



# Unravelling the effect of climate change on fire danger and fire behaviour in the Transboundary Biosphere Reserve of Meseta Ibérica (Portugal-Spain)

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Received: 7 December 2021 / Accepted: 23 June 2022 / Published online: 11 July 2022  
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## Abstract

The impacts of wildfires are increasing in the Mediterranean Basin due to more extreme fire seasons featuring increasingly fast and high-intensity fires, which often overwhelm the response capacity of fire suppression forces. Fire behaviour is expected to become even more severe due to climate change. In this study, we quantified the effect of climate change on fire danger (components of the Canadian FWI System) and wildfire behaviour characteristics (rate of spread and fireline intensity) for the four major Mediterranean forest ecosystems located in the Transboundary Biosphere Reserve of Meseta Ibérica under RCP4.5 and RCP8.5 scenarios. The effect of climate change on wildfire behaviour was supplemented by taking into account net primary production (NPP), hence fuel load. Our results show that the meteorological fire season will start earlier and end later, leading to a significant increase in the number of days with weather conditions that promote high-intensity wildfires, for both climate scenarios. Fuel type shapes how wildfire spread characteristics will unfold. The most relevant changes are projected to occur in pine forests, where a wildfire with median fireline intensity will offer serious resistance to control from spring to autumn. The severity of fire behaviour in shrublands also increases substantially when considering climate change, with high-intensity wildfires potentially occurring in any time of the year. Both deciduous and evergreen broadleaf forests are predicted to typically generate wildfires with low enough intensity to remain within suppression capability. By adjusting fuel load to future climate conditions, our results highlight that fireline intensity in deciduous and evergreen broadleaf forests may not increase during summer, and can even be significantly reduced in shrublands. This study suggests that improved fire planning and management of wildfire-prone landscapes will counteract the effect of climate change on fire behaviour and impacts.

**Keywords** Forest fire · Fuel hazard · Fire suppression · Climate change · Landscape planning

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# 1 Introduction

The occurrence of wildfires is greatly dependent on weather and climate conditions. Particularly, high temperatures, moderate annual precipitation and extended periods of drought are globally associated with the greatest wildfire burned areas (Aldersley et al. 2011). The latest Intergovernmental Panel on Climate Change (IPCC) report suggests that weather conditions driving wildfires have become more frequent over the last decades in many regions of the world, including southern Europe (IPCC 2021). As a result, wildfires at the high end of the fire weather and fire behaviour range, which pose extraordinary challenges to firefighting regardless of the available resources (Fernandes et al. 2016), are increasing in size and/or frequency (Williams et al. 2019; Moreira et al. 2020; Abram et al. 2021). Recently, wildfires have had drastic consequences for human lives and livelihoods and ecosystems across the planet, from Europe (San-Miguel-Ayanz et al. 2020) and Russia (Ponomarev et al. 2015), to Australia (Nolan et al. 2020) and North (Brown 2020; Mass and Ovens 2019) and South America (de la Barrera et al. 2018; Lizundia-Loiola et al. 2020), which is also reflected in a major rise in wildfire-related fatalities throughout Southern Europe from the late 1970s onwards (Molina-Terrén et al. 2019).

Climate and weather conditions that promote large wildfires are common in Mediterranean Europe. The Mediterranean region is affected by recurring wildfires and, on average, about half-million hectares burn every year (San-Miguel-Ayanz et al. 2019). Such extent of burned area results from the combination of fire-prone weather conditions, ongoing rural abandonment and depopulation, which decrease land management practices that reduce fuel biomass (such as farming, grazing and forest management). This in turn leads to an expansion of forest and shrubland and consequently increase in landscape homogeneity, fuel accumulation and connectivity, i.e. potentially higher fire intensity (Pausas and Fernández-Muñoz 2012; Fernandes et al. 2014; Viedma et al. 2015; Moreira et al. 2020). Together, both factors, plus the expansion of wildland-urban interfaces (due to urban expansion to wildland areas and wildland encroachment), originated a complex and challenging scenario for wildfire management (Lahaye et al. 2018; Moreira et al. 2020).

The Mediterranean Basin is a hot spot of climate change (de Sherbinin 2014). Regional climate change projections highlight warmer and drier climates throughout the region, which will significantly increase future fire danger, especially in late spring and early autumn (Calheiros et al. 2021). This is expected to lead to changes in fire regimes, with higher fire danger, and a longer and more severe fire season (Pereira et al. 2002; Turco et al. 2014; Ruffault et al. 2020; Calheiros et al. 2021), even if the Paris agreement efforts to limit the temperature increase to 1.5 °C are successful (Turco et al. 2018). Such harsh conditions may decrease the effectiveness and opportunities for wildfire suppression (Mitsopoulos et al. 2016), pushing local authorities far beyond their response capacities (Castellnou et al. 2019). Nonetheless, climate-induced changes in fire behaviour might be counteracted by lower fuel load because of decreased plant productivity (Dupuy et al. 2020).

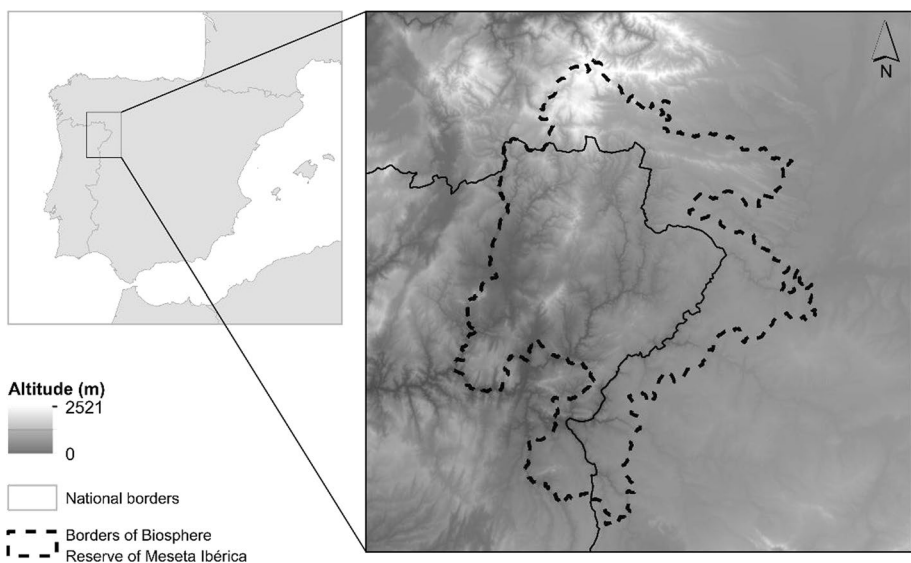
Most fire regime components, as well as the impacts of individual events, are a manifestation of fire behaviour characteristics, e.g. rate of spread (ROS) and fireline intensity (FLI), as driven by the fire environment, i.e. the combination of fuel, weather and terrain influences. If climate change is expected to modify fire danger, then it will influence fire behaviour. However, despite the great focus of research on fire danger in southern Europe under climate change (Dupuy et al. 2020), including its effect on the burned area (a direct outcome of fire behaviour characteristics), very few studies analysed climate change effects on wildfire behaviour, which is acknowledged to be a more important consequence of

climate change than simply total burned area (Kolden 2020; Moreira et al. 2020). Moreover, these applications focus more on the spatiality of fire behaviour change than on temporal change. This means that a single set of meteorological conditions is used to represent a future fire season, often for a period of 30 years (e.g. Kalabokidis et al. 2015; Lozano et al. 2017). To our knowledge, only a couple of studies (Matthews et al. 2012; Wotton et al. 2017) assessed the temporal change in wildfire behaviour (ROS and FLI) under climate change scenarios. We aim to fill this gap by characterizing the monthly effect of climate change in both fire danger and wildfire behaviour metrics for four broad Mediterranean ecosystems types and under two widely used climate change scenarios, RCP4.5 and RCP8.5. We specifically studied the Transboundary Biosphere Reserve of Meseta Ibérica shared between Portugal and Spain and where wildfire incidence is significant.

## 2 Materials and methods

### 2.1 Study area

The target region comprises a total area of 4444.25 km<sup>2</sup>, located in a borderland between Portugal and Spain, in the Transboundary Biosphere Reserve of Meseta Ibérica (Fig. 1). Topography varies widely, from mountains in the north (maximum elevation of ca. 2500 m) to flatter, undulated terrain in the south (minimum elevation of 0 m). Climate is characterized by the prevalence of Csb (dry and warm summer) climate, with a few areas with a Csa (dry and hot summer) climate under the Koppen-Geiger classification (Beck et al. 2018). At the end of the century, considering the RCP8.5 scenario, the Csa climate type will expand to the entire study area (Beck et al. 2018). Annual precipitation varies considerably over the territory, from around 1200 to 700 mm year<sup>-1</sup> following a north–south decreasing gradient (Muñoz-Sabater et al. 2021). Temperature varies along the same gradient, from an



**Fig. 1** Location and altitude of the Transboundary Biosphere Reserve of Meseta Ibérica

annual average of approximately 12 °C in the northern mountainous areas to 17 °C in the southernmost areas (Muñoz-Sabater et al. 2021).

The region went through significant socioeconomic changes over the last several decades, leading to depopulation and abandonment of marginal agricultural land (Azevedo et al. 2011). This, together with mountain afforestation programs in the mid-twentieth century, led to an increase in the number of wildfires and the burned area from 1990 to the mid-2000s, with a small decline in the last decade (ICNF 2015). A joint effect of changes in land use and land cover, topography and vegetation type and structure were found to affect fire behaviour in the area (Azevedo et al. 2011; Silva et al. 2011; Magalhães et al. 2017). Depending on latitude, elevation and human agency, the region is dominated by four distinct woody vegetation types that are broadly representative of those occurring across the Mediterranean Basin, respectively pine forests, evergreen sclerophyllous oak woodlands and forests, deciduous forests and a range of shrubland communities (Fig. S1).

Monthly burned area distribution in the study area is concentrated mainly from July to September (Fig. S2). Another period of relevant wildfire activity can be detected in February and April, mainly due to agricultural stubble burning and for pasture renewal. Typically, the fires occurring in pasture and agricultural lands are smaller than those occurring in shrublands and forests, mostly during summer.

## 2.2 Climate scenarios and data

The future climate was characterized under two distinct climate change scenarios, RCP4.5 and RCP8.5. The former describes a radiative forcing of  $\approx 4.5 \text{ W m}^{-2}$  ( $\approx 650 \text{ ppm CO}_2 \text{ eq.}$ ), implying an increase in global mean surface air temperature of 1.8 °C (1.1–2.6 °C) by the end of the century relative to the historical period of 1986–2005 (Collins et al. 2013). RCP8.5 describes a high-end emission scenario (van Vuuren et al. 2011) radiative forcing of  $\approx 8.5 \text{ W m}^{-2}$  ( $\approx 1370 \text{ ppm CO}_2 \text{ eq.}$ ), with a projected increase in global mean surface air temperature of 3.7 °C (2.6–4.8 °C) in 2100 relative to the same historical period (Collins et al. 2013). The inclusion of more than one climate scenario is useful to assist in the decision-making process (Pedersen et al. 2020).

The following atmospheric variables were selected to compute the fire danger indices used herein: daily total precipitation, daily minimum, mean and maximum temperature, daily minimum, mean and maximum relative humidity and daily mean wind speed. Both observational and simulated data generated by climate models were retrieved within the target region. The ERA5-Land reanalysis dataset (Muñoz-Sabater et al. 2021) was used to characterize the historic period (1989–2005). The climate model simulations were considered for the historic (1989–2005) and future (2031–2050) periods, under RCP4.5 and RCP8.5. A 4-member ensemble of Global Climate Model (GCM)–Regional Climate Model (RCM) chains was provided by the EURO-CORDEX project (<https://www.euro-cordex.net/>). The present study used the variables near-surface temperature, near-surface specific humidity, precipitation, near-surface wind speed, eastward near-surface wind, northward near-surface wind, daily maximum near-surface temperature and daily minimum near-surface temperature from the driving models: MPI-M-MPI-ESM-LR, IPSL-IPSL-CM5A-MR, ICHEC-EC-EARTH and CNRM-CERFACS-CNRM-CM5. Each driving model represents an institute and an RCM model (Table 1). For these projections, the time frequency is daily, the ensemble is r1i1p1 and the experiments were carried out for the historical RCP4.5 and RCP8.5 anthropogenic forcing.

**Table 1** List of regional climate models (RCM) and respective institute and driving model used in this study (EURO-CORDEX Data, 2020; Fraga et al. 2020; Campos et al. 2022)

Institute	Driving model	RCM model
CLMcom	MPI-M-MPI-ESM-LR	CCLM4-8-17
IPSL-INNERIS	IPSL-IPSL-CM5A-MR	WRF331F
KNMI	ICHEC-EC-EARTH	RACMO22E
SMHI	CNRM-CERFACS-CNRM-CM5	RCA4

Daily temperatures and precipitation were bias-corrected at the daily timescale using the quantile-mapping approach and the observation-based E-OBS gridded dataset version 22.0e (Cornes et al. 2018) as a baseline in the historic period (1989–2005). For each model, the same bias correction was applied to both the historic and future periods. The raw climate model data were defined over a  $0.11^\circ$  latitude  $\times$   $0.11^\circ$  longitude ( $\sim 10$  km) and were re-gridded, by bilinear interpolation, to the same grid as ERA5-Land and E-OBS, at a native spatial resolution of 9 km ( $0.10^\circ$  latitude  $\times$   $0.10^\circ$  longitude), thus warranting the overlap of grid boxes from all datasets and variables.

Future changes in the climate variables were calculated by computing the anomalies for each location between future monthly values and the median observed value in the reference period. Fire danger and fire behaviour were calculated for the entire EURO-CORDEX grid within the study area, per climate model and scenario. For each day in the temporal series, we calculated the percentile 95 and the median of the study area. These daily values were then used to represent the fraction of the study area with the highest fire danger and potentially exhibiting a more dangerous wildfire behaviour (percentile 95) and the median hazard in the region (median). We then calculated the monthly value of fire danger and fire behaviour characteristics for each climate model and scenario. Results are showed individually for the percentile 95 and the median of the study area. We used the median monthly value to ensemble the different metrics.

### 2.3 Fire danger and wildfire behaviour characteristics

The Canadian Forest Fire Weather (FWI) Index System (van Wagner 1987) was evaluated as the preferred method for fire danger rating in the Mediterranean region, particularly for the summer season (Viegas et al. 1999) and it has become the standard to assess fire danger at regional to global scales, including in climate change applications (Bedia et al. 2015; Abatzoglou et al. 2019). We evaluated the influence of climate change in the Fire Weather Index (FWI) and its two major sub-indices. These indices are presented and characterized below (van Wagner 1987):

- The Initial Spread Index (ISI) that represents the atmospheric effect in fire-spread rate
- The Buildup Index (BUI) that reflects the drought effect on the amount of fuel available for combustion
- The Fire Weather Index (FWI), a combined outcome of the ISI and the BUI that rates potential fire intensity and is often used by fire management agencies to assess fire danger conditions in the near future

The daily FWI codes are calculated from noon readings of air temperature and relative humidity at a 2-m height, open wind speed at 10 m and 24-h rainfall. However, because of

the study emphasis on potential fire behaviour rather than on fire danger conditions per se, calculation of the indices with an atmospheric component (FFMC, ISI, FWI) was based on daily maximum temperature and minimum relative humidity (e.g. Jolly et al. 2015; Abatzoglou et al. 2018) to capture the hourly peak burning conditions associated to minimum fine dead fuel moisture content. The alternative would be to use daily means of input variables, which is not recommended as it induces a negative bias on FWI estimation (Herrera et al. 2013). The FWI was computed continuously as in previous studies in the Mediterranean Basin (e.g. Calheiros et al. 2021) and in coherence with the potential occurrence of fires throughout the entire year. We developed computational codes using the equations in Van Wagner (1987) to calculate the FWI components.

In Portugal, extreme fire danger corresponds with  $FWI > 38.2$  (Palheiro et al. 2006). Here, we used this FWI threshold to calculate the number of days with extreme fire danger for the historical and future climate (both under RCP4.5 and RCP8.5), following the similar approach of Wang et al. (2015).

Fire behaviour differs between vegetation types for a given fire danger level. Thus, in addition to the fire danger indices, we calculated fire behaviour characteristics (ROS and FLI) for common broad Mediterranean vegetation types. ROS and FLI are defined as follows:

- Rate of spread (ROS) is the linear rate of advance of the fire front. ROS determines the amount of resources needed to contain a wildfire and is the main driver of fireline intensity (Sullivan and Gould 2018).
- Fireline intensity (FLI) is the amount of heat released per unit time and unit length of the fire front ( $\text{kW m}^{-1}$ ). FLI is a major driver of aboveground fire effects and is often used as a proxy for fire suppression difficulty and firefighter safety (Hirsch and Martell 1996).

## 2.4 Fire behaviour modelling

We considered the four generic vegetation types that prevail in the region, respectively long-needle pine forest (*Pinus pinaster*, *P. pinea*), broadleaved deciduous forest (*Quercus pyrenaica*, *Castanea sativa*), broadleaved evergreen forest (*Quercus suber*, *Q. ilex*) and shrubland dominated by *Erica*, *Cytisus*, *Pterospartium* and *Cistus* species. The forest types were assigned fuel models from the Portuguese catalogue (Cruz and Fernandes 2008; Fernandes 2009) for the purpose of fire behaviour simulation, respectively M-PIN, M-CAD and M-ESC. These fuel models assume surface fuel complexes composed of litter and shrubs and their development included parameterization based on field observations of fire behaviour characteristics. Typical (median) values per vegetation type for the fuel and stand descriptors required by the calculations that follow were computed from the national forest inventory plots located within the study region (Fernandes et al. 2019).

The forward (maximum) spread rate of a surface fire was simulated with the model of Rothermel (1972) for flat terrain, which depicts landscape fire spread better (Sullivan et al. 2014), and for baseline live fuel moisture contents for each forest type (Fernandes 2009); because the effect of live fuel moisture content in the model is a mathematical artefact (Catchpole and Catchpole 1991), the estimates were subsequently adjusted as per Rossa and Fernandes (2018). Live fuel moisture content was estimated from the Drought Code (DC) of the Canadian FWI System and an ensemble of representative species in the region (Viegas et al. 2001). The simulations also require “midflame” wind speed, i.e. ~2-m wind

speed, and the moisture content of fine dead fuels, estimated respectively from 10-m open wind speed and the Fine Fuel Moisture Code (FFMC) of the Canadian FWI System (van Wagner 1987), and then adjusted for vegetation type (Fernandes 2009; Pinto and Fernandes 2014; Andrews 2018). Calculation of fire-spread rate for shrubland (SHRUBL) followed the same procedures but was based on the robust empirical model of Anderson et al. (2015). Surface FLI was calculated as the product of ROS, heat of combustion (assumed constant at  $18,000 \text{ kJ kg}^{-1}$ ) and fuel consumption (Byram 1959; Alexander 1982); the latter was estimated as an asymptotic function of the Duff Moisture Code (DMC) of the Canadian FWI (Forestry Canada Fire Danger Group 1992; Fernandes and Loureiro 2013). Assessment of surface fire transition to a crown fire and the type of crown fire (active or passive) followed Van Wagner (1977), but assuming that deciduous broadleaved forest does not support active crowning (Alexander and Cruz 2006; de Groot et al. 2013). Crown fire rate of spread adopted the model of Cruz et al. (2005) for pine forest and assumed Anderson et al. (2015) in broadleaved evergreen forest. Surface and crown fire spread were weighted as a function of crown fraction burned (van Wagner 1993) to calculate the overall fire-spread rate and FLI. Particular relevance was given to  $\text{FLI} > 4000 \text{ kW m}^{-1}$ , as it represents a commonly adopted threshold for extreme fire behaviour phenomena such as crowning and spotting and for ineffective wildfire control operations (Alexander and Cruz 2018; Hirsch and Martell 1996).

The influence of climate change in fire behaviour considers the weather influence in ROS and FLI, and also the potential effect of climate on fuel load, which is essentially restricted to an effect on FLI (Byram 1959). Biomass equates to net primary production (NPP) (Díaz 2013) and climate change is projected to substantially influence NPP (Melillo et al 1993). To represent potential changes in fuel consumption and fireline intensity during a wildfire due to climate change, we assumed that biomass and fuel loading are directly proportional and thus we adjusted fuel loading proportionally to NPP. NPP was calculated for each grid point, using the global equations presented in Del Grosso et al. (2008) based on empirical non-linear relationships with temperature and precipitation. NPP was calculated differently for forest and for shrubland, respectively from temperature and precipitation and from precipitation only. To allow for inspection of the relevance of adjusting fuel load for NPP, the results are presented with and without (fuel load equal to the historical period) considering the NPP effect.

All the analyses and figures were produced with the R software (R Core Team 2020).

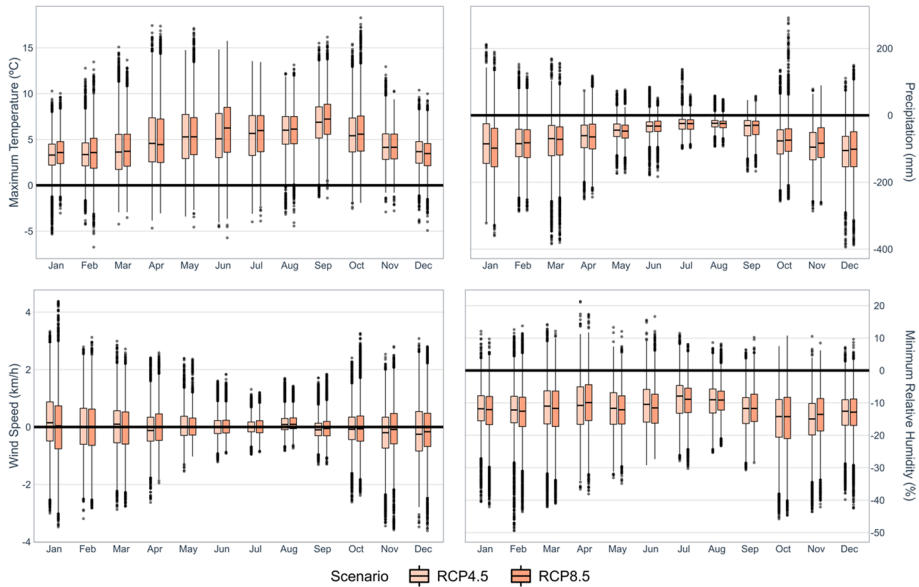
## 3 Results

### 3.1 Climate change and fire danger

#### 3.1.1 Climate analysis

The analysis of future climate, namely in maximum temperature, precipitation, wind speed and minimum relative humidity, reveals significant changes in the short/medium term ( $p$  value  $\leq 0.05$ , except for wind speed; Fig. 2). The maximum temperature is expected to increase every month, with the highest increase being projected for summer and adjacent months (median increase of ca.  $+5^\circ\text{C}$ ). Precipitation is projected to decrease throughout the year, with the highest decrease occurring during winter and autumn (median decrease of approximately 100 mm). Regarding the projected changes in wind speed, no particular





**Fig. 2** Boxplots of monthly differences in maximum temperature (top left), precipitation (top right), wind speed (bottom left) and minimum relative humidity (bottom right), for the 2031–2050 period for the RCP4.5 (light orange) and RCP8.5 (dark orange) scenarios, when compared against the 1989–2005 observed period. Boxplots: percentiles 0, 25, median 75, 100

trend can be identified, with null median monthly changes. The minimum relative humidity is projected to decrease every month, with the highest decreases occurring during autumn. The minimum relative humidity is also projected to decrease in the median between 15 and 10% during summer and adjacent months.

### 3.1.2 Initial Spread Index (ISI)

Figure 3 (top left) shows historical monthly and projected ISI. Historically, the highest values of ISI are restricted to late spring and the summer months (June, July, August and September). When considering future climate, both scenarios point to an increase in the median in all months, with the highest absolute increase in ISI occurring between May and October. Moreover, by mid-century, the months of April, May and October show an ISI value close to the historical summer values.

### 3.1.3 Buildup Index (BUI)

Historical and future BUI are represented in Fig. 3 (top right). Historically, the monthly BUI values for the period peak during summer, with the highest values occurring in August. However, under climate change scenarios, BUI is projected to increase every month, with the highest absolute increases occurring from June to October. In the mid-century period and under both climate scenarios, May, June and October reveal medians similar (when not greater) to those in the current summer months.



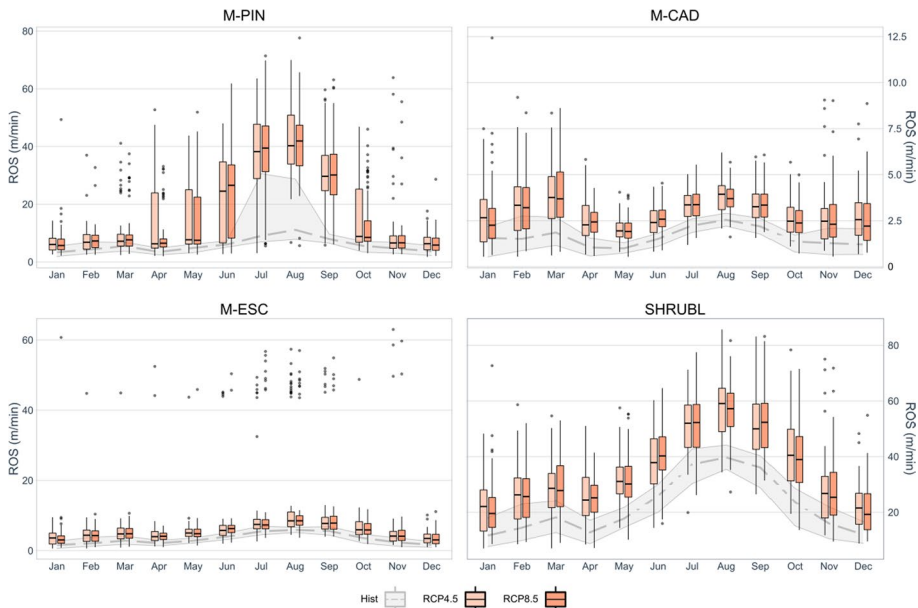


**Fig. 3** Boxplots of monthly ISI (top left), BUI (top right) and FWI (bottom left) for the 2031–2050 period under RCP4.5 (light orange) and RCP8.5 (dark orange) scenarios. Median historical monthly FWI are shown as grey dashed lines, while the percentile 25 and the percentile 75 are represented by the grey shaded area. The average monthly number of days with extreme fire danger (FWI > 38.2, as defined by Palheiro et al. 2006), for both the historical (1989–2005) and future (2031–2050, RCP4.5 and RCP8.5) scenarios, is also shown in the bottom right box. Boxplots: percentiles 0, 25, median 75, 100

### 3.1.4 Fire Weather Index (FWI)

Figure 3 (bottom left) shows the monthly FWI for the historical period and climate change scenarios. For the historical period, the pattern is the same as previously identified, with the highest values limited to the summer months (July, August and September). Under both climate scenarios, the most relevant increases in FWI are projected to occur from May to October, mainly in the spring and autumn (despite a general increase throughout the year). This increase in fire danger results from the increase in both its atmospheric (ISI) and drought (BUI) components.

Historically, days with extreme fire danger (FWI > 38.2) occur mostly in summer months (July, August and September), with an average of 26 days with extreme fire danger (Fig. 3, bottom right). Under the climate scenarios RCP4.5 and RCP8.5, we project a threefold increase in the annual frequency of extreme fire danger days, particularly due to an increase in the frequency of extreme FWI in the summer and adjacent months. In fact, it is expected that nearly all summer days show extreme fire danger.

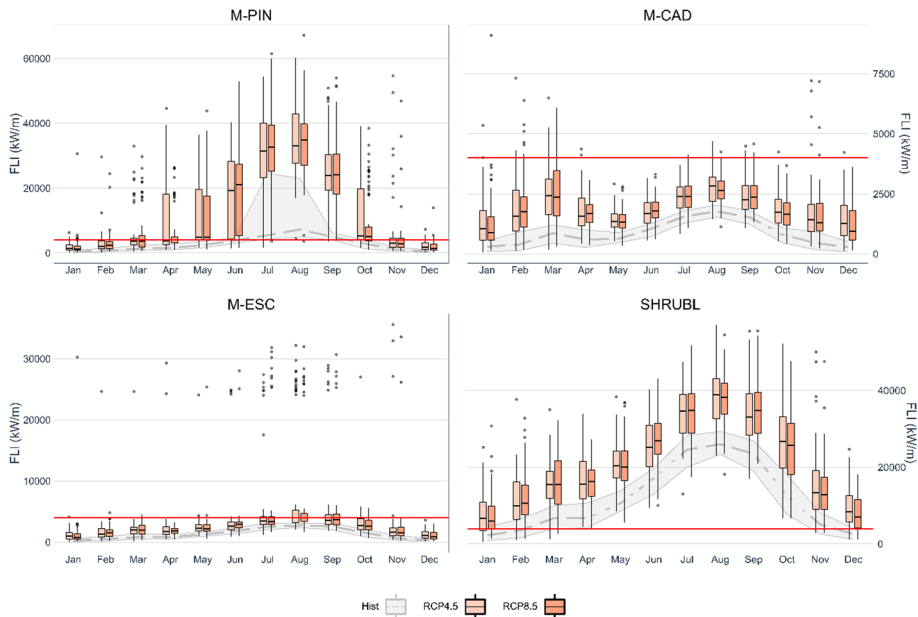


**Fig. 4** Distribution of the simulated rate of spread (ROS) for the different fuel models studied, under climate change scenarios RCP4.5 (light orange) and RCP8.5 (dark orange) for the period 2031–2050. Dashed grey line represents the historical median, while the top limit of the shaded area represents the percentile 75 and the bottom limit represents the percentile 25. Boxplots: percentiles 0, 25, median 75, 100. Note the different scales between vegetation types

### 3.2 Climate change and fire behaviour

#### 3.2.1 Rate of fire spread

Figure 4 depicts the monthly rate of fire spread for the different vegetation types considered, under historical and future climate. As expected, ROS varies greatly amongst vegetation types: shrubland (SHRUBL) and pine forest (M-PIN) exhibit the highest values, while broadleaf, either deciduous (M-CAD) or evergreen (M-ESC), show less extreme values. ROS also shows pronounced intra-annual variability, with the highest ROS values occurring in summer months (July, August and September) for all fuel types. An increase in ROS is projected for all fuel model types under both climate change scenarios. M-PIN shows the highest dispersion of values, mainly in and around summer months, reflecting high variability. SHRUBL also shows an increase in ROS, more pronounced during spring and summer. M-CAD and M-ESC show a small increase in ROS in all months. Nevertheless, M-ESC displays a great number of outliers during summer that suggests some potential to occasionally exhibit extreme ROS values. The non-parametric Wilcoxon signed-rank test showed a significant ROS increase for all months and both climate scenarios when compared to the historical period ( $p \leq 0.05$ ). Monthly ROS is not statistically different between future climate scenarios ( $p > 0.05$ ).



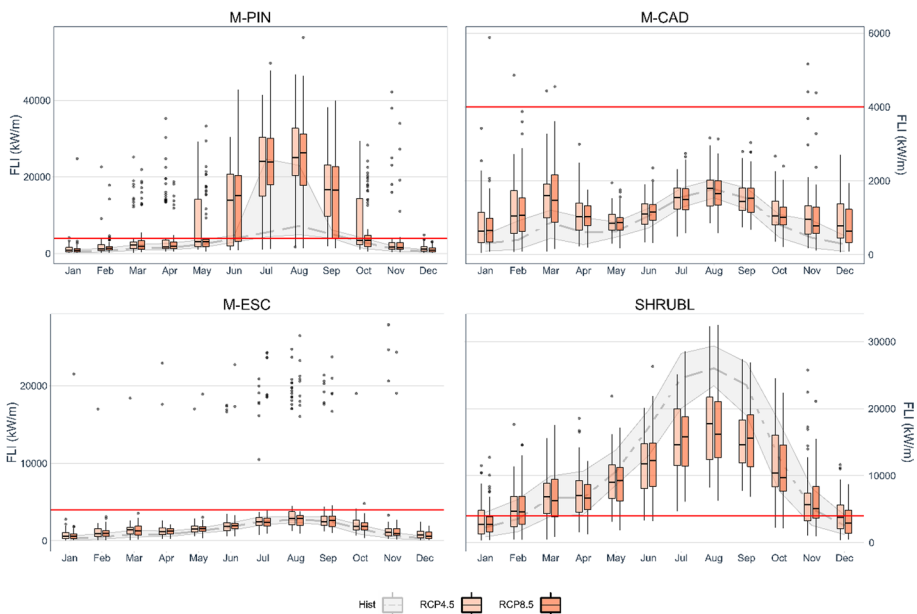
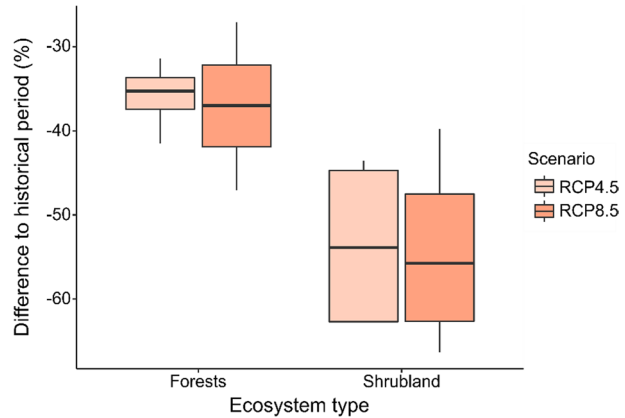
**Fig. 5** Distribution of simulated fireline intensity (FLI) with unadjusted NPP, for the different fuel types, under climate change scenarios RCP4.5 (light orange) and RCP8.5 (dark orange) for the period 2031–2050. The dashed grey line represents the historical median, while the top limit of the shaded area represents the percentile 75 and the bottom limit represents the percentile 25. The solid red line represents the threshold of 4000 kW/m for fireline intensity. Boxplots: percentiles 0, 25, median 75, 100. Note the different scales between vegetation types

### 3.2.2 Adjustment for NPP and fireline intensity

Figure 5 shows the monthly FLI for the historical period (1989–2005) and future climate conditions in the most fire-prone locations of the study area, without the adjustment in NPP (and consequently in the amount of available fuel). Historically, FLI is highly variable between vegetation types. FLI also shows a great intra-annual variance, with the highest values occurring always during summer, regardless of fuel type. Under historical fire danger, fire intensity is distinctively higher in shrubland (SHRUBL). In this fuel type, a wildfire can create problems to suppression during almost the entire year. M-PIN also shows the potential to generate wildfire that can pose a challenge to firefighting operations, mainly during summer (July, August and September). M-CAD and M-ESC are the most benign fuel types, as they typically do not generate wildfires intense enough to compromise effective wildfire suppression, even in summer.

The effect of climate change (under both scenarios) in FLI will lead to significant changes in all months when compared to historical values ( $p \leq 0.05$ ). The most relevant changes are found for M-PIN during summer. Moreover, wildfires challenging suppression operations in M-PIN are no longer typically restricted to summer and become more frequent in spring (May and June) and autumn (October). These latter months are also more variable when compared to the historical FLI. For SHRUBL, fires with high FLI ( $\geq 4000 \text{ kW m}^{-1}$ ) are expected to occur throughout the year. The FLI computed for the M-ESC shows an important increase, namely during the summer months, when the

**Fig. 6** Climate change effect on net primary production (NPP) showed as percentage change to the historical period. NPP change is divided by ecosystem type (forests and shrubland) and climate scenario (RCP4.5 and RCP8.5). Boxplots include the four climate models used for each climate scenario, and show the percentiles 0, 25, median 75, 100



**Fig. 7** Distribution of simulated fireline intensity (FLI) adjusted for NPP, for the different fuel models studied, under climate change scenarios RCP4.5 (light orange) and RCP8.5 (dark orange) for the period 2031–2050. Dashed grey line represents the historical median, while the top limit of the shaded area represents the percentile 75 and the bottom limit represents the percentile 25. The solid red line represents the 4000 kW/m fireline intensity threshold. Boxplots: percentiles 0, 25, median 75, 100. Note the different scales between vegetation types

4000 kW m<sup>-1</sup> threshold is frequently crossed. On the other hand, the FLI for M-CAD shows the highest opposition to climate change effects, with the 75th percentile always below that same threshold. This means that the typical wildfire in the M-CAD fuel type will not imply ineffective fire suppression in any of the climate change scenarios considered.

Figure 6 shows the influence of climate change on NPP. For both ecosystem types, the largest decrease is projected for RCP8.5, despite similar values for RCP4.5. For

shrublands, the projected decrease is more than 50% for the period 2031–2050, while for forests, the projected change is around –35%. Figure 7 is similar to Fig. 5, but now considering changes in NPP and thus in the amount of available fuel. When this adjustment is undertaken, all fuel types exhibit a smaller increase in FLI than when no adjustment in NPP is carried out. A significant FLI increase for M-PIN is projected in almost all months ( $p \leq 0.05$ , except for May), particularly relevant between June and September, with the projected median FLI frequently above the  $4000 \text{ kW/m}^{-1}$  threshold, pointing to more frequent extreme fire events. Regarding M-CAD and M-ESC, both fuel types hint at a significant increase in FLI in early spring and autumn. Nevertheless, FLI in both fuel types is not expected to increase between June and September ( $p > 0.05$ ). Lastly, the future pattern of FLI in shrubland shows the greatest change when adjusting the NPP (compared to not considering changes in NPP). No significant changes in FLI from November to April ( $p > 0.05$ ) occur when adjusting NPP. Nonetheless, FLI decreases significantly in the May to October period when compared with historical FLI ( $p \leq 0.05$ ). This is possibly due to the large decrease in precipitation projected for the study region, which is the only meteorological factor on which shrubland NPP is dependent.

A similar analysis considering the median of the study area instead of the most fire-prone locations (i.e. the 95<sup>th</sup> percentile) is provided herein as Supplementary Information (Figs. S3, S4, S5). The results were similar to those obtained for the most fire-prone locations, with ROS and FLI significantly increasing in all vegetation types and for all months and climate scenarios when compared to the historical period ( $p \leq 0.05$ ). The most relevant changes are found for M-PIN, with wildfires that challenge suppression operations no longer being typically restricted to summer and becoming more frequent in spring and autumn. Fires in SHRUBL burning at  $\geq 4000 \text{ kW m}^{-1}$  may occur in any month. On the other hand, a fire occurring in M-CAD will generally not imply ineffective fire suppression in any of the climate change scenarios considered.

## 4 Discussion

This study improves the current understanding of the potential impacts of climate change on future wildfire potential in typical southern Europe vegetation types, namely through fire behaviour modelling. Vast research had been conducted on the influence of climate change on fire danger prior to this study (e.g. Turco et al. 2014; Ruffault et al. 2020; Calheiros et al. 2021). Nevertheless, the lack of studies assessing the influence of climate change on wildfire behaviour is manifest. In the present study, we specifically address this gap by evaluating the potential influence of climate change on the monthly variability of wildfire behaviour characteristics.

Our analysis of the climate variables (maximum temperature, precipitation, wind speed and minimum relative humidity) revealed significant changes in their monthly values (apart from wind speed). The change to warmer and drier years, particularly during and around summer, is supported by previous studies (Andrade et al. 2014; Soares et al. 2015). As a consequence of the change in these variables, an FWI increase is projected, owing to an increase of both its atmospheric component and its drought component. FWI is indeed projected to increase every month, mainly during late spring, summer and early autumn, resulting in a threefold increase in the annual number of days with extreme fire danger, with a relevant increase from May to October.

Following the projected strengthening in fire danger, a significant increase in wildfire behaviour is expected. Here, we show that ROS and FLI increase significantly for all the vegetation types considered. Despite such increment, fuel type shapes how wildfire spread will unfold. The median-intensity wildfire occurring between June and September during the historical period in pine forest will challenge fire suppression, while shrubland fires display such resistance to control throughout the year. These fuel types are both known to generate high-intensity wildfires (Lecina-Diaz et al. 2014; Anderson et al. 2015). Shrub fuels are especially flammable and can sustain extreme rates of spread and fire intensities, even at moderate fire danger levels (Fernandes 2001; De Luis et al. 2004). On the other hand, a median wildfire occurring in the broadleaved forest during the historical period would neither lead to fast nor to high-intensity wildfire, which is consistent with burn severity studies (Fernandes et al. 2010; Saulino et al. 2020). This is because of intrinsic litter properties, either high compactness or fast decomposition (Varner et al. 2015), combined with shading levels that constrain flammability directly through micrometeorology and indirectly by selecting for mesophytic species in the understory (e.g. Nowacki and Abrams 2008).

When considering climate change scenarios without the NPP adjustment resulting from changes in temperature and precipitation, and hence the amount of fuel, ROS and FLI significantly increase every month, for all the selected fuel types. Because wind speed is not projected to differ from historical values, the increase in ROS is mostly an outcome of drier fuels, both dead and alive. The most relevant changes are projected to occur for pine forest, where a median wildfire in the period 2031–2050 can offer serious resistance to control from spring (May and June) to autumn (October). The magnitude of fire behaviour in shrublands also increases substantially, with high-intensity wildfires potentially occurring in any month. Similar results (increase in the intensity of the fires that exceed the capacity of suppression) were also obtained for the Canadian boreal forest (Wotton et al. 2017). Regarding deciduous and evergreen broadleaf, both are typically (median) predicted to generate wildfires with intensity low enough to be within suppression capability (except for the M-ESC type in August). Evergreen broadleaf show a large number of outliers in fire behaviour metrics. Such can be explained by the transition from a surface fire to a crown fire (a rare event in this type of vegetation). Altogether, although considering sporadic episodes of crown fires, an expanded presence of broadleaved forest in the landscape, especially deciduous, would contribute to mitigate the consequences of climate change on wildfire activity and severity. However, climate change in the study region will also diminish the presence of the biophysical envelope under which those species thrive (Costa et al. 2017).

The adjustment of fuel load through the NPP highlights a different pattern than that previously discussed. Decreased biomass production due to the underlying drier conditions throughout the year determines that the FLI in M-ESC and M-CAD may not increase during the summer months, and can even be significantly reduced in SHRUBL. On the other hand, FLI in M-PIN significantly increases in almost all months, even with a lower fuel load. Overall, whether considering changes in NPP and fuel load or not, the studied fuel types will burn more intensely during spring and early autumn. This may lead not only to a longer fire season (Calheiros et al. 2021) but also, as shown by the increase in the FLI, to the occurrence of extreme wildfire events in spring and autumn, namely in M-PIN and SHRUBL. Moreover, a future reduction in primary productivity coupled with more frequent fire may also slow postfire regeneration and hinder full recovery, thus compromising ecosystem resilience (Halofsky et al. 2020; Pontes-Lopes

et al. 2021) and promoting forest to shrubland conversion (Acácio et al. 2009), hence faster spreading and higher intensity fires.

Our findings indicate that fuel loading should be considered when projecting future changes in fire behaviour. We acknowledge that various limitations can further contribute to the (already relevant) uncertainty of climate projections and scenarios (Hausfather and Peters 2020; Peters et al. 2020; Pedersen et al. 2021), such as assuming a linear relationship between climate and NPP and biomass production (see e.g. Duveneck and Thompson 2017). Notwithstanding, our results reveal that for the study area and period analysed, none of the wildfire behaviour characteristics significantly differ between RCP4.5 and RCP8.5. Such similarity between climate scenarios in the region of the Transboundary Biosphere Reserve of Meseta Ibérica is consistent with other studies for the same area (e.g. Freitas et al. 2022). This indicates that both climate scenarios are spatially and temporally consistent for this period (despite significant differences towards the end of the century (Calheiros et al. 2021). Similar results were obtained by Wotton et al. (2017) for Canada, with identical ROS and FLI found for RCP4.5 and RCP8.5 for the 2030 period. This can be largely explained by the similar changes in the climatic variables driven by pathways of anthropogenic radiative forcing that diverge more significantly from the mid-century onwards.

Our projected increases in fire behaviour magnitude indicate increased burned area, as the latter increases nonlinearly with ROS, and both the ROS and FLI constrain the ability to contain a wildfire. However, the projections are consistent but not directly comparable with the various studies that extrapolate (and probably exaggerate) future burned areas in Europe based on historic fire-weather relationships (Dupuy et al. 2020). Future wildfire activity will be dictated by fire danger in its atmospheric and drought (fuel availability) components, but also by changes in vegetation (including NPP) and fuels, and in ignition rates (Bradstock 2010), plus fire management policies (Moreira et al. 2020).

## 5 Conclusion

We have shown that climate change will increase fire danger, increasing the frequency of fire weather conditions associated with large wildfires in the target region. Both RCP4.5 and RCP8.5 point to an increase in fire-spread rate and fireline intensity in the fuel types considered, which are broadly representative of the Mediterranean Basin. Nonetheless, while pine forests and shrublands may experience an increase in fire intensity to levels that further exceed wildfire suppression capacity, mainly from spring to autumn, broadleaved forests will not typically exceed such thresholds.

The consistency in results regardless of the climate scenario considered reinforces the need to address the effects of climate change in wildfires when planning future management (Moreira et al. 2020). Although we acknowledge that the “challenges of wildfire management through the twenty-first century include not just dealing with an increased number of fires, but also an increased incidence of unmanageable crown fire” (Wotton et al. 2017), our results clearly show that climate change effects in certain fuel types, such as broadleaved forests, may not imply further ineffectiveness of firefighting operations in the medium term. Likewise, landscape-level fuel treatments that reduce fuel load will be crucial to mitigating the future fire regime. Hence, through better planning and management of wildfire-prone landscapes, decision-makers would be, consequently, protecting communities, even when considering climate change.



**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10584-022-03399-8>.

**Funding** This research was funded by Portuguese national funds through FCT-Foundation for Science and Technology, I.P., under the FireSmart project (PCIF/MOG/0083/2017). The authors would like to acknowledge the support of FCT by providing funding to the Forest Research Centre (UIDB/00239/2020) and the Centre for the Research and Technology of Agro-environmental and Biological Sciences (UIDB/04033/2020). B.A. Aparício was also supported by the individual research grant from the FCT (UI/BD/150755/2020).

**Data availability** The datasets generated during this study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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