniques should be carefully analysed in Portugal.

Within the period of 2001–2019, several years recorded more than 100 000 hectares of BA (figure 1(a)), being the fire seasons of 2003, 2005 and 2017 the most catastrophic ones in Portugal (figure 1(a)). The northern and central regions of the country were the most affected by fires in all three years, with mixed forests and needle-leaved forests being the most damaged ecosystems (figure 1(b)). In 2017, mixed forests represented 45%, and needle leaved forest 33% of the total BA of that year, and in 2003, 84% of the total BA was represented by mixed forests. Moreover, between 2001 and 2019, many of these areas burned 2–3 times, and a small fraction of pixels burned more than three times in this period (figure S2).

The fire season of 2017 was particularly catastrophic, not only due to the recorded BA but also due to the economic losses and more than a hundred human casualties (Turco *et al* 2019).

2.3. Methods

2.3.1. Hot and dry impacts on vegetation activity

GPP, LST and NDWI were aggregated to monthly values and the corresponding monthly standardised anomalies, respectively GPP_{ANOM}, LST_{ANOM} and $\text{NDWI}_{\text{ANOM}}$, were calculated at pixel-level by subtracting the median seasonal cycle and dividing by the long-term standard deviation of the 2001–2019 period. To avoid the signature of extreme hot and dry fuel conditions occurred in 2003, 2005 and 2017, these three years are excluded from the median seasonal cycle.

Extreme hot and dry fuel conditions during the fire season of 2017 were analysed both for the study area and, afterwards, only over the 2017 burned pixels. Considering the importance of understanding the impact of each extreme climatic condition in burned vegetation, the definition of a threshold for the anomalies of temperature and water availability is a key point in this study. In this context, on one hand, Seneviratne *et al* (2012) pointed out that regions with soil moisture anomalies below -1σ during summer can be defined as being under agricultural drought. On the other hand, Buras *et al* (2020) showed that during the heatwaves of 2003 and 2018 in Europe, large areas that were severely affected by those events exceeded temperature anomalies of 1σ. Therefore, we classified points with LST_{ANOM} ($\text{NDWI}_{\text{ANOM}}$) higher (lower) than 1σ (-1σ), respectively, as areas under hot (dry) conditions.

The BA are then separated into four categories: Burned only, B ($\text{LST}_{\text{ANOM}} < 1\sigma$ and $\text{NDWI}_{\text{ANOM}} > -1\sigma$), Hot and Burned, HB ($\text{LST}_{\text{ANOM}} > 1\sigma$), Dry and Burned, DB ($\text{NDWI}_{\text{ANOM}} < -1\sigma$) and Hot, Dry and Burned, HDB, ($\text{LST}_{\text{ANOM}} > 1\sigma$ and $\text{NDWI}_{\text{ANOM}} < -1\sigma$).

The impacts of hot and dry fuel conditions on burned vegetation productivity were assessed through the computation of cumulative density functions (CDFs) of GPP_{ANOM}, LST_{ANOM} and $\text{NDWI}_{\text{ANOM}}$ of the three fire seasons. Each of the variables were aggregated in two seasons, in order to observe the climatological and ecological conditions on BAs during the pre-fire season (March, April and May—MAM) and fire season (June, July, August, September and October—JJASO).

2.3.2. Logistic regression models

The meteorological conditions experienced preceding the fire season can influence biomass accumulation and modulate the potential risk of wildfires. Following the methodology of Bevacqua *et al* (2021), logistic regression models were used to identify the influence of hot and dry fuel conditions, as well as the preconditioning effects of vegetation productivity before the fire season on wildfires occurrence in 2003, 2005 and 2017.

In our work, the occurrence of BAs can be considered a binary time-series, being 0: no BA and 1: BA, and the predictors GPP_{ANOM}, LST_{ANOM} and $\text{NDWI}_{\text{ANOM}}$ are continuous variables. Therefore, on a first step, the predictors of each fire season (standardised anomalies) were averaged in two seasons, defining two different datasets: spring (MAM) and extended fire season (JJASO).

The generalised equation of logistic regression (equation (1)) allows the estimation of probabilities of the dependent variable through the calculation of coefficients of independent variables:

$$p\left[Y=1\right]=\frac{1}{1+\exp\left(b_0+b_1X_1+\cdots+b_nX_n\right)} \qquad (1)$$

where b_0 represents the interception, and b_n are the regression coefficients of each variable X_n. In our analysis, we infer the influence of each variable on BA based on the regression coefficients.

Three different models were fitted for this purpose. A first simple model, that considers the dependence of BAs exclusively on hot and dry fuel conditions of the fire season, being $\text{BA} = \text{f}\ (\text{LST}_{\text{JJASO}}$ and $\text{NDWI}_{\text{JJASO}})$. A second model that, besides fire season climatological conditions includes vegetation productivity during spring, being $\text{BA} = \text{f}\ (\text{GPP}_{\text{MAM}}, \text{LST}_{\text{JJASO}}, \text{NDWI}_{\text{JJASO}})$. The third model fits the BA with both ecological and climatological parameters, but only in spring, to understand how climatological conditions modulate the vegetation dynamics in pre-fire season: $\text{BA} = \text{f}\ (\text{GPP}_{\text{MAM}}, \text{LST}_{\text{MAM}}, \text{NDWI}_{\text{MAM}})$.

The three models are then compared, and their performance are evaluated through parameters such as Akaike criteria (AIC), pseudo *r*-squares and *p*-values.

3. Results

3.1. Pre-fire and fire season conditions

Two major wildfire events occurred in 2017: one in June, linked to an unprecedented heatwave, low humidity rates and unstable atmosphere (Sánchez-Benítez *et al* 2018), and one in October. Figure 2 shows that, in June, about 94% of BA was simultaneously burned and under hot and dry fuel conditions (HDB) while only 5% of BA was classified as hot (HB) or dry (DB) and just 1% was only burned and neither affected by hot or dry fuel conditions (B). This reveals a strong selectivity of fire for compound hot and dry fuel conditions since the overall area under hot/dry fuel conditions (HD) was much lower (42%) than for BA. Relatively to October, 96% of the

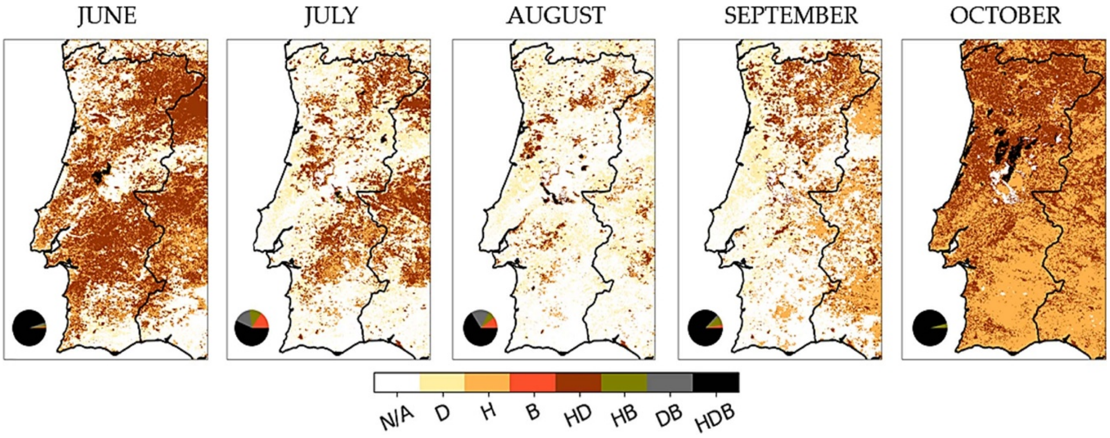

Figure 2. Classes of climatic conditions during the fire season of 2017: D—Dry; H—Hot; B—Burned; HD—Hot and Dry; HB—Hot and Burned; DB—Dry and Burned; HDB—Hot, Dry and Burned. The monthly pie charts represent the percentage of burned area which were affected by hot (HB), dry (DB), hot and dry (HDB), or none of these conditions (B).

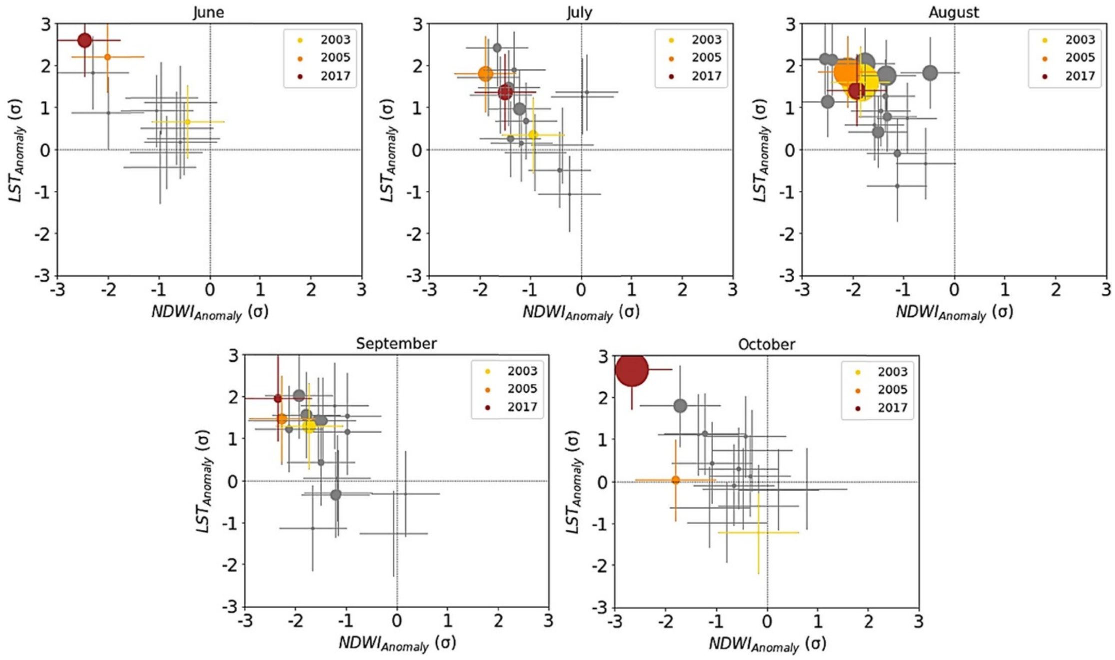

Figure 3. Spatial monthly mean values of LST_{ANOM} and $NDWI_{ANOM}$ over the burned areas of fire seasons between 2001 and 2019. The years of 2003, 2005 and 2017 are represented in different colors. Lines represent the monthly spatial standard deviation. Marker sizes are proportional to the extension of burned area in the correspondent month.

BA was classified as HDB whereas only 0.2% was just B and less than 4% of the BA was classified as hot (HB) or dry (DB). By contrast, 55% of the country was in hot conditions (H) and 41% under hot and dry fuel conditions (HD). In the other months, HDB pixels were found among 56%, 66% and 87% of total burned pixels in July, August and September, respectively, compared to 37%, 17%, and 25% of the overall area being classified as HD.

The summer of 2017, characterized by anomalous hot and dry fuel conditions over Portugal, stood out from the other fire seasons. Figure 3 shows that the spatial mean of LST_{ANOM} in monthly BA was always higher than 1σ between June and September, being about 3σ in June and in October, revealing the persistency and the amplification of hot conditions throughout summer. High LST_{ANOM} were accompanied by a permanent reduction of NDWI from June onwards, reaching values below -2σ in almost all months.

Besides 2017, strong anomalies were also detected in 2003, especially in August when the large fires mainly occurred, and in 2005, with a strong persistency of negative $NDWI_{ANOM}$ during all season (figure 3). However, the results show that the hot and dry fuel conditions of these fire seasons have frequently the same magnitude when compared with others years of 2001–2019 period which did not record extreme fire seasons, even when compared

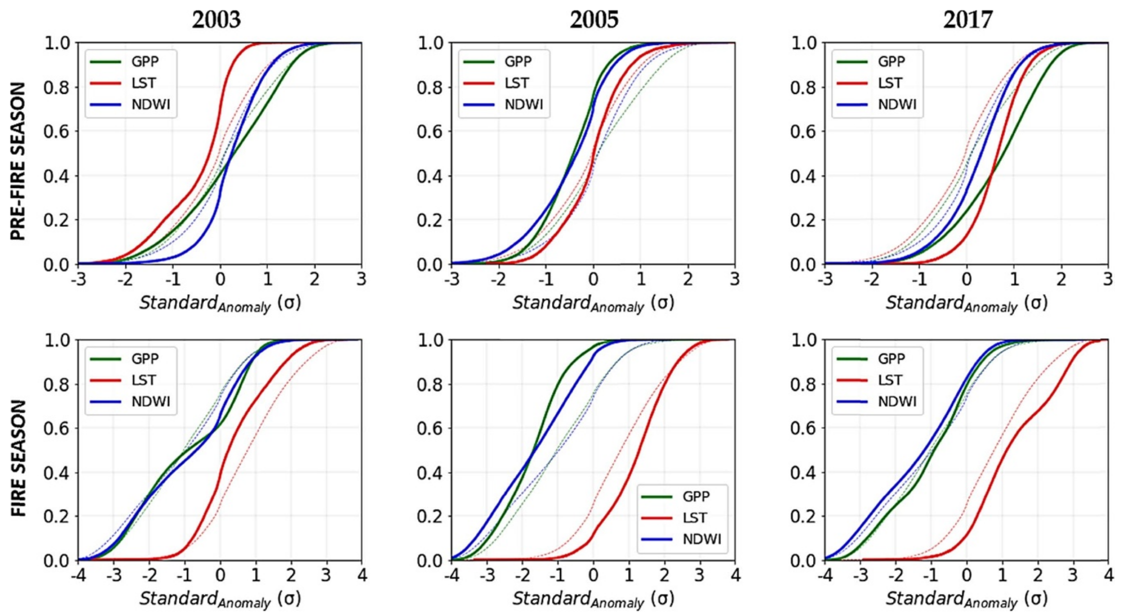

Figure 4. CDFs of GPP_{ANOM}, LST_{ANOM} and $NDWI_{ANOM}$ in pre-fire (MAM) (top panels) and fire season (JJASO) (bottom panels) over the fire season of 2003 (left panels), 2005 (central panels) and 2017 (right panels). Dashed lines represent, for each variable, the anomalies of respective burned areas of all fire seasons between 2001 and 2019.

with the 2017 one, that can be related with vegetation state and fuel accumulation.

The anomalous climatological and ecological conditions in 2017 can be observed in figure 4 (right bottom panel). During the fire season, about 35% of BA revealed $LST_{ANOM} > 2\sigma$ and $NDWI_{ANOM} < -2\sigma$ and, consequently, these stress conditions were mirrored on vegetation productivity, with about 50% of BA revealing $GPP_{ANOM} < -1\sigma$. When compared with the fire seasons of 2003 and 2005, which can also be considered extreme, there are significant differences. In 2003, only 5% of BA revealed $LST_{ANOM} > 2\sigma$ and 30% had $NDWI_{ANOM} < -2\sigma$ (left bottom panel) whereas in 2005, 20% of BA had $LST_{ANOM} > 2\sigma$ and about 35% revealed $NDWI_{ANOM} < -2\sigma$ (right central panel).

These fire season's conditions revealed, generally, stronger anomalies when compared with the other fire seasons between 2001 and 2019 (dashed lines), which, in association, might promote more extreme fire seasons.

The climatological and ecological conditions experienced in spring might had a high relevance on summer fires and strongly contributed to exacerbate the summer fire risk in 2017. According to figure S3, in 2017, wet conditions were registered in March and April ($NDWI_{ANOM} > 1\sigma$) combined with warm anomalies, especially in April (LST_{ANOM} between 1 and 2σ). Warm and wet conditions are favourable to vegetation in this period, which is expressed on higher productivity than average, as shown in figure 4 (top right panels). In fact, the CDF of GPP (green curve) in spring months reveals a shift towards higher anomalies, with 80% of 2017 BA showing $GPP_{ANOM} > 0$, indicating a high activity of vegetation in pre-fire season. This situation was possibly promoted by higher temperatures (red curve) and water availability on vegetation (blue curve), both with positive anomalies. In comparison with the other fire seasons, in 2003, about 60% showed positive GPP_{ANOM} (top left panel) and in 2005, that probability decreased to 20% (top central panel) and remained predominantly below the normal values during the entire pre-fire season.

These different patterns both in spring and summer in 2017, compared with the other two fire seasons, were likely a strong factor influencing such a catastrophic fire season. A strong shift is verified on GPP_{ANOM} and $NDWI_{ANOM}$ towards negative values from pre-fire to fire season, which means that a rapid depletion of water on vegetation led to disturbances on productivity and promoted an increment on fire hazard during the fire season. Therefore, we explore the different role of each climatic and ecological variable on wildfires.

3.2. Influence of different variables on BA

As discussed previously, temperature and water availability on ecosystems had a strong influence on vegetation productivity, both in spring and fire season. In this context, logistic regression models were used to assess and analyse the role of each variable on BA. The first model adjusts the BA exclusively with LST_{JJASO} and $NDWI_{JJASO}$. The fitted coefficients, expressed on table 1, reveal a stronger influence of water availability on vegetation in 2017 ($NDWI_{JJASO}$: -0.90 against LST_{JJASO}: 0.69), indicating that summer water availability depletion had a greater influence on BA. The same pattern was verified during 2005, with

Table 1. Logistic regression that fits BA with LST_{JJASO} and $NDWI_{JJASO}$ for the three fire seasons 2003, 2005 and 2017. The coefficients of each variable are determined, as well as the interception and statistical parameters AIC and pseudo-r^2.

$BA = f(LST_{JJASO}, NDWI_{JJASO})$

					Statistical parameters	
Years	Model	Interception	LST	NDWI	AIC	Pseudo r^2
2003	LST_{JJASO}	−4.03	2.28	−1.28	146 905	0.305
2005	$NDWI_{JJASO}$	−5.59	0.48	−0.84	157 302	0.048
2017		−5.07	0.69	−0.90	216 542	0.088

Table 2. Same as table 1 but for logistic regression that fits BA with GPP_{MAM}, LST_{JJASO} and $NDWI_{JJASO}$.

$BA = f(GPP_{MAM}, LST_{JJASO}, NDWI_{JJASO})$

						Statistical parameters	
Years	Model	Interception	GPP	LST	NDWI	AIC	Pseudo r^2
2003	GPP_{MAM}	−4.24	0.81	2.21	−1.46	143 748	0.320
2005	LST_{JJASO}	−5.08	2.08	0.67	−1.45	131 395	0.205
2017	$NDWI_{JJASO}$	−5.70	1.01	0.85	−0.83	208 132	0.123

$NDWI_{JJASO}$: −0.84 (against LST_{JJASO}: 0.48), while, in 2003, LST_{JJASO} revealed a more influent role on BA than $NDWI_{JJASO}$ (coefficients of 2.28 and −1.28, respectively). All values were statistically significant (p-values < 0.001).

The next step consisted of the analysis of whether the addition of vegetation productivity conditions in spring yields a better performance, compared with the first model. According to table 2, the statistical metrics suggest an improvement on the estimation of BA drivers, with lower AIC values and higher pseudo r-squares within the three fire seasons.

The introduction of spring vegetation productivity information allows to a more accurate interpretation of the main drivers of BA. In fact, the GPP_{MAM} in 2017 revealed to be the most influent driver on BA, as the fitted coefficients were GPP_{MAM}: 1.01; LST_{JJASO}: 0.85; $NDWI_{JJASO}$: −0.83. The same pattern was observed for BA in 2005, where the coefficient of GPP_{MAM} stood out from the other variables (2.08 against LST_{JJASO}: 0.67; $NDWI_{JJASO}$: −1.45). Moreover, the addition of vegetation productivity parameter highly improved the performance of the model in 2005, as pseudo r-squared raised from very low values (0.048) on the first model to 0.208 and AIC substantially decreased. In this model, all coefficients were statistically significant (p-values < 0.001). In 2003, despite the slight improvement on model's fit compared with the first one, the LST_{JJASO} remained the most influent driver on BA.

The model that fits the BA with both climatological and ecological conditions, but in spring, showed a lower performance compared with the other two models (table S2). Nevertheless, in 2017, the positive signal of coefficients in GPP_{MAM} and $NDWI_{MAM}$, and the negative signal of LST_{MAM}, is coherent with the increasing probability of BA in summer, as the conjunction of water availability and temperatures favourable to higher vegetation productivity in growing season can potentiate the accumulation of biomass in pre-fire season and promote an increment of fire risk in summer.

4. Discussion

In this work, we focus our analysis on the extreme fire season of 2017 in Portugal. Hot and dry fuel conditions during the whole fire season were suggested to be the main cause of the widespread large fires (Turco *et al* 2019). In this context, using remotely sensed data of land surface temperature (LST), water availability on vegetation (NDWI) and gross vegetation productivity (GPP), we were able to characterize the exceptional characteristics occurred during the pre-fire season and in fire season, and therefore assess how the BA were strongly modulated by climatological and ecological conditions.

Summer conditions had a preponderant role on large fires propagation in 2017. Our results show a stronger persistency of simultaneous hot and dry fuel conditions over BA, especially in June and October, which indicate a selectivity of fires for areas under hot conditions and vegetation water stress, i.e. dry fuel. Moreover, when compared with 2003 and 2005, the 2017 fire season reveals a higher frequency of out-of-range hot and dry fuel conditions on mainland country, exacerbating the favourable conditions to unprecedent wildfires. We find a synergy between the three types of extreme events over several areas, which is a cause of concern, as the likelihood of frequent and intense co-occurrence of extreme events like droughts and heatwaves is projected to increase in the future in Mediterranean region (Zscheischler *et al* 2018, Zhou *et al* 2019).

The ecosystems of this region are adapted to water-limited conditions and hot summers

(Caldeira *et al* 2015, Martínez-de la Torre and Miguez-Macho 2019). However, in 2017, the rapid vegetation water depletion in late spring/early summer, which persisted and intensified until October, resulted in increased fuel dryness and thus enhanced the propensity to burn. Combined with pre-conditioning effects of the warm and relatively wet spring, that led to increased productivity before summer, all contributed to an anomalous fire season. Similar patterns were observed over Greece in 2007 (Gouveia *et al* 2016), when summer heatwaves and dry fuel conditions promoted large fires in the region. Furthermore, wide similarities were found with 2003 case. Our results showed not only the fuel accumulation in spring season and early summer, derived from positive anomalies of GPP, but also the strong influence that LST had on BA during this year, led to the second strongest fire season in Portugal and agreeing with the results of Trigo *et al* (2006) and Gouveia *et al* (2012).

The period between spring and early summer has a high influence on the accumulation of biomass and, thereby, on the potential for wildfire propagation (Pausas and Paula 2012). Our analysis using logistic regression models allowed to understand how vegetation productivity in pre-fire season was an important factor on fire occurrence in summer. Vegetation productivity in the Mediterranean ecosystems is strongly correlated with water availability in pre-fire season but weakly correlated in summer season, being the conjunction of these variables, a causal effect to fuel build up and fire risk increase in summer (Xystrakis *et al* 2014, Bergonse *et al* 2021). Consequently, two different regimes were distinguished by analysing the three fire seasons, in terms of productivity levels and potential occurrence of fires, namely: (a) pre-conditioning effects of vegetation activity and fuel accumulation before the two most destructive fire seasons (2003 and 2017); (b) higher propensity for wildfires in areas with low vegetation productivity, as a consequence of persistent drought stress (2005). This later situation highly resulted from the severe drought of 2004/2005 in Iberian Peninsula (García-Herrera *et al* 2007) which extended up to 6–8 months on the southwestern and western sectors of region (Gouveia *et al* 2009, Ermitão *et al* 2021). Furthermore, our results agree with Xystrakis *et al* (2014) and Bergonse *et al* (2021) observations, regarding the spring precipitation for fuel build up, or summer dry conditions for fuel dryness, can be both causal effects of fires.

Our study assesses both pre-fire and fire season climatological and ecological conditions that, in association, originated an exceptional fire season. Nevertheless, some aspects were not addressed here, which have high influence on fires propagation and intensity, and might be smoothed out in this analysis. We found low values of pseudo-r^2, which may be associated to some of those aspects, namely the influence that meteorological conditions, such as daily temperatures, relative humidity and wind speed, have during the fire events (Rodrigues *et al* 2020, Vieira *et al* 2020). Moreover, other factors, such as topography, LC, land use changes and management policies were not addressed and those have shown to modulate wildfires propagation and influencing their magnitude, as verified in wildfire occurrence in Australian and Spanish forest fires (Adame *et al* 2020, Lindenmayer *et al* 2020).

5. Conclusions

Projections show a high increase on BAs extension by the end of the century in Mediterranean region (Amatulli *et al* 2013) associated with more frequent hot and dry fuel situations as those experienced in Portugal in 2017.

Here, we evaluated the role of vegetation activity and dryness in spring and summer in explaining the three most destructive fire seasons in Portugal, with a focus on 2017. We found two different regimes, one dominated by pre-conditioning effects of vegetation activity in spring and early summer, and another with a predominance of fuel dryness in amplifying fire risk in summer.

Fire season conditions had a preponderant influence on 2017 wildfires propagation and intensity, especially in June and October, when major fire events took place. Our findings stress the role that the simultaneous occurrence of various extreme events, which is in this case, hot and dry events, exacerbated the fire hazard over the region.

The important role of vegetation activity preceding the fire season indicates that fuel management could be an effective way to mitigate future BAs, even if in part. Such practices are common in other fire prone regions but require the development of necessary infrastructure in the future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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All authors participated in the conceptual design of the study and contributed to the interpretation and analysis of the results and the redaction of the manuscript. T E made the calculations, figures and tables and wrote the manuscript. Each of the co-authors

contributed to the formal analysis and methodology of the work, performed a thorough revision of the manuscript, provided useful advice on the intellectual content and improved the English language. All authors read and agreed to the published version of the manuscript.

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