Journal of Environmental Management 322 (2022) 116134

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Trajectories of wildfire behavior under climate change. Can forest management mitigate the increasing hazard?

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ARTICLE INFO

Keywords:
Fire behavior
Climate change
Forest dynamics
EU-forest policies
Fuel moisture

ABSTRACT

Mediterranean forests and fire regimes are closely intertwined. Global change is likely to alter both forest dynamics and wildfire activity, ultimately threatening the provision of ecosystem services and posing greater risks to society. In this paper we evaluate future wildfire behavior by coupling climate projections with simulation models of forest dynamics and wildfire hazard. To do so, we explore different forest management scenarios reflecting different narratives related to EU forestry (promotion of carbon stocks, reduction of water vulnerability, biomass production and business-as-usual) under the RCP 4.5 and RCP 8.5 climate pathways in the period 2020–2100. We used as a study model pure submediterranean Pinus nigra forests of central Catalonia (NE Spain). Forest dynamics were simulated from the 3rd National Forest Inventory (143 stands) using SORTIE-nd software based on climate projections under RCPs 4.5 and 8.5. The climate products were also used to estimate fuel moisture conditions (both live and dead) and wind speed. Fuel parameters and fire behavior were then simulated, selecting crown fire initiation potential and rate of spread as key indicators. The results revealed consistent trade-offs between forest dynamics, climate and wildfire. Despite the clear influence exerted by climate, forest management modulates fire behavior, resulting in different trends depending on the climatic pathway. In general, the maintenance of current practices would result in the highest rates of crown fire activity, while management for water vulnerability reduction is postulated as the best alternative to surmount the increasingly hazardous conditions envisaged in RCP 8.5.

1. Introduction

Wildfires are the main disturbance affecting forest ecosystems worldwide and arguably the most important in Mediterranean-type ecosystems (Bowman et al., 2009; San-Miguel-Ayanz et al., 2012). In recent years, many Mediterranean regions of the world - including western U.S. states, southern and western Europe or Australia - have reported an increase in climatic fire danger and extreme events, experiencing record-breaking fire seasons (Abram et al., 2021; Williams et al., 2019). These events are undeniably prominent features among the threats climate warming poses to forests and society (Dupuy et al., 2020; Seidl et al., 2017).

A key challenge for wildfire science and management is to adequately project future changes in fire hazard (probability of occurrence of an event with a given intensity). Understanding where and how fire behavior patterns may change in the forthcoming decades is critical to plan and manage the necessary resources (Syphard et al., 2018). To date, most studies of the dynamics of fire risk in the Mediterranean region focused on forecasting hazard conditions using meteorological indicators (e.g., fire weather danger indices; Barbero et al., 2019; Bedia et al., 2014), or fire regime and behavior (Mitsopoulos et al., 2016; Rodrigues et al., 2020; Salis et al., 2019) without considering neither the dynamics of plant communities nor the changes in fuel availability and its connectivity (Gil-Tena et al., 2019; Morán-Ordóñez et al., 2020).

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https://doi.org/10.1016/j.jenvman.2022.116134
Received 25 March 2022; Received in revised form 26 August 2022; Accepted 27 August 2022

However, setting the human factor aside, climate-vegetation-fire interactions play a fundamental role in defining fire regimes (Resco de Dios, 2020). Climate variations can alter the patterns and types of plant communities; in turn, it is the vegetation that withstands fire, whose incidence is also conditioned by climatic fluctuations. Hence, the common practice of not considering vegetation dynamics introduces significant uncertainty in projections based solely on climate models since fuel moisture, abundance and structure are key features behind fire incidence and behavior (Syphard et al., 2018).

Fuel moisture content, defined as the water content per unit of dry weight of fuel, plays a crucial role in fire ignition and behavior, especially in down dead wood materials. When fuel moisture content is high, fire flammability and ignition probability are low and vice versa. Additionally, when moisture content is low, the rate of spread is higher and fires can quickly develop into uncontrollable events (Matthews, 2014; Sharples et al., 2009). Moisture content of the living vegetation can also promote fire spread, ultimately determining fire intensity and burning extent (Dennison and Moritz, 2009; Pellizzaro et al., 2007). Climate projections in southern Europe envisage temperature rise and reduction (or at least non-increase) of summer precipitation (Lionello and Scarascia, 2018) and, therefore, a decrease of FMC in the future (Bedia et al., 2014, 2015; Varela et al., 2019). However, climatic conditions are not the only variables influencing fuel moisture content and fire behavior. Forest, stand and tree features, such as tree position, understory layers, branch arrangement (ladder fuels), canopy structure or density can determine the potential for crowning, rate of spread or burning intensity (Flannigan et al., 2016; Kucuk et al., 2007; Sánchez-Pinillos et al., 2021; Scott and Burgan, 2005). Hence, forest management can help to improve forest resilience to wildfires by modifying key structural attributes of forests (Coll et al., 2021; Duane et al., 2019; Fernandes, 2013, p. 201; Morán-Ordóñez et al., 2020, 2021).

A paradigm shift towards proactive wildfire management is being advocated for as an alternative to fire suppression and exclusion policies (Moreira et al., 2020; Wunder et al., 2021), although costs are preventing its widespread implementation. At the same time, the promotion and protection of forests and the ecosystem services they provide (such as biodiversity, water or timber production) is becoming a central issue in forest management planning and sustainable development facing global change (Costanza et al., 1998; Schröter et al., 2005). However, although forest management and forest fire mitigation are related to some extent, they do not always synergize. For example, the changes in forest structure needed to promote certain ecosystem services might exacerbate or foster fire hazard, but little is known on how different management alternatives can affect the risk of forest fire.

In a recent paper, Morán-Ordóñez et al. (2020) examined the impact of four different forest management strategies based on EU forestry policies (business as usual, reduction of forest vulnerability to drought, promotion of bioenergy, and carbon storage) on the provision of several ecosystem services, under two climatic pathways (RCP 4.5 and RCP 8.5) over the XXI century. In this study, we add insights into the effects and implications of forest management under these scenarios (policy plus climate) in terms of fire hazard. For that, we use the framework developed by Morán-Ordóñez et al. (2020) and evaluate fire behavior (fire rate of spread and crown fire initiation potential) when forest management strategies based on socio-economic factors - not aimed at fire

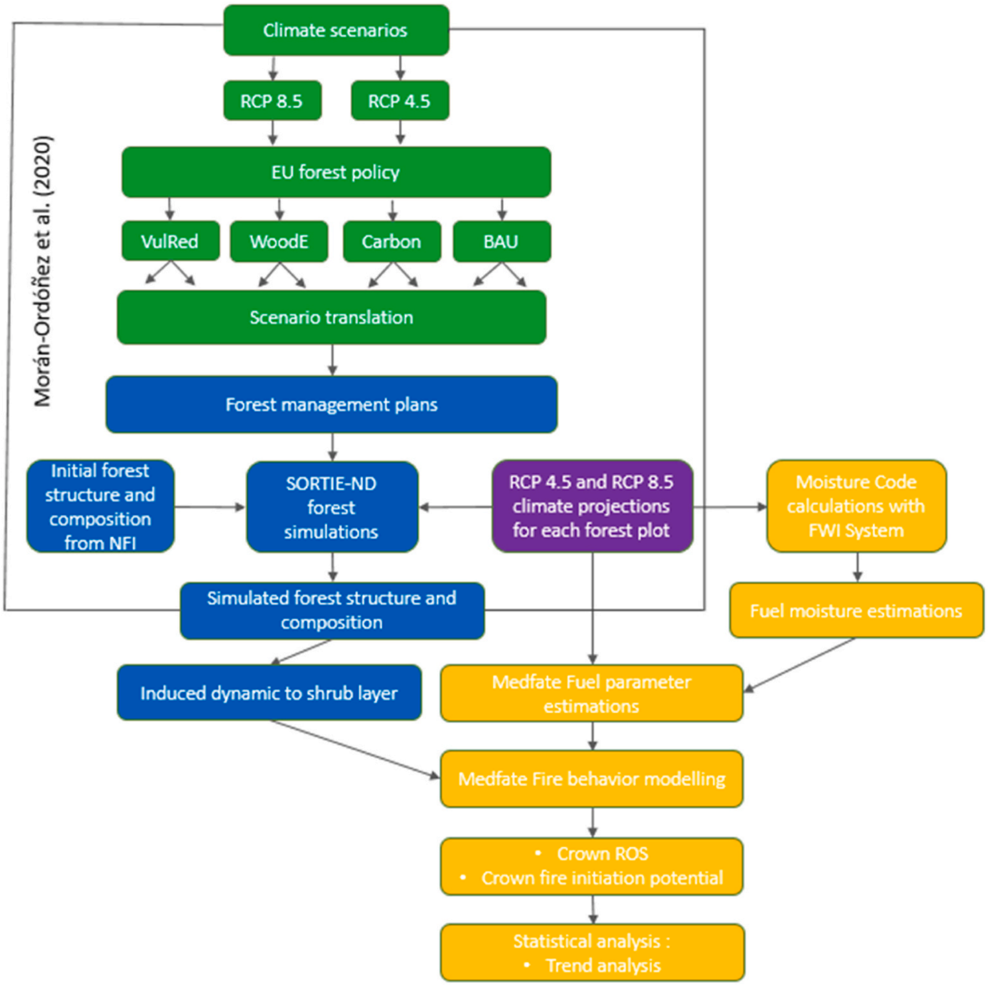

Fig. 1. Diagram showing the workflow used to obtain fire behavior data incorporating outputs from Morán-Ordóñez et al. (2020). Color codes meaning: green – the first part of the study, including scenario defining and translation; blue – the second part with the main focus on forest dynamics modeling, yellow – third part with a focus on fire behavior modeling, purple – data that have been used as an input in more than one part of the study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

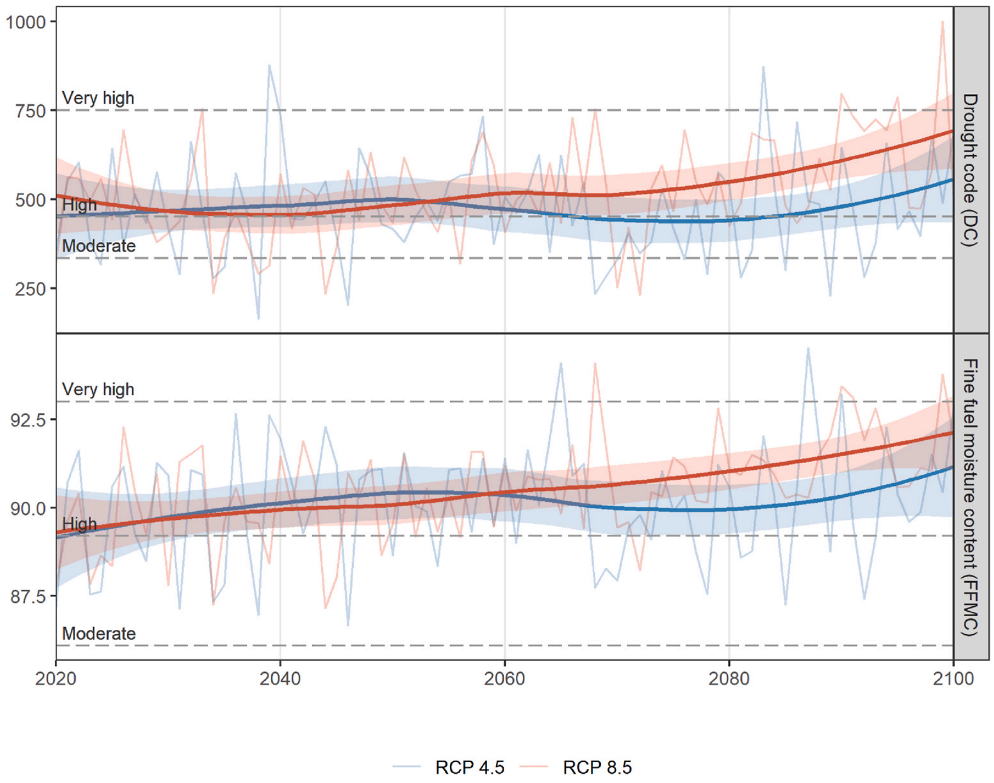

Fig. 2. Projected annual average Drought Code (DC) and Fine Fuel Moisture Content (FFMC) over the study area for the period 2020–2100 under RCP 4.5 and RCP 8.5. Solid light lines represent mean values from all plots; solid thick lines depict the trend with locally estimated scatterplot smoothing approach (LOESS); transparent halo outlines the variability range of the LOESS profile; dashed lines indicate fire weather danger thresholds for FFMC and DC according to the European Forest Fire Information System.

reduction under climate change - are implemented. We intend to answer the following questions: (1) How is fire weather evolving over time under different climate change scenarios? (2) What is the role of forest management in fire behavior potential? (3) Which management scenarios help in mitigating fire hazard?

2. Methods

This work was developed in three main stages (Fig. 1). The first includes the definition of climate and forest management scenarios and their translation into forest treatment plans (section 2.2). The second part comprises the simulation of forest structure and dynamics with Sortie-ND (section 2.3). The third and last part was dedicated to the estimation of parameters related to canopy and fuel moisture content to then simulate fire behavior (section 2.4).

2.1. Study area

The study area was set in “El Solsonès’’ county (Catalonia), in the Northeast of Spain (Fig. 2). “El Solsonès” extends over circa 1000 km^2 covered mostly by forest and agricultural lands, being sparsely populated. The region is located in the pre-Pyrenees, depicting a sharp south-north altitudinal gradient with elevation ranging from 400 to 2400 m. a. s.l. Accordingly, the climatic conditions vary between the northern and southern ends of the county transitioning from Mediterranean to Oceanic conditions – Csa to Cfb according to the Koppën climate types (Beck et al., 2018). In the southern end, precipitation peaks during spring and autumn with dry and warm conditions in summer, with an annual average of 600 mm. In the northern part of the county, the precipitation is more evenly distributed throughout the year, raising up to 1000 mm per year (de Aragón et al., 2007) with cooler temperatures. Approximately 65% of the area is covered by dense pine forests with dominant species being *Pinus nigra Arnold, Pinus sylvestris* L. *and Pinus halepensis Mill.* Fire occurrences in “El Solsonès” county have a return interval between 70 and 90 years. On average, occurrence is 25 or less fires per year, with an affected area around 10 ha. However, as in all of Catalonia, extreme fire events have occurred in the past. For example, in 1998 a single fire event burned over 23,000 ha of *Pinus* and mixed forestlands in El Solsonès.

This study focuses on pure black pine (*Pinus nigra*) stands of “El Solsonès’’ county. These forests are dominant in the area, and they currently cover almost 20,000 ha. Input data on forest structure and composition for simulations were gathered from 143 permanent plots of this forest type that were measured during the third Spanish National Forest Inventory (NFI3, DGNC, 2007). The Spanish NFI survey measures a network of plots using a regular sampling strategy at the intersections of a 1 × 1 km UTM grid revisited approximately every 10 years. Each plot consists of four concentric fixed circular areas with radii of 5, 10, 15 and 25 m, used for acquisition of different tree, stand and site variables.

2.2. Scenario description

The study combined two climate scenarios (under their respective carbon emission pathways) and four forest management scenarios. Climate pathways (RCPs 4.5 and 8.5) were chosen due to their contrasting nature and widespread use in research in Europe (C3S, 2017). Forest management scenarios were designed according to the prospective European Union forest policy narratives developed in the European Forest Sector Outlook Study (UNECE, 2011); hence none of the scenarios were designed to directly reduce fire hazard.

2.2.1. Climate change pathways

We investigated two carbon emission pathways: RCPs 4.5 (Wise et al., 2009) and 8.5 (Riahi et al., 2011). RCP 4.5 represents a climate scenario based on the assumption that carbon emissions will be reduced by the end of this century; while pathway 8.5 assumes business as usual conditions where carbon dioxide emissions will be sustained until the end of the century. Climate prediction data were based on the EU-CORDEX project (available at Earth System Grid Federation; http://esgf.llnl.gov/) for the period 2016–2100. Data were obtained according to the CNRM-CERFACS-CNRM-CM5 global model that was later regionalized (CCLM4-817 and RCA4 dynamic models) at 11 km resolution. Model predictions included daily precipitation, minimum and maximum temperature, relative humidity, radiation and wind speed estimations. To acquire future climate conditions for each forest stand, predictions were downscaled, and bias corrected for both climate pathways and regional models at a 1 × 1 km resolution. The meteorological input for climate projections comes from the Spanish Bureau of Meteorology (AEMET) and the Meteorological Service of Catalonia. Climate models and forecasts were produced using the *meteoland* package in the R environment (Cáceres et al., 2018). For a more complete and detailed description of climate projections' methods and inputs see the supplementary materials in Morán-Ordóñez et al. (2020).

2.2.2. *Forest policy and management scenarios*

We used the four forest policy scenarios described in Morán-Ordóñez et al. (2020). They were based on four plausible EU policies grounded in the EU bioeconomy strategy and the European Forest Sector Outlook Study (EFSOS) (UNECE, 2011). These scenarios were specifically designed to account for the particularities of the target species and the study area. Each combination of policy and climate scenario was then translated into stand-based forest management plans with the assistance of local stakeholders, including forest owners and experts. In all cases, we assumed *Pinus nigra* stands will continue to be managed as pure monospecific stands over the entire period of analysis, i.e., we did not consider succession processes or changes in the dominant species. Likewise, management scenarios showcase a set of treatments focused on the canopy layer, assuming that harvest residues are removed, hence potentially underestimating surface fire behavior.

The first policy scenario was named '**promotion of wood energy'** and assumes the EU is moving towards carbon neutrality by gradually substituting non-renewable resources through biomass extraction. This scenario envisages a promotion of EU internal markets in biomass fuels through subsidies and seeks maximizing biomass extraction. The management plans consisted of short rotations (80–90 years) and the application of 1–3 thinning treatments, depending on the climatic scenario. The main objective of the second scenario was climate change mitigation through the '**promotion of carbon storage'.** This scenario focuses on the production of durable wood products that ensure long-lasting fixation of carbon. Trees must achieve a big diameter at harvest, which requires longer rotations than usual, especially in the case of RCP8.5 (>200 years). The third scenario seeks the '**reduction of forest vulnerability to climate change'** and, more particularly, increasing forest resilience to drought conditions. It is built upon the fundaments of eco-hydrological forest management, which advocates early and intense thinnings to improve tree vigor and resilience (del Campo et al., 2017). The fourth scenario embeds '**business as usual'** practices, which correspond to the most regular management of *Pinus nigra* in the study area: selective cuttings (also called high grading), i.e., the removal of the biggest trees per plot every 15 or 20 years. Therefore, it serves as a reference/baseline for comparison. Further details on the forest policy scenarios can be found in Morán-Ordóñez et al. (2020), and the details of the management plans for *Pinus nigra* are depicted in Supplementary Materials (Table S1). We built a specific silvicultural regime for each of the 143 plots and 8 scenarios, based on the management plans and the initial forest structure of the plot. The silvicultural regimes included the year, intensity, and type of harvest to apply (thinning, seeding or final harvests).

2.3. *Modeling forest dynamics*

Forest dynamic simulations under each of the eight scenarios (two climate and four management scenarios) were conducted using the software SORTIE-ND v7.06 (http://www.sortie-nd.org) in each forest inventory plot (n = 143). SORTIE-ND is a spatially explicit and individual-based model, i.e., it simulates tree development for each single tree within a given forest plot. Tree development is defined by the species, size, climate, and competition with neighbors. SORTIE-ND outputs contain annual estimates of stand structure and composition, derived from the simulation of the size, species, and position of every individual tree in the plot, including deadwood and its decay dynamics. The parameters needed to run the simulations of forest dynamics were acquired from Gómez-Aparicio et al. (2011) and Ameztegui et al. (2015, 2017). We retained the outputs in the 80-year-period from 2020 to 2100 to conduct the simulations of fire behavior potential.

SORTIE-ND model enables the simulation of dynamics of the tree canopy layer but holds no capabilities to characterize the variation over time of the understory. But surface fuels are a key parameter of potential fire behavior influencing propagation rates and the onset of crown fire activity (Cruz et al., 2014). In Mediterranean forest communities, such as *Pinus nigra* forests, the density of the shrub layer is strongly tied to the canopy layer (Coll et al., 2011). Empirical relationships between the maximum shrub cover and the basal area of the tree canopy have been established, depicting a gradual increase in shrub cover as the canopy layer opens. In this sense, we leverage the empirical relationships ($R^2 = 0.484$) fitted for Pinus nigra stands by Coll et al. (2011) to induce temporal dynamics in the surface strata:

$$\ln(\mathrm{MaxSCov}) = 4.9023–0.0005\ \mathrm{BA}^2\ \text{-}0.0597\ \mathrm{Ele} \quad (1)$$

whre MaxSCov is the maximum percent cover of the shrub layer, BA (m2 ha-1) is the basal area and Ele is elevation (m.a.s.l. X 100).

Using the basal area outputs from SORTIE-ND and the elevation of each plot, we calculated the percent cover of shrubs for a given year and plot. Then we calculated the relative change between years as a measure of the potential change in the shrub layer. The obtained ratio is applied to the percent cover of shrub as it is reported in the NFI in the first year (2020), subsequently updated on a yearly basis during the period of analysis. To account for the delay in the response of the shrub layer we calculated a 3-year moving average of the ratio of change and applied a 2-year delay. For example, in case of a heavy thinning being applied, the increase in shrub layer density due to more open canopy would be fully noticeable approximately three years after the treatment. We estimated the amount of litter fuels as function of live fuels using *medfate* (v2.7.3), an R package that provides a wide array of functions to simulate forest functioning and dynamics, using cohort-based description of forest stands. *medfate* calculates the amount of litter as a function of shrub dynamics, hence it varies temporally. It estimates 1 h woody fuels and leaf litter from standing biomass of small branches (<6.35 mm) and leaves for trees and shrubs assuming a continuous input of litter. The variation in accumulated litter is described by the combination of the differential equation by Birk & Simpson (1980) and the regression model of Meentemeyer (1978).

2.4. *Modeling potential fire behavior*

2.4.1. *Fuel moisture content estimations*

Fuel moisture content is one of the most important variables in fire behavior affecting, among others, the rate of spread of a fire. To properly capture FMC conditions we must estimate both the 'alive' and 'dead' fractions (Danson and Bowyer, 2004). The fuel moisture content of dead fuels (litter, herbaceous, shrub and woody fractions) mostly depends on atmospheric conditions and fuel physical and chemical characteristics, and it changes frequently as a result of atmosphere processes (Aguado et al., 2007; Resco de Dios et al., 2015). Alive FMC (aFMC) is harder to determine because it also depends on soil conditions, water uptake through roots, transpiration, survival adaptations and plant phenological and biological processes (Nolan et al., 2018; Viegas et al., 2001), thus being species-dependent (Jurdao et al., 2012). dFMC and aFMC were derived from the Fine Fuel Moisture Content (FFMC) and Drought Code (DC) components of the Canadian Fire Weather Index (FWI), respectively. FWI is one of the main components of the Canadian Forest

Fire Danger Rating System, and it allows assessing the severity of fire weather conditions (Wotton, 2009). First, we calculated the FWI using the *cffdrs* package in R from daily precipitation, average temperature, relative humidity, wind speed data, latitude, and longitude values assembled from climate projections (see section 2.2.1). FWI calculations (initialized in 2015 to ensure the proper estimation of DC) were repeated for each climate projection. Output included daily data for all 80 years (2020–2100), being later aggregated as the 97th percentile of FWI, selecting FFMC and DC accordingly. Dead litter fuel moisture content (dFMC) was calculated according to Wotton (2009):

$$\mathrm{dFMC}_{\mathrm{litter}} = 147.2 * \mathrm{FFMC} \qquad (1)$$

where FFMC is the 97th percentile of each year (Alcasena et al., 2019; Cruz et al., 2014). Dead fuel moisture for herbaceous, shrub and woody fractions were calculated adding 1% to the $\mathrm{dFMC}_{\mathrm{litter}}$ value (Matthews, 2014; National Wildfire Coordinating Group, 2021a).

Live Fuel Moisture content (aFMC) for shrubs was calculated using an equation developed by Viegas et al. (2001):

$$\mathrm{aFMC} = c\ (\mathrm{DC})^{d} \qquad (2)$$

where *c* and *d* are coefficients of power-law fitting for various fuels by Viegas et al. (2001). In this case, coefficients of the most common shrub species over the study area (*Rosmarinus officinalis*) were used, whose values were $c = 771.8$ and $d = -0.343$. It was assumed that canopy moisture was equal to shrub moisture plus 30% (Balaguer-Romano et al., 2022; National Wildfire Coordinating Group, 2021b) while herb moisture is usually 30% lower (Scott and Burgan, 2005).

2.4.2. *Fire behavior simulation*

Fire behavior calculations were conducted using the *medfate* package in R (De Cáceres et al., 2015). Fuel characteristics were modeled from yearly forest dynamic outputs of SORTIE-ND (see section 2.3). The necessary inputs of fuel moisture content and wind speed were obtained from climate projections (see sections 2.2.1 and 2.4.1). Both fuel characteristics and fire behavior processes are based on a modification of the Fuel Characteristics Classification System (FCCS) described by (Prichard et al., 2013). One of the main differences regarding the original FCCS is that in *medfate* the fuelbeds are divided in five strata (canopy, shrub, non-woody vegetation, fine woody materials and leaf litter), while FCCS also includes ground fuels (De Cáceres et al., 2021).

Yearly wildfire behavior simulations were conducted for the eight combinations of forest management and climate scenarios in the 143 plots within the study region over an 80-year period (2020–2100). From the wide array of outputs *medfate* provides we selected the surface and crown fire rates of spread (ROS; m min^{-1}) and the crown fire initiation index (CFII; 0–9, dimensionless). The ROS is a key indicator of wildfire hazard and holds a close relation to fire intensity and the geometry of the flame front. Also, active crown fires are the most hazardous propagation mode, often beyond suppression capacity (Pastor et al., 2006). The crown fire initiation index allows us to further understand the likelihood of experiencing an active crown fire event. In order to account for the sensitivity of fire behavior outputs to some critical parameters, simulations were reproduced considering (i) stationary surface fuels (shrubs density kept constant over the analysis period) and canopy fuel moisture equal to woody live fuel moisture content; and (ii) considering non-stationary and canopy fuel moisture equal to woody live fuel moisture content.

2.5. *Statistical analysis*

Trend analysis tests were subsequently applied to the yearly time series of fire behavior outputs to simplify the interpretation and assess their temporal dynamics. We addressed temporal evolution using the Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) to determine whether there were any significant temporal trends in climate, FMC, ROS and crown fire initiation index under both emission pathways. The Sen's slope (Sen, 1968) was used to complete the information from the MK by determining the steepness of the monotonic trend slope, thus quantifying the degree of change and enabling trend comparisons. As input to these statistical analyses, we entered the yearly mean values across all plots for all variables (FFMC, DC, ROS and CFII) except for wind speed and crown fire initiation potential. For wind speed we used the 97th percentile, while for crown fire initiation potential we used the median value. All statistical procedures and plots were developed using the R statistical programming language (R Core Team & R Development Team Core, 2017).

3. Results

3.1. *Climate and fire weather trends*

Projected climate trajectories under RCPs 4.5 and 8.5 were markedly distinct, with the gap between them increasing after 2050 (Fig. S1 and Table S2). Temperature depicts over the study region a clear warming trend, being particularly daunting under RCP 8.5, with an increment on average temperature of 4 °C between 2020 and 2100. Annual mean precipitation and relative humidity projections both showed a downward trend, albeit with greater variability than temperature. Again, the most pronounced change is envisaged under RCP 8.5 during the second half of the century. Wind speed is the only climate feature that would remain stationary regardless of the climatic pathway. These climate trends translate into increasingly hazardous fire weather conditions in terms of FFMC and DC (Fig. 1). Under RCP 4.5, FWI components increase until mid-century followed by a hiatus of approximately 40 years (around 2080) but increasing again towards the 2100. RCP 8.5 exhibit a steady and sustained increase through the century, reaching very high danger conditions in 2100 ($\mathrm{FFMC} \geq 93$ and $\mathrm{DC} \geq 794.5$ according to the European Forest Fire Information System, EFFIS). Consequently, the temporal increasing trends on DC and FFMC were only significant ($p < 0.05$) under the conditions predicted in RCP 8.5 (Table 1).

3.2. *Fire behavior pathways*

The rate of spread of surface fires under RCP 4.5 conditions showed small differences between management scenarios in terms of raw speed and temporal trends (Table 2). But increasing trends were forecasted under RCP 8.5 in the ‘business as usual’ and ‘wood energy’ scenarios.

Crown fire initiation indices were similar for all management scenarios at the beginning of the study period (year 2020), diverging after 2040 and becoming increasingly different after mid-century for certain scenarios (Fig. 3; Fig. S2; Fig. S3). Under both climatic pathways, the ‘wood energy’ scenario would achieve the highest crown fire initiation index (CFII) rates, ranking even above the ‘business-as-usual’ scenario. Meanwhile the management scenario with the lowest CFII rates differs between the two carbon emission pathways. In the case of RCP 4.5 the

Table 1
Results of Mann-Kendall and Sen's slope test for a linear trend for the period 2020–2100 over the study area for annual mean values of Drought Code (DC) and Fine Fuel Moisture Content (FFMC).

FWI component	Climate scenario	MK test p-value	Sen's slope	Average 2020–2030	Average 2090-2100
Drought Code (DC)	RCP 4.5	0.964	0.033	468.5 ± 107.2	506.5 ± 133.6
	RCP 8.5	0.001	2.122	488.9 ± 98.8	676.5 ± 154.3
Fine Fuel Moisture Content (FFMC)	RCP 4.5	0.403	0.007	89.7 ± 1.6	90.6 ± 1.7
	RCP 8.5	<0.001	0.031	89.4 ± 1.4	92.0 ± 1.9

Table 2

Results of Mann-Kendall and Sen's slope test for a linear trend in the period 2020–2100 over the study area for annual median of crown fire initiation index and crown fire rate of spread per forest management scenario and RCP.

Fire behavior feature	Climate pathway	Forest management scenario	MK test trend p-value	Sen's slope	Average 2020–2030	Average 2090-2100
Surface rate of spread (m min-^{1})	RCP 4.5	Vulnerability reduction	0.554	−0.002	6.22 ± 0.415	6.19 ± 0.71
		Business as usual	0.182	0.005	6.42 ± 0.412	6.75 ± 0.739
		Wood energy	0.355	0.003	6.06 ± 0.404	6.11 ± 0.661
		Carbon storage	0.248	0.003	6.22 ± 0.384	6.52 ± 0.571
	RCP 8.5	Vulnerability reduction	0.105	0.004	6.16 ± 0.44	6.53 ± 0.592
		Business as usual	0.005	0.012	6.43 ± 0.423	7.24 ± 0.639
		Wood energy	0.003	0.008	6.09 ± 0.389	6.5 ± 0.564
		Carbon storage	0.248	0.003	6.22 ± 0.384	6.52 ± 0.571
Crown fire initiation index	RCP 4.5	Vulnerability reduction	0.000	−0.012	4.58 ± 0.154	3.93 ± 0.248
		Business as usual	0.252	−0.001	4.69 ± 0.159	4.59 ± 0.219
		Wood energy	0.002	0.006	4.49 ± 0.193	4.6 ± 0.252
		Carbon storage	0.000	−0.011	4.44 ± 0.158	3.69 ± 0.187
	RCP 8.5	Vulnerability reduction	0.000	−0.010	4.33 ± 0.229	4.08 ± 0.646
		Business as usual	0.022	0.002	4.71 ± 0.171	4.82 ± 0.178
		Wood energy	0.045	0.009	4.52 ± 0.135	4.79 ± 0.228
		Carbon storage	0.000	−0.009	4.57 ± 0.153	3.95 ± 0.127
Crown fire rate of spread (m min-^{1})	RCP 4.5	Vulnerability reduction	0.549	−0.005	9.94 ± 1.21	10 ± 1.57
		Business as usual	0.363	0.010	13.5 ± 1.61	14.7 ± 2.43
		Wood energy	0.560	0.005	8.26 ± 1.01	8.11 ± 1.3
		Carbon storage	0.102	0.014	9.86 ± 1.14	11.1 ± 1.65
	RCP 8.5	Vulnerability reduction	0.050	−0.013	9.21 ± 1.47	8.11 ± 2.52
		Business as usual	0.000	0.034	13.5 ± 1.4	16.1 ± 1.74
		Wood energy	0.053	0.017	8.36 ± 0.832	9.13 ± 1.1
		Carbon storage	0.000	0.046	9.74 ± 0.956	13.5 ± 1.43

'carbon storage' scenario presented the lowest crown fire potential followed by 'vulnerability reduction', swapping positions under RCP 8.5. However, it is worth noting that the CFII in the 'vulnerability reduction' scenario shows a sudden rise after 2080 that is not forecasted for 'carbon storage'. Nevertheless, a significant decreasing trend ($p < 0.05$) was predicted in both scenarios. In the 'business as usual' scenario, CFII remained stable -yet high-regardless of the RCP considered (Table 2; Table S3; Table S4).

Predictions for crown fire rate of spread (ROS) differed between forest management and climate scenarios (Fig. 2). For both climate pathways, the highest values of crown ROS were predicted in the 'business-as-usual' scenario while the lowest values were predicted under the 'wood energy' scenario. The least hazardous scenario in RCP 8.5 alternated between 'wood energy' and 'vulnerability reduction', the latter being more efficient towards the end of the century while the first showed stronger variations increasing after mid-century. The crown ROS output in the 'carbon storage' alternative varied significantly between RCPs. Under RCP 4.5 it remained close to 'vulnerability reduction' (same as in CFII) but under RCP 8.5 it would depict a sustained increase rising from 17 m min^{-1} in 2020 to 25 m min^{-1} in 2100, standing the closest to 'business-as-usual' conditions. Trend detection indicated that crown fire ROS can be considered stationary under RCP 4.5 regardless of the management alternative considered (except 'carbon storage' when canopy fuel moisture was considered equal to woody live fuel moisture, which depicted a significant increase; Table S3), though the situation would be very different under RCP 8.5 (Table 2; Table S3; Table S4) where all management alternatives envisaged an increasing trend except for 'vulnerability reduction', which pointed towards a steady shrink in ROS.

Accounting for CFII and ROS together revealed 'vulnerability reduction' as the safest management scenario in terms of fire hazard mitigation (Fig. 4). This scenario provided a good balance between diminishing crowning potential while keeping the ROS not only low (also in case of surface ROS) but decreasing all over the century. Under RCP 4.5 it was close to 'carbon storage' and could even be considered more efficient than 'wood energy' which stood higher in terms of CFII but lower in ROS. However, under RCP 8.5 it was markedly the best candidate since it minimized both metrics. Temporal variability was lower, which granted the confidence that fire outputs would not escalate or peak at any time. Nevertheless, any management scenario would improve 'business-as-usual' conditions.

3.3. *Sensitivity to modeling assumptions*

The comparison of fire behavior outputs under different assumptions -stationary surface fuels and canopy moisture equal to woody live fuel moisture content-revealed consistent temporal profiles in the forecasted dynamics (Fig. 3; Fig. S2; Fig. S3), with only slim differences regarding the baseline.

When shrub dynamics were disregarded (Fig S3 and Table S4), the trend analysis suggested both increasing and decreasing trajectories despite the steady decrease in fuel moisture content (Fig. 2). Conversely, inducing shrub dynamics led to only positive significant trends with an increase of 0.5 m min^{-1} the rate of spread in all the simulations conducted. The trends and dynamics in crown fire activity were similar among the two parameterizations of surface fuels, though both crown fire initiation potential and rate of spread were slightly lower in the non-stationary shrub layer experiment.

The main difference was found in crown fire ROS under RCP 4.5, which depicted a significant increase in the 'carbon storage' when canopy fuel moisture was considered equal to woody live fuel moisture; Table S3), a trend that does not appear in the baseline scenario (canopy moisture 30% higher than shrub's), which suggests no significant dynamics in all management scenarios.

4. Discussion

This study proposes and exemplifies an integrative modeling framework that considers the influence of climate, forest dynamics and management on wildfire behavior. Our results revealed that, despite the clear influence exerted by climate, forest management can modulate fire behavior potential. In general, the maintenance of current management practices would result in high rates of crown fire activity, while active forest management oriented to reduce the vulnerability of forests to drought could mitigate the increasingly hazardous conditions envisaged under RCP 8.5.

4.1. *Effects of forest management and climate scenarios on fire hazard*

Forest management plans hold the potential to override climate-

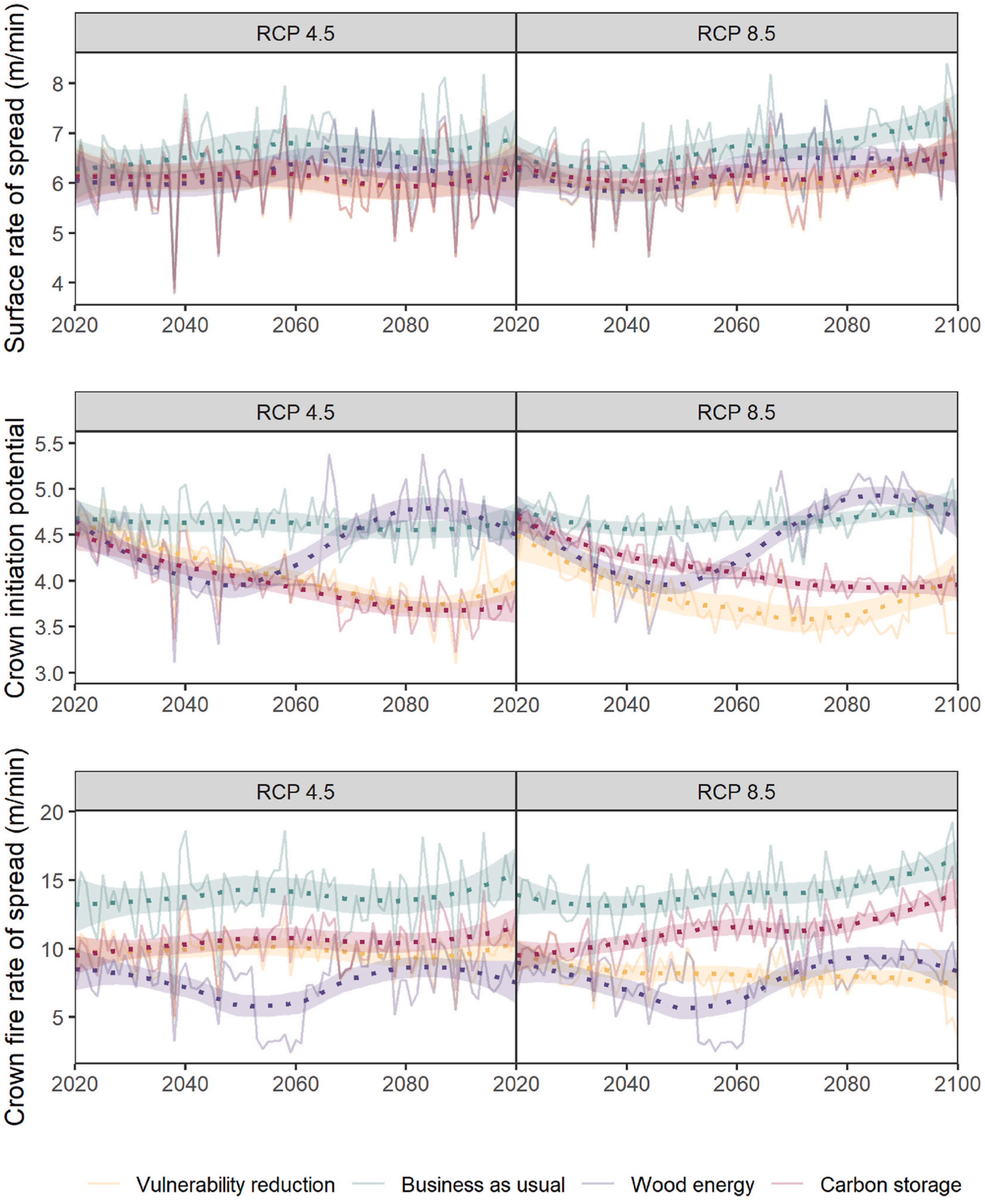

Fig. 3. Projected changes in fire behavior between 2020 and 2100 based on different climatic and management scenarios. Top: median annual surface rate of spread; Mid: median annual crown fire initiation index; Bottom: Solid lines represent mean values from all plots; dotted lines depict the trend with locally estimated scatterplot smoothing approach (LOESS); transparent halo outlines the variability range of the LOESS profile.

induced changes in fire behavior. According to previous studies (Johnston et al., 2021; Palmero-Iniesta et al., 2017; Piqué and Domènech, 2018) forest management can reduce ROS, even though its effectiveness depends on several factors, such as treatment intensity (Cochrane et al., 2012) or the interaction with the understory (Madrigal et al., 2017). Despite our focus being placed in canopy dynamics, our modeling approach suggested an increase in surface fire rate of spread under current management prescriptions ('business as usual') or linked to the promotion of biomass as an energy resource in a 4C° warming scenario (RCP 8.5). Our results support forest management as a key driver of crown fire initiation, drawing diverging trajectories depending on the management alternative. Scenarios implementing intense and regular thinning treatments (e.g., 'vulnerability reduction' and 'wood energy') attained the highest potential to reduce crown fire activity (Johnston et al., 2021). The use of regular thinning is known to increase the crown base height of the remaining trees (Piqué and Domènech, 2018) thus reducing the gap between the understory and the canopy layer and through this the crowning potential (Cruz et al., 2014). Shrub removal can indeed change the fire behavior (Madrigal et al., 2017). The shrub layer greatly determines flammability, amount of fuel, surface ROS and crowning potential through fuel ladders. For instance, opening the canopy through thinning operations can enhance shrub growth and biomass through increased light interception in the understory (Fig. S6) although the temporal variation in fuel characteristics of Mediterranean understory layers tends to be rather small (Sánchez-Pinillos et al., 2021). Unfortunately, this study did not include height shrub dynamics because these processes are not implemented in the current version of SORTIE-ND, though we do incorporate the variation in shrub density as

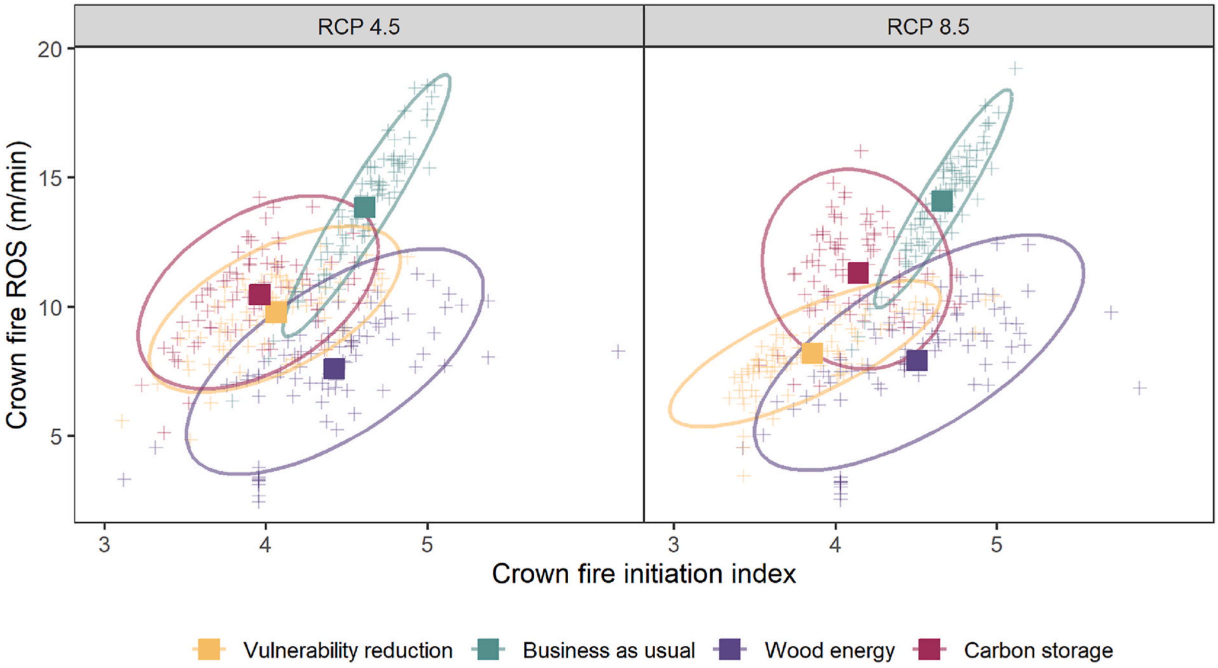

Fig. 4. Comparative summary of crown fire behavior dynamics. Small crosses show annual averages of fire behavior metrics. Squares and ellipses indicate the mean and degree of dispersion for each management scenario.

a result of changes in tree basal area, which enabled some degree of response to fuel treatments. Moreover, live moisture content can vary from species to species (Jurdao et al., 2012), and here we assumed it to be the same for all species. Therefore, we acknowledge there is room for improvement in the determination of CFII.

The carbon emission pathway exerts a high influence on the crown rate of spread output. Under RCP 8.5 forest management influence was especially evident and each management scenario followed their own path. Nevertheless, 'vulnerability reduction' was the only management strategy that reduced crown fire ROS throughout the simulation period. Silvicultural itineraries applied with the objective to reduce drought vulnerability include the use of early, regular, and intense (in terms of percentage of basal area removal) thinnings under RCP 8.5. These treatments increase the space between the canopies of the remaining trees leading to a reduction of crown ROS values (Fig. S6; see also Jiménez et al., 2016). It is worth mentioning that the positive effect of the thinning treatments on crown ROS may only take place if regular interventions are planned. In the opposite case (i.e., if a unique thinning treatment is applied), the enhanced crown development of the remaining trees in response to the intervention may rapidly lead the stand to pre-thinning horizontal continuity values (Ameztegui et al., 2017). Conversely, the highest crown ROS was obtained in the 'business as usual' scenario followed by 'carbon storage'. Both management strategies encompass lower intensity harvests that can lead to higher horizontal continuity in the forest. In the case of 'business as usual', this can be aggravated by the high densities and small mean diameter achieved by the trees, which entails a higher proportion of dead branches and a higher vertical fuel continuity.

This study builds on the ecosystem service evaluation made by Morán-Ordóñez et al. (2020) on the same study area, who also concluded management plays a stronger role than climate in terms of future ecosystem service provision by Mediterranean forests. In this regard, the capacity of forest management to reduce fire hazard should be evaluated against other potential benefits (or trade-offs) for the forest health itself and the benefits people get from them, so that more informed decisions can be made, and negative trade-offs can be minimized. For example, Morán-Ordóñez et al. (2020) projected the 'business-as-usual' scenario to provide the highest levels of habitat for biodiversity, carbon storage and soil erosion mitigation capacity among all scenarios by the end of the century. But as shown here there is a high probability these projections might never be eventuated because of the high fire potential associated to the forest structure resulting from this management (high basal area and stem density leading to high CFII and ROS). Moreover, while fires are the main disturbance of Mediterranean forests, these trade-offs between forest management, service provision and forest vulnerability reduction should be evaluated considering other potential disturbances that will increase in the face of climate change such as pests, pathogens or prolonged droughts (Seidl et al., 2017).

The comparison between stationary vs non-stationary shrub layer suggests the latter to be more realistic. Actually, the first shows decreasing trends in the surface rate of spread in some management scenarios, despite the increasing FFMC and DC (hence decreasing moisture content). After inducing shrub dynamics only positive trends were significant while the rate of spread output increased. Overall, the trends and dynamics in crown fire activity were similar, though both crown fire initiation potential and rate of spread were slightly lower in the non-stationary shrub layer experiment.

4.2. Modeling framework and potential limitations

Our modeling framework proved a valuable approach to assess fire risk under different management and climate scenarios, and to provide valid tools for forest managers and decision-makers. Nonetheless, it has some limitations that must be considered to properly frame our findings. Some of them are inherited from the capability of SORTIE-ND to simulate vegetation dynamics, which does not include shrub dynamics. We have incorporated the dynamism of the shrub layer using empirical relationships based on basal area, but we are still keeping shrub height constant, hence CFII outputs should be carefully considered. Likewise, we assume no forest succession nor changes in dominant species throughout the simulated period. However, we find this assumption rather realistic, given that the management scenarios were designed with local experts based on the achievement of specific objectives through pine management, and thus assumed the dominance of pine throughout the simulated period. Obviously, further analyses considering transitions into *Quercus* species (e.g., *Quercus ilex; Quercus faginea*) would lead to a more complete picture of the forecasted dynamics (Martín-Alcón and Coll, 2016), but were beyond the aim of this study.

Furthermore, fire behavior simulation involves a large number of parameters influencing the outcomes, being particularly prone to errors when fuel treatments are involved such as uncertainties in projecting fuel accumulation and the role of decomposition or the effects of canopy openness in wind speed (Hanan et al., 2022; Varner and Keyes, 2009). The results from the sensitivity analysis suggest that the trajectories in crown fire metrics are consistent, but small changes were observed in the surface rate of spread. By incorporating the temporal variation of the shrub layer the trajectories for surface ROS seem more realistic, i.e., slight increase towards 2100, specially under RCP 8.5 and business as usual management. In this regard, it must be noted that the assumption of complete removal of harvest residues after treatment may lead to slight underestimation of surface fire behavior and crown fire initiation potential due to the reduced surface fuel load.

Finally, our approach focuses on analyzing the potential fire behavior, though it does not account for fire regime interaction with vegetation. We assumed that suppression is completely successful and no other disturbance affect stands, i.e., only forest management modifies forest structure. Studies that explicitly account for full interactions among fire, climate, vegetation have been implemented using dynamic global vegetation models (Hantson et al., 2016). Yet, such models often struggle to represent interannual variations in fire activity and observed trends (Forkel et al., 2019; Hantson et al., 2020; Jones et al., 2022). In order to overcome these limitations projections and relationships about the probability of ignition or the capability to contain fires under climate warming scenarios could be accounted for (Rodrigues et al., 2022).

5. Conclusions

Under ongoing climate warming conditions, fuel moisture content is expected to decline, worsening fire weather conditions, and increasing fire danger, and hence, hazard. However, in this study we showed forest management can play a key role at modulating future wildfire conditions or forest vulnerability to fire. Our findings stress the importance of devising appropriate management plans and evidence how placing the focus on a particular forestry narrative can lead to very contrasting situations under different climate conditions. In general, the maintenance of current practices would result in the highest rates of crown fire activity. Jointly accounting for the potential for crown fire initiation and the subsequent rates of spread reveals that the 'vulnerability reduction' management scenario, initially targeted at minimizing forest vulnerability to drought, is the soundest management alternative -among the ones we tested-due to its ability to minimize and reduce crowning while keeping rate of spread not only low but decreasing over the century. Likewise, it has been also projected to be highly efficient in providing certain ecosystem services such as harvested timber and water supply. Conversely, the promotion of certain forest management goals, such as wood energy production, may be only safe to encourage under RCP 4.5. The integration of management strategies that seek to reduce vulnerability to disturbances while ensuring the provision of reasonable amounts of other services is however to explore, and merits further research.

Author contribution

Lauma E. Miezite: Conceptualization, Methodology, Writing – original draft, Data curation, Formal analysis, Writing- Reviewing and Editing. **Aitor Ameztegui**: Supervision, Software, Resources, Funding acquisition. **Miquel De Cáceres**: Software, Writing- Reviewing and Editing. **Lluís Coll**: Writing- Reviewing and Editing, Funding acquisition. **Alejandra Morán-Ordóñez**: Resources, Writing- Reviewing and Editing, **Cristina Vega-García**: Writing- Reviewing and Editing, Funding acquisition. **Marcos Rodrigues**: Conceptualization, Visualization, Writing – original draft, Supervision, Project administration, Funding acquisition, Writing- Reviewing and Editing.

Data statement

Forest inventory data can be freely downloaded from the website of the Ministry for Ecological Transition and the Demographic Challenge (https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3_bbdd_descargas.htm.aspx). Climate prediction data were based on the EU-CORDEX project (available at Earth System Grid Federation; http://esgf.llnl.gov/). The original weather data is available at the Spanish Meteorological Agency upon request.

Funding

This work was funded by the Spanish Ministry of Science and Innovation, projects FIREPATHS (PID 2020-116556RA-I00) and UMBRACLIM (PID 2019-111781RB-I00), and by the ERANET FORESTERRA project INFORMED (grant number: 29183). LEM was funded with a scholarship by the MSc in European Forestry Programme at the University of Lleida. This work was also funded by project FirEUrisk - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116134.

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