Spatiotemporal trends in burn severity in the last two decades for mainland Portugal

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Abstract

Wildfires can pose severe threats to human lives and assets as well as to biodiversity on a global scale. Due to climate, land-use changes, and often inadequate forest management, wildfire regimes are also in transition, causing modifications in these disturbance events' spatial distribution, timing, size, frequency, and severity. In particular, increasing fire severity causes slower post-fire recovery times and a depletion in the resistance and resilience capacities which potentially trigger regime shifts in the state of ecosystems.

Satellite remote sensing (SRS) Earth Observations (EO) allow us to characterize the ecological impacts of wildfires and assess spatiotemporal trends in fire severity. The SeverusPT project is currently pursuing the objective of harnessing SRS/EO time series to characterize wildfire severity and assess its impacts on ecosystems. Our primary objectives of this exploratory research paper are two-fold: (i) assess national and regional spatiotemporal trends in fire severity and burnt area, and (ii) evaluate if fire severity regionally scales up with the total burnt area.

Satellite image time series (SITS) from Terra/MODIS were obtained to calculate fire severity through the Normalized Burn Ratio (NBR) and the difference between pre- and post-fire (ΔNBR). Trend analyses were employed to quantify fire severity and burned area spatiotemporal patterns. Linear regression assessed the association between total burnt area by year/region (predictor) and fire severity (response).

Preliminary results show that at a national level, from 2001 until ca. 2008 - 2009 there was a general decrease in fire severity, followed by a reversal of this trend. This turning point has led to a general increase, with new severity highs formed in 2017 and 2020. We also found wide variation in fire severity at the regional level (NUTS-III), and trend analysis displayed that most regions increased both in burned area and severity.

Linear regression showed that burned area and fire severity are correlated despite this association being highly structured at the regional level, forming a continuous spectrum from highly area-severity coupled regions (e.g., AM Porto, Médio Tejo, Viseu, Coimbra, Alto-Minho) to less coupled ones (e.g., Cávado, Trás-os-Montes, Alentejo). These results may support that the increasing amount and size of burnt area will scale up into higher fire severity for specific regions.

These preliminary results from the SeverusPT project show that MODIS image time series allow assessing the spatial variation and the temporal trends of fire severity in a standardized and synoptic fashion. Future research using Landsat time series will aim to further assess these trends and profit from the data archive and the increased spatial resolution of this satellite mission. Mapping fire severity, its spatiotemporal variation and addressing its environmental drivers are now more crucial than ever to understand its dynamics and support fire management and prevention.

1. Introduction

Fire can relevantly introduce (socio-)ecological disturbances worldwide, impacting ecosystem composition, structure, functioning, and the provision of ecosystem services to humanity (Bowman et al., 2009). Modification of fire regimes due to global environmental changes is thus at the forefront of social concerns motivating the improvement of policy and planning instruments regarding fire risk management and land tenure/use, natural resource management, and territorial governance.

Despite the vast investments in fire suppression, extreme fire events have increased across Mediterranean Europe. These extreme events, exacerbated by global climate change and fuel accumulation, often override the capacity of fire-suppression systems, putting human lives and livelihoods at risk. Assessing and predicting the effects of those events on ecosystems (i.e., fire severity), especially under a changing climate, is paramount for adequate fire prevention and fighting.

Surprisingly, there is a significant gap of publicly available, standardized and validated datasets on fire severity. Overcoming this gap is the central goal of SeverusPT, which is currently developing a framework for assessing, mapping and predicting fire severity based on satellite indicators of ecosystem functioning. A combination of metrics derived from satellite multi-spectral images (e.g. the difference Normalized Burn Ratio; ΔNBR), with data collected in-field (e.g. through the Composite Burn Index; CBI) is being exploited to assess fire severity (e.g. Cardil et al., 2019), conveying post-fire measures of environmental and ecological impacts due to fire (e.g., Koutsias et al., 2013; Tedim et al., 2017).

Our primary objectives with this exploratory research are two-fold: (i) assess national and regional spatiotemporal trends in fire severity and burned area, and (ii) evaluate if fire severity regionally scales up with total burnt area (i.e., a putative and here tentatively called "fire area – severity coupling" hypothesis).

2. Methods

2.1. Study area

This study area comprises mainland Portugal covering an area of approximately 89,100 Km^2, considered one of the countries of southern Europe with a greater incidence of forest fires in the last decades. Elevation ranges from 0 to 1993 meters, with the mountain areas occurring mainly in the north. The climate ranges from temperate Atlantic in the northwest to dry Mediterranean in southern regions. The average annual temperature varies from 4 °C in the northern mountainous interior to 18 °C in the south.

2.2. Time series data and statistical analyses

Satellite image time series (SITS) from Terra/MODIS product MOD13Q1 (version-006) containing vegetation indices at 16-day/250m were obtained to calculate fire severity through the Normalized Burn Ratio (NBR) index. NBR consists of the normalized difference between the near-infrared band #2 (NIR, 858 nm) and the shortwave-infrared band #7 (SWIR, 2130 nm), as:

$NBR = (NIR_{b2} - SWIR_{b7})/(NIR_{b2} + SWIR_{b7})$ (Eqn. 1).

A high NBR value typically characterizes normal or "healthy" vegetation, whereas low values indicate bare ground and/or recently burnt areas. Delta NBR, calculated as the difference between the pre-fire and the post-fire NBR, was used as an estimate of fire severity as:

$\Delta\mathrm{NBR} = \mathrm{NBR}_{pre\_fire} - NBR_{post\_fire}$ (Eqn.2).

A higher value of ΔNBR generally indicates more severe damage, whereas negative values may indicate less severely affected areas or even short-term recovery following a fire. To calculate a standardized annual time-series of $\Delta\mathrm{NBR}$ between 2001 and 2020 for mainland Portugal, we considered the characteristic phenology of fire mostly concentrated around summer/early-fall months (Marcos et al., 2019) and defined the post-fire period from September-November and the pre-fire between March-May. Within the pre- and post-fire periods, all available NBR images were averaged through the median hence applying the following formula:

$\Delta\mathrm{NBR} = \mathrm{median}(\mathrm{NBR}_{\{Mar-May\}}) - \mathrm{median}(NBR_{\{Sep-Nov\}})$ (Eqn.3).

As a non-parametric/rank-based measure, the median is less affected by cloud cover and noise in the data. All Eqn.1-3 calculations were performed using Google's Earth Engine planetary-scale geospatial analysis platform (Gorelick et al., 2017). Based on the annual ΔNBR time series, we extracted the values only for fire perimeters (at annual time steps) identified in the National Burnt Area Database (NBAD) for mainland Portugal from 2001to 2020 (ICNF, 2022). NBAD was also employed to calculate the total burnt area and the distribution of fire perimeters at the regional NUTS-III inter-municipal level using R statistical software and the *terra* package (Hijmans, 2022). National and regional-level statistics of fire severity based on quantiles were calculated. Annual time-series plots (employing loess/moving-average smoother) were employed to assess spatiotemporal patterns of severity. Linear regression was employed to assess the relation (i.e., the degree of coupling) between total burnt area by year/region (predictor) and fire severity (response). The coefficient-of-determination (R^2) and the F-statistic p-value were estimated to convey the strength of this association and its statistical significance.

3. Results and Discussion

3.1. General trends of fire severity in the last two decades (2001 – 2020) in mainland Portugal

These preliminary results from the SeverusPT project show that MODIS image time series allow assessing the spatial variation and the temporal trends of fire severity in a standardized and synoptic fashion. Satellite data is particularly useful to assess micro- to mesoscale variation in severity (Fig.1–a) and identify slightly scorched or unburnt "islands" which hold particular relevance for post-fire biological/ecological recovery (e.g., Santos et al., 2022) across different time-frames (Torres et al., 2018) and ecosystem dimensions (Marcos et al., 2021). Such variations in fire severity can be caused by a multitude of factors such as the spatial distribution, type, state, shape, and vertical structure of fuels, as well as microclimate and weather conditions, topography, geomorphology and fire suppression efforts. These factors combine to shape the fine-scale and anisotropic variations, with fire edges typically exhibiting lower severity (Fig.1–a). SITS also excel in characterizing temporal trajectories in severity with widely different profiles from triangular patterns (potentially showing cyclical decreases and increases in biomass triggered by highly frequent fires with, respectively, less and more severity, Fig.1–b). In contrast, we also found areas with increasing fire severity where, potentially, biomass decreases caused by fire are unmatched by fast recovery times and progressive post-fire biomass accumulation coupled with fire-prone weather conditions in subsequent events.

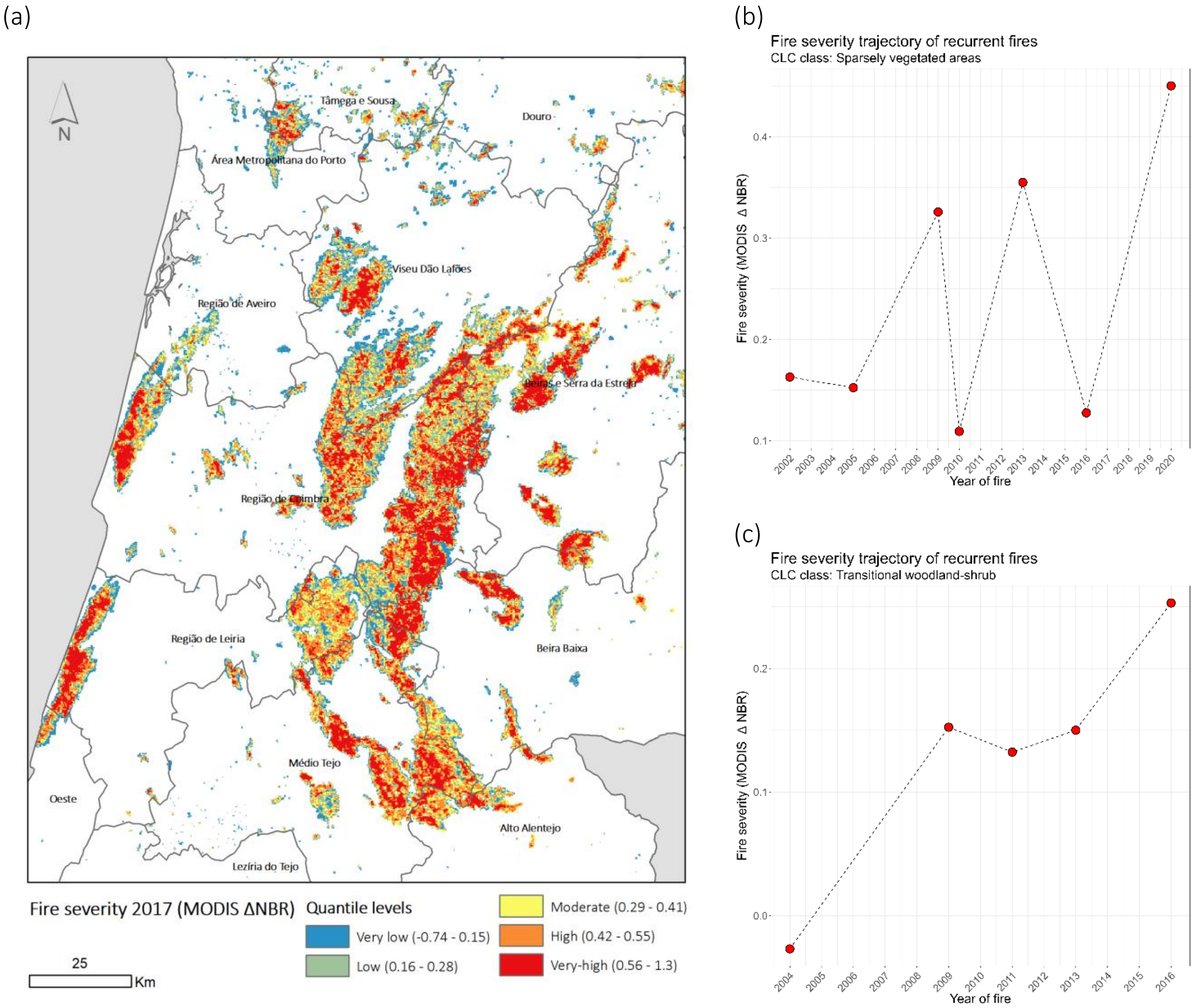


Figure 1 – (a) MODIS ΔNBR image shows the spatial variation of fire severity within and between fire perimeters of 2017. Each severity level is based on the 20% quantiles of the annual distribution. (b) and (c) comprise two illustrative severity trajectories for recurrent fires in a sparsely vegetated area following a triangular pattern (b) and transitional woodland-shrubland (c) with a monotonic linear increase trend in severity. Each point in these plots shows the severity of each fire event for a given area.

Preliminary results also show that, at a national level from 2001 until ca. 2008 - 2009 there was a general decrease in fire severity, followed by a reversal of this trend. This turning point has led to a general increase with new severity highs formed in 2017 and 2020 (Fig.2). This trend reversal also led us to separately consider this nested period of 2008 – 2020 for subsequent analyses.

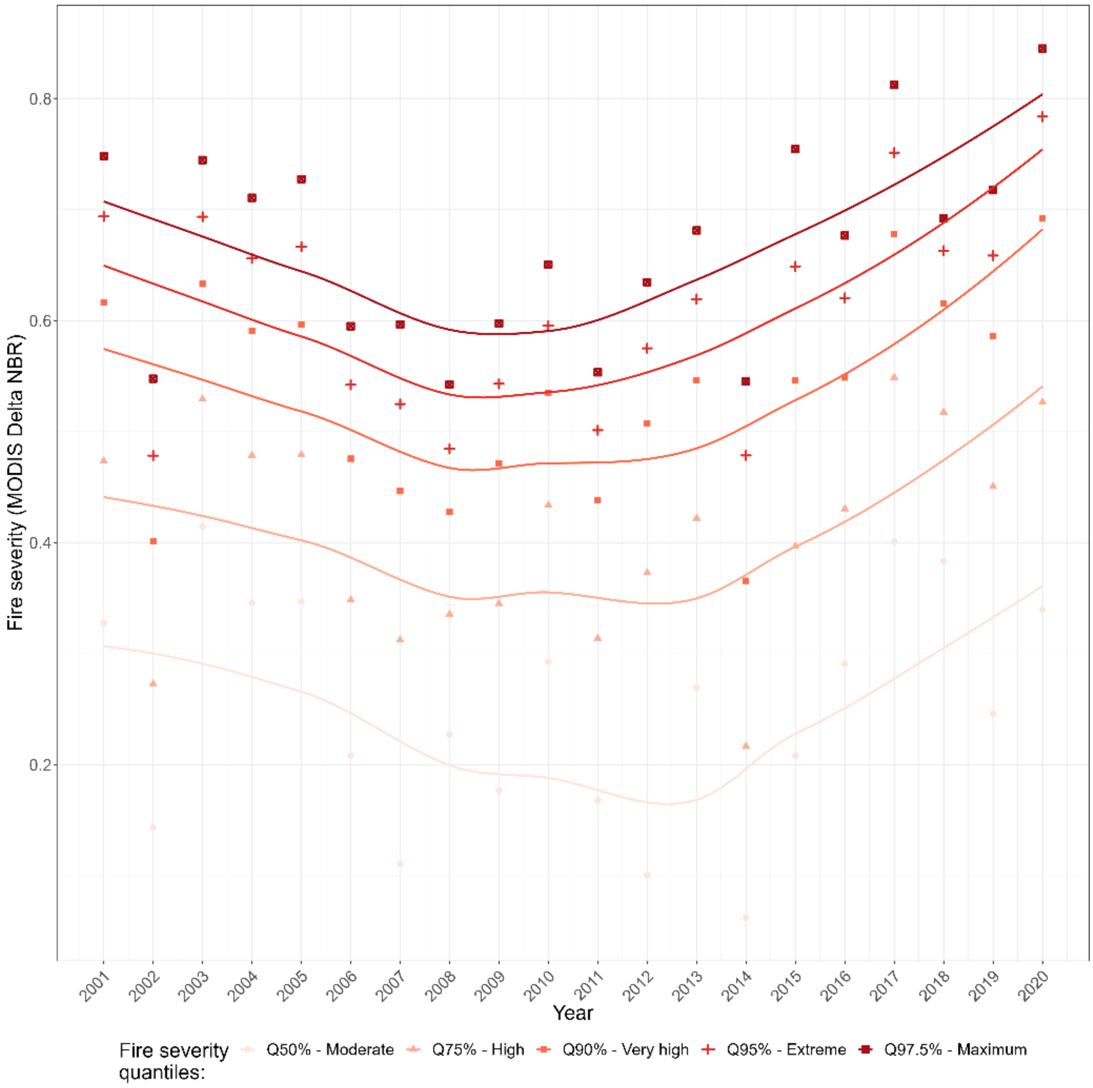


Figure 2 – Fire severity trends for mainland Portugal between 2001 and 2020 across different severity levels based on distribution quantiles (Q50% - moderate, Q75% - High, Q90% - very-high, Q95% - extreme and Q97.5% - maximum).

Moreover, preliminary results also show that there is wide variation in fire severity at the regional level (considering NUTS-III inter-municipal units; Fig.3) with the Region of Aveiro, Ave, Área Metropolitana do Porto, Médio Tejo, Terras de Trás-os-Montes and Alto-Minho recording the most significant increases since 2008 from average (50% quantile) to very high severity fires (97.5% quantile).

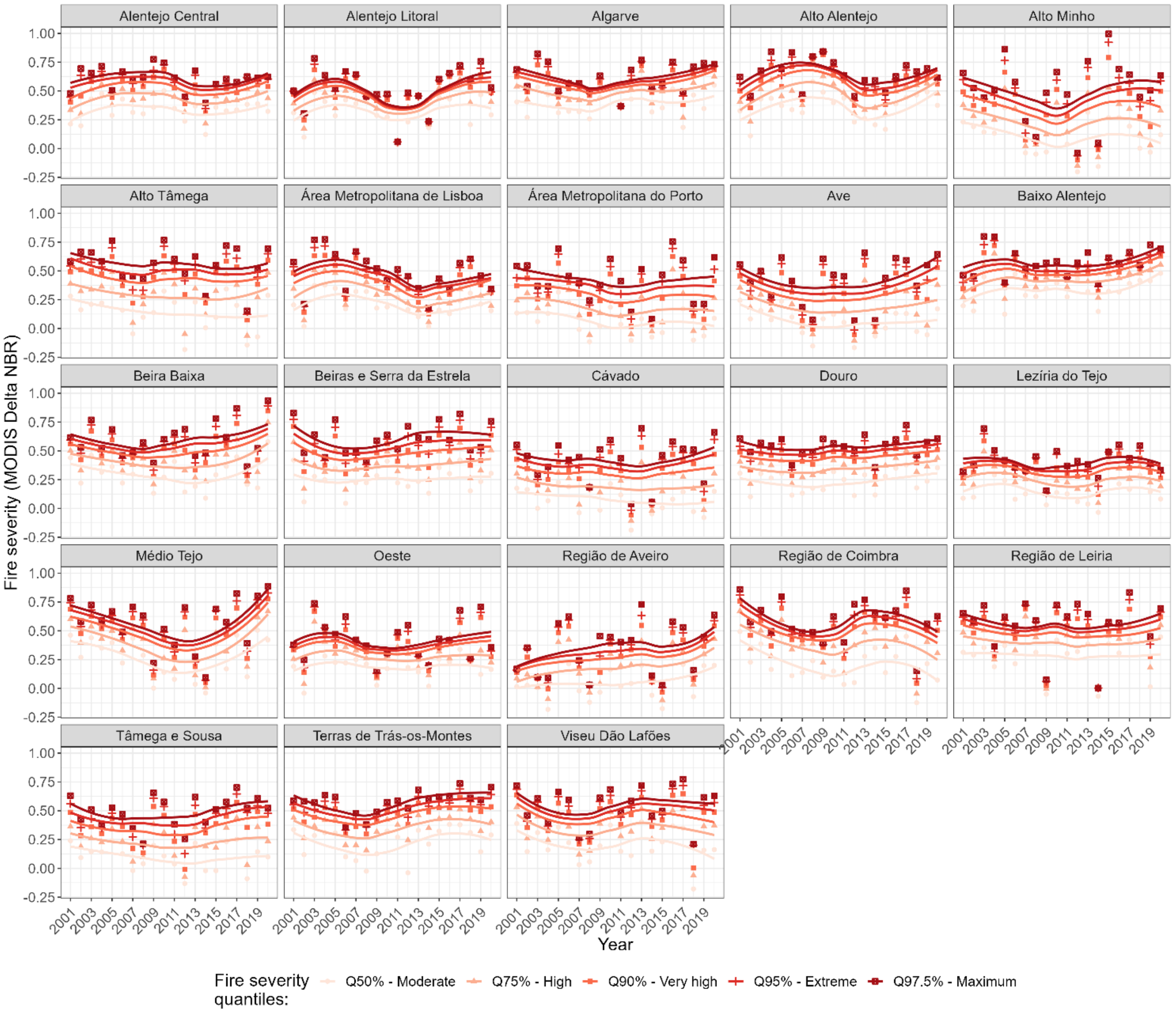
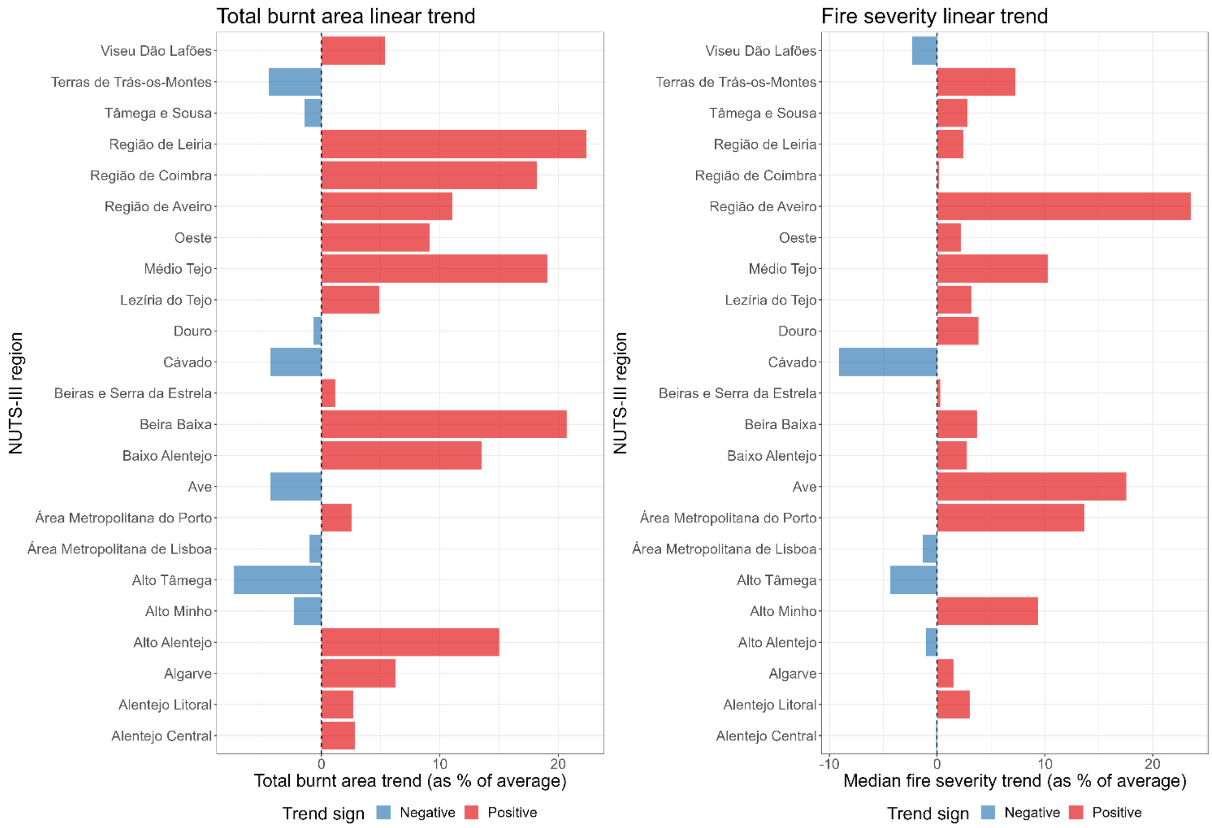


Figure 3 – Fire severity trends for mainland Portugal intermunicipal regions (NUTS-III) between 2001 and 2020 across different severity levels based on distribution quantiles (Q50% - moderate, Q75% - High, Q90% - very-high, Q95% - extreme and Q97.5% - maximum).

When comparing the temporal trends of burnt area *vs* median fire severity across NUTS-III regions (for 2008-2021; following the trend reversal period), preliminary results show that the most frequent class is the one combining the increase of both burnt area and severity (Fig. 4). These regions are primarily located in the country's centre portion (from AM Porto to Lezíria do Tejo) and south (Alentejo Litoral/Sul) portions. Slightly more complex combinations occur in the north with decreased trends in burnt area and severity for Cávado and Alto Tâmega regions. In contrast, a combination of burnt area decrease and severity increase is found for Alto Minho, Ave, Tâmega-Sousa, Douro and Trás-os-Montes regions. We found few regions with burnt area increase and severity increase trends, including Viseu-Dão-Lafões, and Alto/Central Alentejo.

(a)



(b)

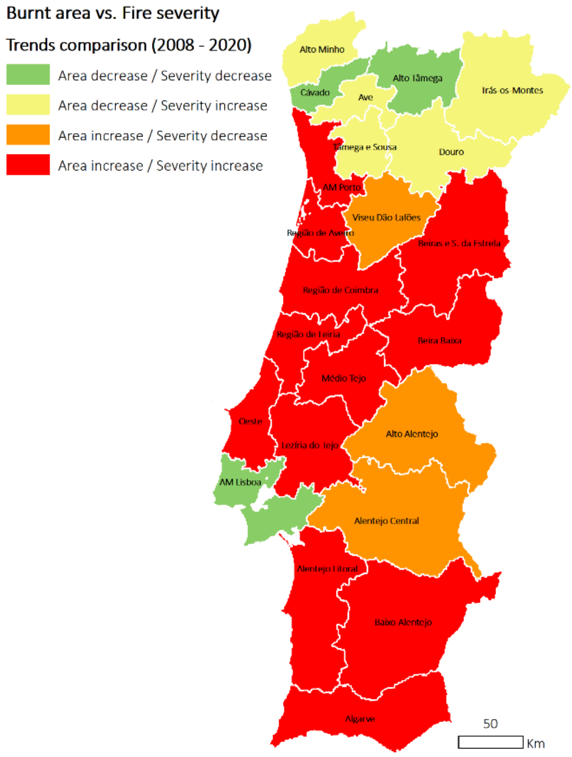


Figure 4 – Comparison of temporal trends of total burnt area *vs* fire severity across inter-municipal regions of mainland Portugal (NUTS-III), considering the period 2008-2021

(a) Linear trend analysis was employed and expressed as the percentage of average change. The trend sign is positive, i.e., increasing impact across time in the burnt area and/or fire severity, and negative if otherwise.

(b) Map depicting the combination of trends for the burnt area and fire severity for different NUTS-III regions.

Linear regression analyses allowed us to evaluate that burnt area and fire severity are indeed correlated. However, the nature of this relationship is highly structured at the regional level, forming a continuous spectrum of variation from highly area-severity coupled regions – with a higher coefficient of determination (R^2) values (e.g., AM Porto, Médio Tejo, Viseu, Coimbra, Alto-Minho; Fig.5) – to uncoupled regions (e.g., Cávado, Alentejo) with lower regression R^2's.

These results may support the (tentatively called) "fire area – severity coupling" hypothesis, in which, for specific regions (Fig.6), the increasing amount and size of burnt area will scale up into higher fire severity.

Overall, "coupled" regions are located in the northern and central portions of the country (exceptions to Cávado, and Trás-os-Montes; Fig.6) and the southern-most region of Algarve. For these regions, the observed fire area-severity scale-up will potentially cause a higher depletion of ecosystems functioning capacities and resilience and trigger longer recovery times (Marcos et al., 2021; Torres et al., 2018).

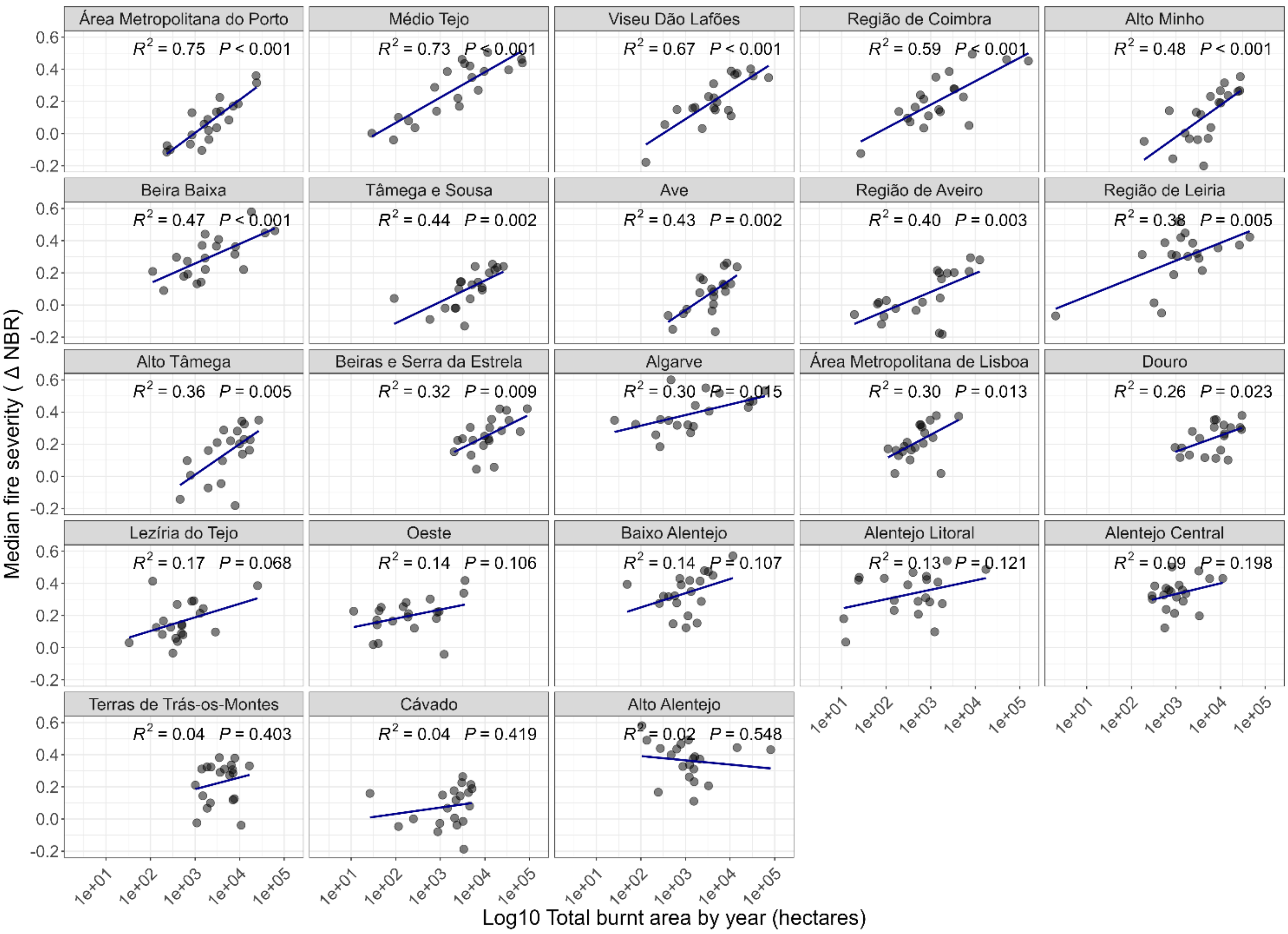


Figure 5 – Linear regression plots between total burnt area per year (2001-2020) and median fire severity (MODIS ΔNBR). Plots are shown for are all mainland NUTS-III regions and displayed by decreasing R^2 value.

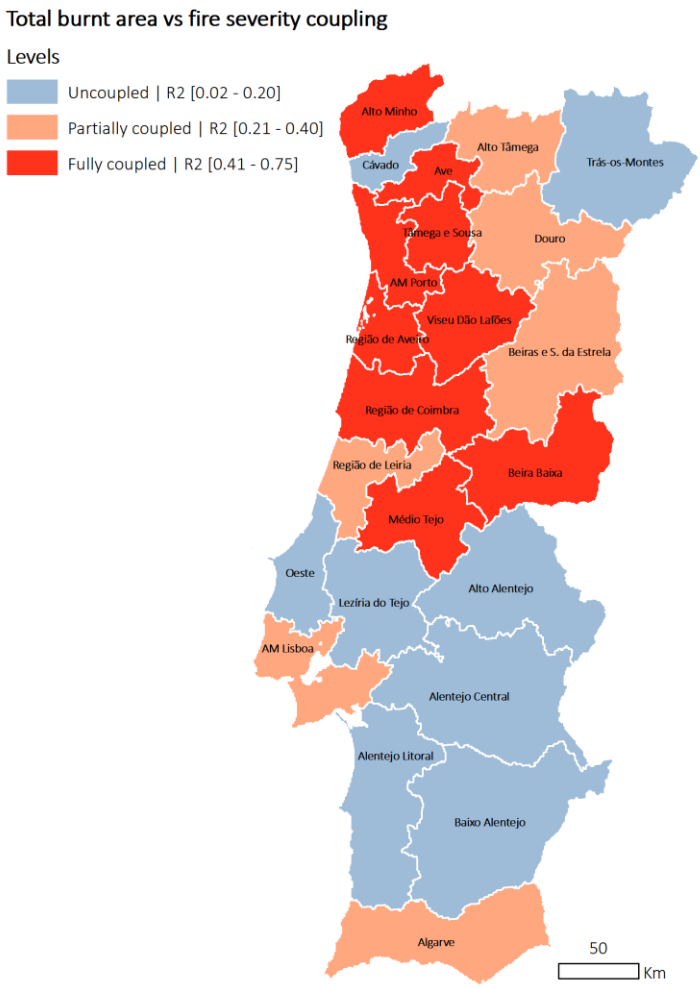


Figure 6 – Coupling between total burnt area (2001-2020) and fire severity assessed through MODIS ΔNBR.

4. Final remarks and future work

Mapping fire severity, its spatiotemporal variation and addressing its environmental drivers are now more crucial than ever to understand its dynamics and support fire management and prevention. This exploratory research shows preliminary results from the SeverusPT project addressing these goals and exploring trends and the regionally varied scaling between burned area and fire severity.

Such phenomena must be adequately addressed with different strategies across distinct regions to contain and prevent further damage from wildfires to ecosystems. Future work will examine and attempt to model the drivers of the *"fire area – severity coupling" hypothesis* and exploit finer-scale satellite image time series and improved algorithms to expand current results. In particular, Landsat time series will aim to further assess these trends and profit from the long historical data archive and the increased spatial resolution of this satellite mission.

severuspt

SeverusPT - A web-based data product and service for fire severity assessment and prediction in mainland Portugal (PCIF/RPG/0170/2019)

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