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Wildfire connectivity under drought-induced impacts and landscape management strategies

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Abstract:	Global warming and land-use changes have increased wildfire risk in Mediterranean regions. Landscape management strategies (LMS) have the potential to reduce extreme wildfire behavior through the maintenance and recovery of traditional agroforestry mosaics. However, we still have very limited knowledge about LMS viability regarding their interaction with the ongoing scalation of drought-induced forest mortality. Here, we assess how drought impacts interact with LMS to shape wildfire connectivity in the Barcelona Metropolitan Region (NE, Spain). We simulated forest dynamics and fire connectivity from 2015 to 2050 under a Business-as-usual LMS by applying process-based modeling and considering two climatic scenarios differing in the degree of drought intensity. Then, we analyzed differences in wildfire connectivity patterns arising from the interaction between drought events and three alternative LMS: Crop-recovery, Harvesting-increase, and Drought-stands-logging. According to our simulations, forest dynamics and drought-induced impacts modified stand structures and fine fuel loads, ultimately reducing fire connectivity by 2040-2050. A larger fire connectivity reduction occurred under a higher incidence of extreme-drought events, although this scenario was also associated with short-term fire connectivity peaks. Crop-recovery decreased fire connectivity regardless of the drought intensity, while Harvesting-increase resulted in fire connectivity patterns similar to Business-as-usual under both climatic scenarios. Drought-stands-logging resulted in the greatest and more spatially even reduction in fire connectivity when simulated under high drought intensity, due to the elimination of short-term peaks following drought episodes. In conclusion, there is room for combining drought-induced impacts with LMS to reduce wildfire connectivity at regional scales in fire-prone Mediterranean areas.

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Wildfire connectivity under drought-induced impacts and landscape management strategies

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Dear Editor,

I would like to kindly ask you to consider our research article entitled *"Wildfire connectivity under drought-induced impacts and landscape management strategies"* for publication.

Recent climate and landscape alterations have led to strong changes in fire regimes that threaten both the environment and society. Landscape management strategies (LMS) have the potential to reduce wildfire risk through the recovery of agroforestry mosaics in which fire spreads more slowly, burns with less intensity, and is less costly to suppress. However, we still have very limited knowledge about LMS viability in reducing wildfire connectivity at regional scales, due to the uncertainties arising from their interaction with the ongoing scalation of drought-induced forest mortality episodes.

In this study we assess the extent to which the effects of extreme drought events interact with LMS to influence fire connectivity in the Barcelona Metropolitan Region (NE Spain). We show how drought-induced effects can reduce wildfire connectivity, and how the interaction between these effects and landscape management strategies can further increase this reduction. A higher incidence of extreme drought events resulted in greater mid-term reductions in fire connectivity, although this scenario was also associated with short-term peaks in fire connectivity. Therefore, we show how there is room for combining drought-induced impacts with LMS to reduce fire connectivity in the mid-term while eliminating short-term peaks at local and regional scales in fire-prone Mediterranean areas.

To the best of our knowledge, this study represents the first attempt to explore through process-based modeling how drought-induced impacts can interact with landscape management strategies to shape fire connectivity.

All authors have read and approved the final version of the manuscript. This manuscript is not under consideration for publication elsewhere. Finally, we declare that we do not have any conflict of interest.

Thank you for your consideration.

Sincerely,

Dr. Rodrigo Balaguer-Romano, on behalf of all authors

Highlights

- Forest dynamics and drought impacts modifies stand structure and fine fuel load
- Extreme droughts result in mid-term fire connectivity declines and short-term peaks
- Drought impacts and LMS interaction reduce wildfire connectivity at regional scale
- *Crop-recovery* reduces fire connectivity, *Harvesting-increase* equals *Business-as-usual*
- *Drought-stands-logging* results in the greatest and evenly fire connectivity decline

Abstract

Global warming and land-use changes have increased wildfire risk in Mediterranean regions. Landscape management strategies (LMS) have the potential to reduce extreme wildfire behavior through the maintenance and recovery of traditional agroforestry mosaics. However, we still have very limited knowledge about LMS viability regarding their interaction with the ongoing scalation of drought-induced forest mortality. Here, we assess how drought impacts interact with LMS to shape wildfire connectivity in the Barcelona Metropolitan Region (NE, Spain). We simulated forest dynamics and fire connectivity from 2015 to 2050 under a *Business-as-usual* LMS by applying process-based modeling and considering two climatic scenarios differing in the degree of drought intensity. Then, we analyzed differences in wildfire connectivity patterns arising from the interaction between drought events and three alternative LMS: *Crop-recovery*, *Harvesting-increase*, and *Drought-stands-logging*. According to our simulations, forest dynamics and drought-induced impacts modified stand structures and fine fuel loads, ultimately reducing fire connectivity by 2040-2050. A larger fire connectivity reduction occurred under a higher incidence of extreme-drought events, although this scenario was also associated with short-term fire connectivity peaks. *Crop-recovery* decreased fire connectivity regardless of the drought intensity, while *Harvesting-increase* resulted in fire connectivity patterns similar to *Business-as-usual* under both climatic scenarios. *Drought-stands-logging* resulted in the greatest and more spatially even reduction in fire connectivity when simulated under high drought intensity, due to the elimination of short-term peaks following drought episodes. In conclusion, there is room for combining drought-induced impacts with LMS to reduce wildfire connectivity at regional scales in fire-prone Mediterranean areas.

Key words

Climate-change adaptation, drought-induced forest mortality, forest dynamics, process-based modeling, wildfire management, wildfire risk.

1. Introduction

Climate change is rising the frequency, intensity and duration of heat waves and extreme drought events in Mediterranean regions (IPCC, 2023). Several studies have related climate aridification with fire season lengthening, concluding that climate change is escalating fire danger by increasing the availability of wildfire fuels, *i.e.* plant biomass (Balaguer-Romano et al., 2023). Furthermore, the cessation of traditional silvicultural and agricultural practices has led to shrub encroachment and forest densification in many areas (Palmero-Iniesta et al., 2020), increasing fuel loads and their vertical and horizontal connectivity (Salis et al., 2022). In these landscapes, drought episodes trigger spatial connectivity between dry vegetation patches at the landscape-scale, paving the way for the occurrence of extreme wildfire events (Duane et al., 2021a). Thus, despite Mediterranean forests are naturally fire-prone ecosystems, recent climate and landscape alterations have led to strong changes in fire regimes that threaten both the environment and society (Rodrigues et al., 2023).

From a landscape-scale perspective different strategies have been proposed to cope with the ongoing fire risk escalation (Neidermeier et al., 2023). In the Euro-Mediterranean countries, landscape management strategies (LMS) aim to increase land-cover and fuel-structure heterogeneity by preserving or promoting the traditional agroforestry mosaics in which wildfires spread more slowly, burn with less intensity, and are less costly to suppress (Lecina-Diaz et al., 2023; Moreira et al., 2011). Thus, the recovery of former croplands can increase forest cover discontinuity and establish a sort of “agricultural belts” protecting urban areas from wildfires while facilitating firefighting operations (Aquilué et al., 2020; Moreira and Pe’er, 2018). Additionally, an increase in forest silviculture practices, like wood harvesting and stand thinning, can also contribute to reducing fire risk by diminishing fuel loads and the fuel ladder (Palmero-Iniesta et al., 2017; Piqué and Domènech, 2018). However, up to date the implementation of these landscape management strategies has mostly failed due to a lack of economic viability and the ongoing rural depopulation (Lasanta et al., 2017). Therefore, forest encroachment and reduced management practices persists in Mediterranean-type landscapes (Roces-Díaz et al., 2021), while future socioeconomic scenarios even forecast an increasing abandonment of rural activities (Perpiña Castillo et al., 2021).

Simultaneously to passive forest expansion after land abandonment, an increase in drought-induced forest mortality episodes is also occurring in recent years (Hartmann et al., 2022; Xu et al., 2024). Forest mortality episodes trigger the amount and connectivity of dry fuels increasing fire rates of spread at short (annual) time scales (Stephens et al., 2018). Yet, there is uncertainty surrounding whether a higher incidence of extreme drought events may interact with forest dynamics to affect fire behavior at longer time scales. Mid-term (decadal) effects of drought-induced impacts on forest dynamics could result in a reduction of tree density and fine fuel loads at the stand-level, thereby declining crown fire potential but increasing surface fire intensity (Stephens et al., 2018). It also remains unexplored how the effects of extreme drought episodes can interact with management strategies that seek to reduce fire risk at the landscape level. Furthermore, given the negative short-term effects of drought on fire behavior, it would be interesting to assess to which extent fire risk can be reduced by partial logging activities in drought-affected stands to reduce fuel loads and dry fuels connectivity immediately after the drought episode.

Notwithstanding the potential of LMS to shape fire behavior, we still have very limited knowledge about their performance at regional-scale and their effectiveness in interaction with the incidence of extreme drought events forecasted for the next decades. These uncertainties arise from the few empirical evidence and the fact that fire behavior models are not designed to capture the effects of drought events on forest dynamics (Dickman et al., 2023). However, these uncertainties could be reduced through the application of process-based models to simulate forest functioning and dynamics in a spatially explicit context, thanks to their ability to mechanistically represent the interaction between drought-induced impacts and species-specific physiological responses (Torres-Ruiz et al., 2023). In addition, process-based models can incorporate land-use change projections from landscape models, such as the recovery of croplands, as well as simulate forest harvesting scenarios. Finally, the outputs from process-based simulations of forest dynamics can be used as inputs in fire behavior models to estimate fire connectivity metrics at different temporal and spatial scales. Thus, while fire behavior describes expected local properties of fires, such as the rate of spread, connectivity outputs describe the spatial arrangement of areas with similar fire properties that could facilitate a contiguous fire spread across the landscape (Buchholtz et al., 2023). Overall, coupling process-based simulations with fire behavior models appears an attractive tool for exploring and evaluating the interaction between drought intensity, forest dynamics, and management strategies in shaping wildfire components at the landscape-scale.

In this study we sought to assess to which extent the impacts of extreme drought events interact with LMS to affect fire connectivity in the Barcelona Metropolitan Region (BMR). To meet this objective, we simulated forest dynamics and functioning using the process-based model MEDFATE (De Cáceres et al., 2023) in different settings: (i) historic forest dynamics from 2015 to 2023 under a demand-based management scenario defined by current wood harvesting metrics in the region; (ii) future forest dynamics until 2050 under a *"Business-as-usual"* LMS in which we replicated the same harvesting metrics of the historic period under two projected climatic scenarios differentiated by the degree of drought intensity (*low-drought* and *high-drought*); and (iii) future forest dynamics until 2050 under both climatic scenarios modeling three alternative LMS: recovery of former agricultural lands recently abandoned (*Crop-recovery*), increase of current wood harvesting rates under a bioeconomy-oriented strategy (*Harvesting-increase*), and partial logging of drought-affected forest stands (*Drought-stands-logging*). Finally, we applied the OMNISCAPE algorithm (Landau et al., 2021) to model historic (2020-2023) and future (2040-2050) fire connectivity and compared the results of each LMS under both climatic scenarios. Overall, we hypothesize temporal and spatial variations in fire connectivity values from historic to future periods mediated by the interplay between forest dynamics (*i.e.* plant growth-mortality and forest succession) and drought intensity effects. We also hypothesize that the application of alternative LMS will result in a reduction in fire connectivity, although this would vary depending on the strategy applied and the level of drought intensity considered. This study represents the first attempt to explore through process-based modeling to which extent drought-induced impacts can interact with landscape management strategies to shape fire connectivity at a regional scale in a fire-prone Mediterranean area.

2. Materials and methods

2.1. Study area

With 313,000 ha and a population of 5.4 million people, the Barcelona Metropolitan Region (BMR) in NE Spain, is one of the most densely populated regions in Europe (1,730 people per km^2). The climatic and topographic contrasts (elevation range from 0 to 1,700 m), together with a historical and continued presence of human settlements, have resulted in a heterogeneous landscape. However, the BMR has experienced significant changes in land-use and land-cover since the 1950s, when the abandonment of former cropland areas gave way to passive forest expansion processes that have increased forest and shrubland cover at the expense of agroforestry mosaics (Palmero Iniesta et al. 2021). Furthermore, the sprawl of housing and infrastructures during the last decades (Bar-Massada et al., 2023) has increased wildland-urban interface areas (WUI). Therefore, the current land cover map (Fig. 1, ICGC, 2018) shows that wildland areas, including forests and shrublands cover up to 58% (180,000 ha), while cropland areas occupy 18% (58,000 ha) and artificial uses, including urban areas and infrastructures cover up to 23% (71,000 ha). Increasingly frequent extreme drought events have triggered forest mortality episodes in the region, resulting in an unprecedented number of hectares of drought-affected stands in recent years (*i.e.* 66,500 ha in all Catalonia in 2023; Banqué and Vayreda, 2023). Moreover, the BMR is a fire-prone area with recurrent wildfires associated to heat wave episodes (Alcasena et al., 2019), with 70 fire events being recorded between 2000 and 2023 that reached a total burned area of 5,700 ha (GENCAT, 2024).

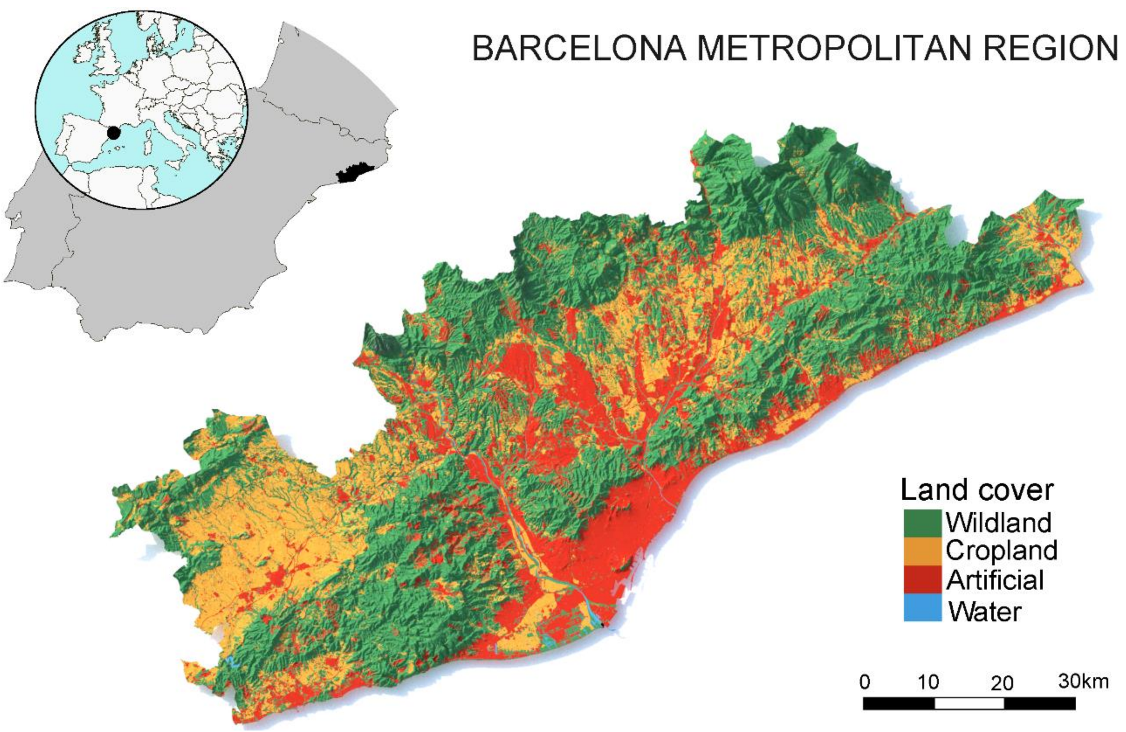

Figure 1. Barcelona Metropolitan Region location, topography, and land cover types (ICGC 2018).

2.2. Forest dynamics modelling

We simulated forest functioning and dynamics using the MEDFATE process-based model (available in the R package *"medfate" v.4.8.0,* De Cáceres et al. 2023) by using "*medfateland*" *(v.2.5.2)*, an R package that applies the model to a spatially explicit context (De Caceres et al., 2025). The performance of the MEDFATE model in simulating forest dynamics was previously evaluated and validated with observed data from plots of the Spanish National Forest Inventory located within the region of study area (De Cáceres et al. 2023). To create the model spatial inputs, we first rasterized the study area at 200 m resolution (4 ha) per grid cell. Then, in each cell with a wildland cover (*i.e.* forest and shrubland areas), we loaded topographic, soil, and vegetation data to simulate forest dynamics (*i.e.* plant growth-mortality and forest succession) at the stand-level (landscape initialization data input description and sources in Supplementary Information S1). The resulting initialized landscape showed that 90% of wildland cells were composed of forests, including both tree and shrub species within the overstory and understory stratums, while the remaining 10% were composed of shrublands, only including shrub species. Whereas shrubs species within forest cells (90%) were included in forest dynamics simulations, shrubland cells (10%) were assumed not to change their status in terms of biomass during the simulations. Forest stands were mostly dominated by coniferous species, with *Pinus halepensis* (Aleppo pine) being dominant in 50% of the forest cells, followed by *Quercus ilex* (Holm oak) and *Pinus pinea* (Stone pine), each dominant in 15% of the forest cells (see Supplementary information S2). As forest stands structure and composition were obtained from the fourth Spanish National Forest Inventory, which was carried out in 2015, we ran a first round of forest dynamics simulations corresponding to the 2015-2023 period (hereafter, historic period). We then took the forest stands structures obtained at the end of this period as a starting point for simulations of future forest dynamics up to 2050. To examine the effects of drought intensity, future forest dynamics simulations were simulated under two projected climatic scenarios, differentiated by the incidence of extreme drought events, hereafter referred to as *low-drought* and *high-drought* climatic scenarios (meteorological data input description and sources in Supplementary Information S3). To account for the incidence of forest management on forest dynamics, simulations from 2015 to 2023 were run under a demand-based management scenario defined by the average recorded volumes of wood harvested per species and county between the 2010-2020 period, which resulted in 99,500 m^3 yr^{-1} (wood harvesting data in Supplementary Information S4). Silvicultural management parameters were established and simulated following the guidelines for sustainable forest management in Catalonia (ORGEST). Wood harvesting activities were allowed to occur in any forest cell except those with a slope above 40%, as it barely occurs owing to challenges for equipment and material transport (Neidermeier et al., 2023). We then applied the same demand-based management scenario and silvicultural prescriptions to simulate forest dynamics from 2024 to 2050 under both climatic scenarios (*low-drought* and *high-drought*). As we were maintaining current wood harvesting rates and no changes in other land covers were simulated, hereafter we refer to this first future forest dynamics projection as the *Business-as-usual* landscape management strategy.

2.3. Alternative landscape management strategies (LMS)

We evaluated the interaction between the two climatic scenarios and three alternative LMS potentially influencing wildfire behavior: i) recovery of former agricultural lands recently abandoned to diminish forest connectivity (hereafter *Crop-recovery*), ii) increase of current wood harvesting rates under a bioeconomy-oriented strategy aimed to reduce fuel accumulation (hereafter *Harvesting-increase*), and iii) partial logging of dead trees in drought-affected forest stands to test for the effects of focusing management on forests affected by these increasing disturbance events (hereafter *Drought-stands-logging*). The comparison in these three LMS were co-designed in a workshop with key stakeholders (including forest landowners, forest managers, representatives of rural-development-agencies and representatives of protected areas) from the BMR (https://www.wilde-project.eu/news/stakeholder-engagement-workshop-in-the-barcelona-metropolitan-region).

To model the *Crop-recovery* LMS, we first obtained the location of former croplands from the “recoverable-agricultural-land” map developed by the Barcelona Provincial Council (DIBA, 2023). This map represents the former agricultural sites that were abandoned after 1956, excluding sites with a slope greater than 40% and a size of less than 1000 m^2. To increase the degree of feasibility of this LMS we only considered the recovery of former agricultural lands currently classified as abandoned croplands or pastures, excluding areas that have recorded passive forest expansion processes and are currently classified with forestry land-use (SIGPAC, 2022). Next, we took the forest dynamics simulations under the *Business-as-usual* scenario but changing in one step the land cover type to "cropland" in all wildland cells that included more than 51% of "recoverable-agricultural-land" areas. After all, in this LMS we modeled the recovery of 17,000 ha of former agricultural lands, decreasing the forest surface in the BMR by 10% and increasing 33% the current croplands cover. To model the *Harvesting-increase* LMS, we simulated forest dynamics under a demand-based management scenario that increases the species-specific volumes of wood harvested applied in the *Business-as-usual* LMS by 60% according to target predicted by the regional government (Banqué et al., 2023), resulting in an annual rate of wood harvesting of 160,000 m^3 yr^{-1}. Finally, in the *Drought-stands-logging* LMS we used the forest dynamics simulations from the *Business-as-usual* scenario but we excluded from the annual wildfire modelling framework (described below) the dead fine fuel loads at a given cell if the forest stand recorded a mortality rate higher than 5% during a given year, as this is the minimum threshold to identify a drought-induced forest mortality episode according to Banqué and Vayreda (2023).

2.4. Wildfire modelling

We estimated the annual characteristics of live and dead fine fuels for each wildland cell applying the Fuel Characteristic Classification System model (Prichard et al., 2013) implemented in the "*medfate*" R package (fine fuel modeling framework in Supplementary Information S5). We then used fine fuel characteristics and the slope of the terrain values to model local fire behavior in each wildland cell and year. Fire behavior was modeled under the standard conditions of 24 km h^{-1} wind speed (at 6 m over vegetation) and 97^{th} percentile fuel moisture conditions (5% to 3% for dead fuel moisture, 45% and 90% for live herbaceous and woody fuel moisture; Keane, 2015). We modeled the annual crown and surface fire rate of spread (ROS, m min^{-1}), keeping only the highest value in each wildland cell. We assigned a minimum ROS of 0.1 m min^{-1} to all cropland cells, and missing values to all artificial cells. Finally, we applied ROS raster maps in the *"Omniscape.jl" (v 0.6.2)* circuit-based algorithm (Landau et al., 2021) to estimate fire connectivity across the BMR. Thus, OMNISCAPE estimated in each 4-ha grid cell the number of cumulative pathways for fire to spread by assuming that a fire originates in source cells with high ROS values and flows to adjacent cells within a moving window (Omniscape initialization data input description and files in Supplementary Information S6).

2.5. Data analysis

We estimated average fire connectivity values per cell during the historic period from 2020 to 2023 (as 2020 was the first year that could account for the dead fine fuels loads of the last 5 years; Supplementary Information S5) and at the future period from 2040 to 2050 considering each climatic scenario and LMS combination. For data analyses and visualization, we classified average fire connectivity values of the historic period into 20 quantiles, by defining connectivity classes with the same frequency of occurrence. Connectivity classes from 0 to 10 were consider as “low” fire connectivity, whereas classes from 11 to 20 were considered as “high” connectivity. We applied these 20 quantiles to classify all future fire connectivity values and examine changes in the frequency of connectivity classes and the corresponding area affected. We also estimated delta values (Δ) to assess fire connectivity frequency changes between the historic and future periods, between both climatic scenarios (to assess drought intensity effects), and between the *Business-as-usual* and the other three LMS.

3. Results

3.1 Historic fire connectivity (2020-2023)

The average fire connectivity modeled in the historic period (2020-2023) showed a spatial NW-SE gradient from lower to higher values (Fig. 2). These patterns were driven by fire ROS values which ranged from 0 to 230 m min^{-1} with a mean of 28.5 ± 0.1 (Fig. S7). As we purposedly kept constant the values of the fire weather components (*i.e.* wind speed and fuel moisture) in fire behavior assessments, fine fuel characteristics were the primary driver of fire connectivity. Therefore, fire connectivity values showed a spatial matching with forest stands composition, as the areas with lower values matched with forest stands dominated by broadleaf species (mostly *Quercus spp.*), while higher fire connectivity values were related to forest stands dominated by more fire prone coniferous species (mostly *Pinus halepensis*, see Supplementary Information S2).

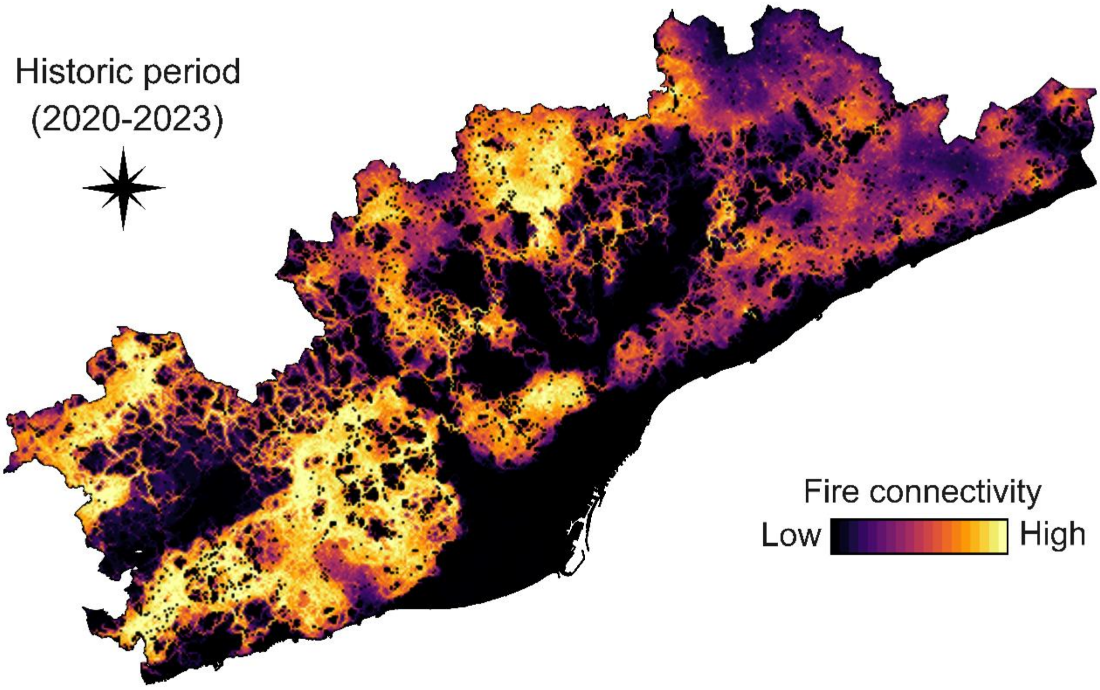

Figure 2. Average fire connectivity values modeled in the historic period (2020-2023). Dark and light colors represent areas with lower and higher fire connectivity values, respectively. Fire connectivity values refer to the cumulative pathways for fire to spread and to connect areas with modeled high fire rate of spread (ROS m min^{-1}).

3.2 Future fire connectivity (2040-2050)

We recorded an overall but moderate reduction in fire connectivity at the end of both *Business-as-usual* simulations (2040-2050), regardless of which climatic conditions were used (*i.e. low-drought,* Fig. 3a or *high-drought,* Fig. 3b). Thus, the average historic fire connectivity value of 184.5 ± 0.8 (representing the cumulative pathways for fire to spread) declined to 173.4 ± 0.7 and to 150.5 ± 0.6 when simulated under *low*- and *high-drought* conditions, respectively (Table 1). Even though average fire connectivity decreased at the regional-scale, we also recorded fire connectivity increases at local-scales in both future drought scenarios. Thus, 31% and 22% of the study area recorded fire connectivity increases from historic to future periods under *low*- and *high-drought* conditions respectively (orange areas in Fig. 3a-b). We observed a spatial matching between these fire connectivity changes from historic to future periods and fine fuel loading changes at canopy, shrub and ground woody layers (Fig. S8), indicating that simulated plant growth-mortality and forest succession processes modified stand structures resulting in a reduction of the fine fuel load by the 2040-2050 decade.

Table 1. Distribution of fire connectivity values in the historic period (2020-2023), and in the future period (2040-2050) modeled under *low-drought* and *high-drought* climatic scenarios considering the *Business-as-usual* (BAU), *Crop-recovery* (CRO), *Harvesting-increase* (HAR) and *Drought-stands-logging* (LOG) landscape management strategies.

	Historic (2020-2023)	*Low-Drought (2040-2050)*				*High-Drought (2040-2050)*			
		BAU	*CRO*	*HAR*	*LOG*	*BAU*	*CRO*	*HAR*	*LOG*
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1st Q.	41.0	44.4	36.7	43.8	43.3	38.5	31.5	38.3	30.3
Median	113.2	113.6	101.6	113.7	110.9	98.7	89.0	99.1	82.7
Mean and SE	184.5 ± 0.8	173.4 ± 0.7	164.4 ± 0.7	171.5 ± 0.7	170.8 ± 0.7	150.5 ± 0.6	143.1 ± 0.6	148.5 ± 0.6	133.0 ± 0.5
3rd Q.	266.5	259.6	246.6	257.6	255.3	225.9	215.1	223.5	200.7
Max	1,870.3	1,760.1	1748.7	1757.8	1722.7	1,430.2	1446.4	1617.2	1287.6

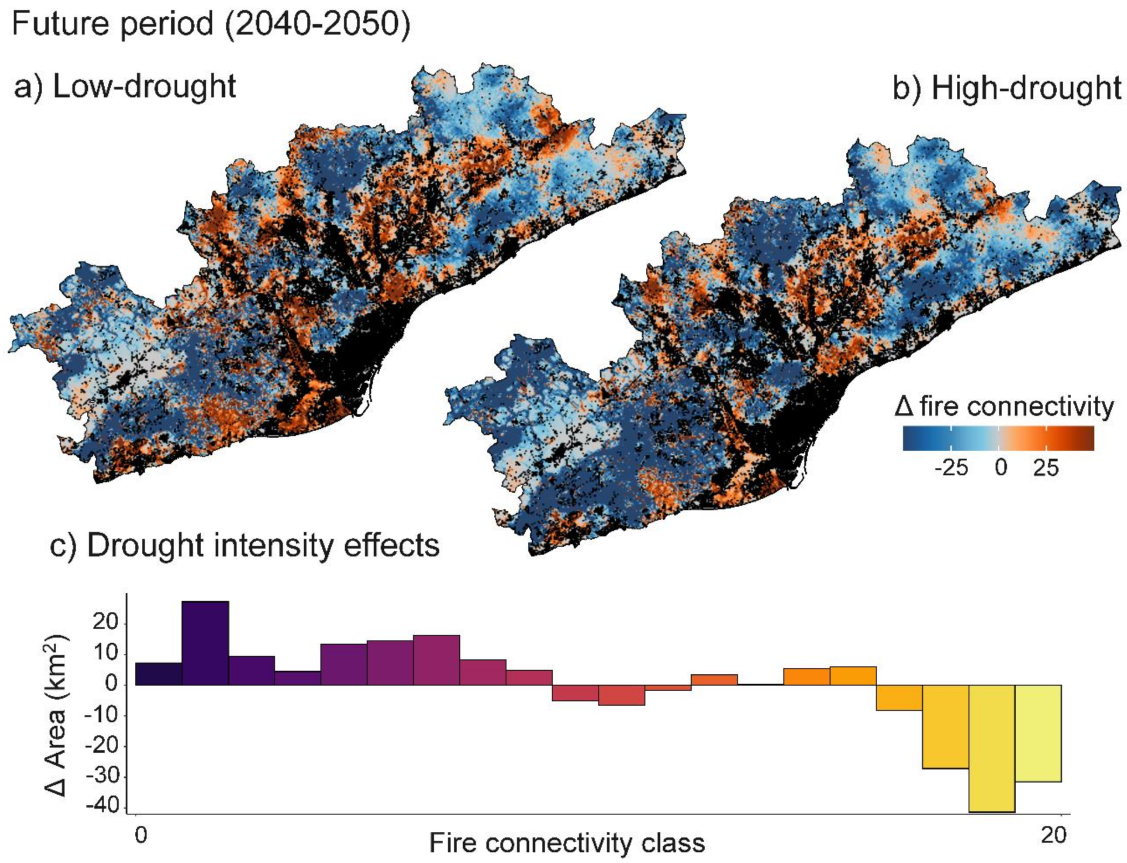

Figure 3. Delta (Δ) fire connectivity estimated as the difference between historic (2020-2023) and future (2040-2050) fire connectivity values modeled considering the *Business-as-usual* (BAU) landscape management strategy under: a) *low-drought* and b)

high-drought climatic scenarios. Orange and blue colors represent areas recording fire connectivity increases and decreases respectively. c) Effect of drought intensity on fire connectivity is estimated as the difference between *low-drought* and *high-drought* results. The histogram represents the relative changes in the BMR surface (Δ km^2) that recorded each of the 20 fire connectivity classes ranging from low to high values.

3.3 Drought intensity effects on fire connectivity

We found that higher drought intensities resulted in greater fire connectivity reductions at the end of the future periods (2040-2050). Specifically, future fire connectivity simulated under the BAU *low-drought* scenario decreased ca. 6%, with respect to historical period, whereas simulations under the *high-drought* scenario led to an average decrease of 18.5% (Table 1). Delta values (the difference between the two drought scenarios) showed that a higher incidence of extreme drought events increased the surface of low fire connectivity classes (*i.e.* 1 to 10) by 10,100 ha, while decreasing a similar surface of high fire connectivity classes (*i.e.* 11 to 20; Fig 3c). Furthermore, we observed a spatial matching between changes in fire connectivity and the effects of drought intensity on forest dynamics and stand structures. Specifically, we observed that a higher incidence of extreme drought events increased tree mortality rates and reduced plant growth, causing a long-term reduction in stand basal area and fine fuel loads across all layers (canopy, shrub and ground woody) by the 2040-2050 period (Fig. S9). However, we also observed drought-induced fire connectivity peaks in the short-term (annual scale). Specifically, we observed that during extreme drought periods, such as in the year 2049 when the *high-drought* climatic scenario forecasted an aridity index value of 0.22 (1980-2023 mean AI = 0.55 ± 0.02), average dead fuel loads raised up to 0.3 ± 0.02 kg m^{-2} (2020-2023 mean dead FL = 0.1 ± 0.02 kg m^{-2}), leading to the highest annual fire connectivity value recorded in the complete series of both climatic scenarios simulations (Fig. 4).

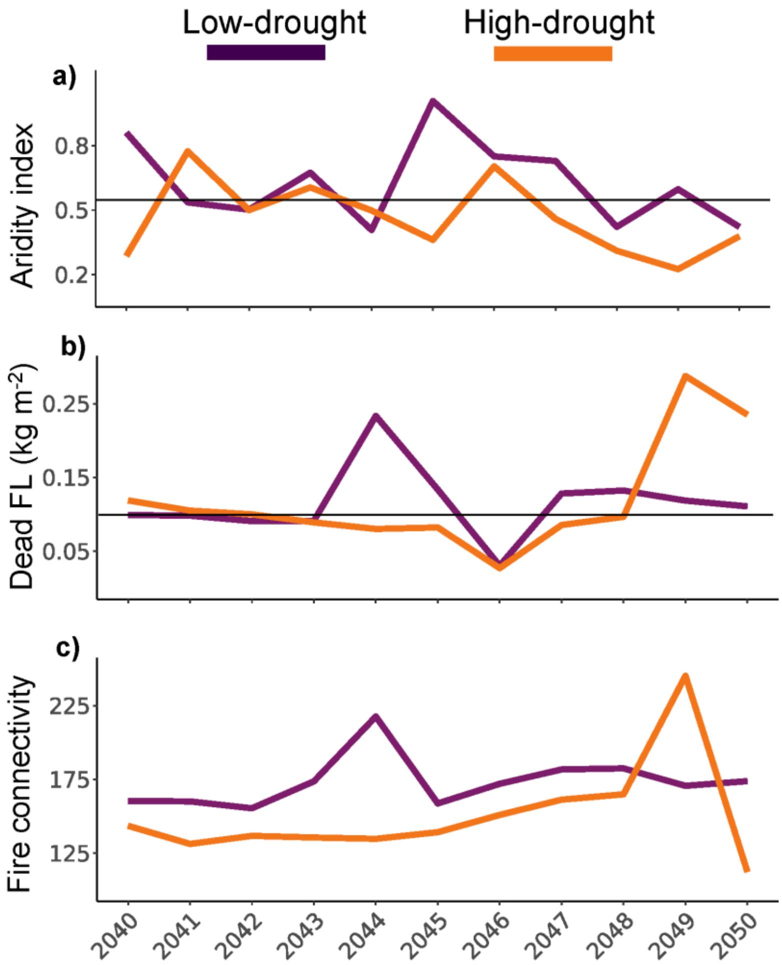

Figure 4. Annual trends in the 2040-2050 period of: a) aridity index, b) average dead fuel load (kg m^{-2}), and c) average fire connectivity. Values correspond to both climatic scenarios, *low-drought* in purple and *high-drought* in orange. Plots a) and b) include a horizontal line to show the average AI value of the 1980-2023 period (0.55) and the average dead fuel load value of the 2020-2023 period (0.1 kg m^{-2}).

3.4 Alternative landscape management strategies

The application of alternative landscape management strategies showed different effects on fire connectivity depending on the strategy applied and the degree of drought intensity considered (Table 1, Figure 5). *Crop-recovery* reduced fire connectivity by the 2040-2050 period under both climatic scenarios (Fig. 5a-b), achieving a total average decrease of 11% and 22% when simulated under *low-drought* and *high-drought* conditions, respectively (Table 1). However, these reductions were not spatially uniform, as this strategy also resulted in narrower wildland corridors that concentrate the cumulative pathways for fire to spread, increasing fire connectivity at some locations (Fig. S10c-d). *Harvesting-increase* supposed a yearly extraction rate that represents 8.5% of all stands biomass growth. Yet, the application of this strategy resulted in relatively low and random levels of fire connectivity changes in each climate scenario (Fig. 5c-d), both in terms of average-level effects (total decrease of 7% and 19% under *low*- and *high-drought* conditions, respectively, Table 1) and spatial patterns (Fig. S10e-f). *Drought-stands-logging* LMS simulated under *high-drought* conditions resulted in the greatest effects (Fig. 5f), achieving a total average fire connectivity reduction of 28% (Table 1). Furthermore, this fire connectivity reduction was more spatially uniform across the whole study area (Fig. S10h). An average of 7,500 would be yearly managed (*i.e.* 4.6% of all forest cells) under high-drought conditions, while the mean yearly dead fine fuel extraction represented 2% of all fine fuels. However, we found that, when simulated under *low-drought* conditions, the *Drought-stands-logging* strategy produced only small improvements in the fire connectivity reductions achieved with the *Business-as-usual* LMS (Fig. 5e), both in terms of the regional average connectivity (total decrease of 7.4%, Table 1) and spatial connectivity patterns (Fig. S10g). Thus, under *low-drought* conditions an average of 2,500 ha would be yearly managed (*i.e.* 1.6% of all forest cells), while the mean yearly dead fine fuel extraction represented 0.3% of all fine fuels.

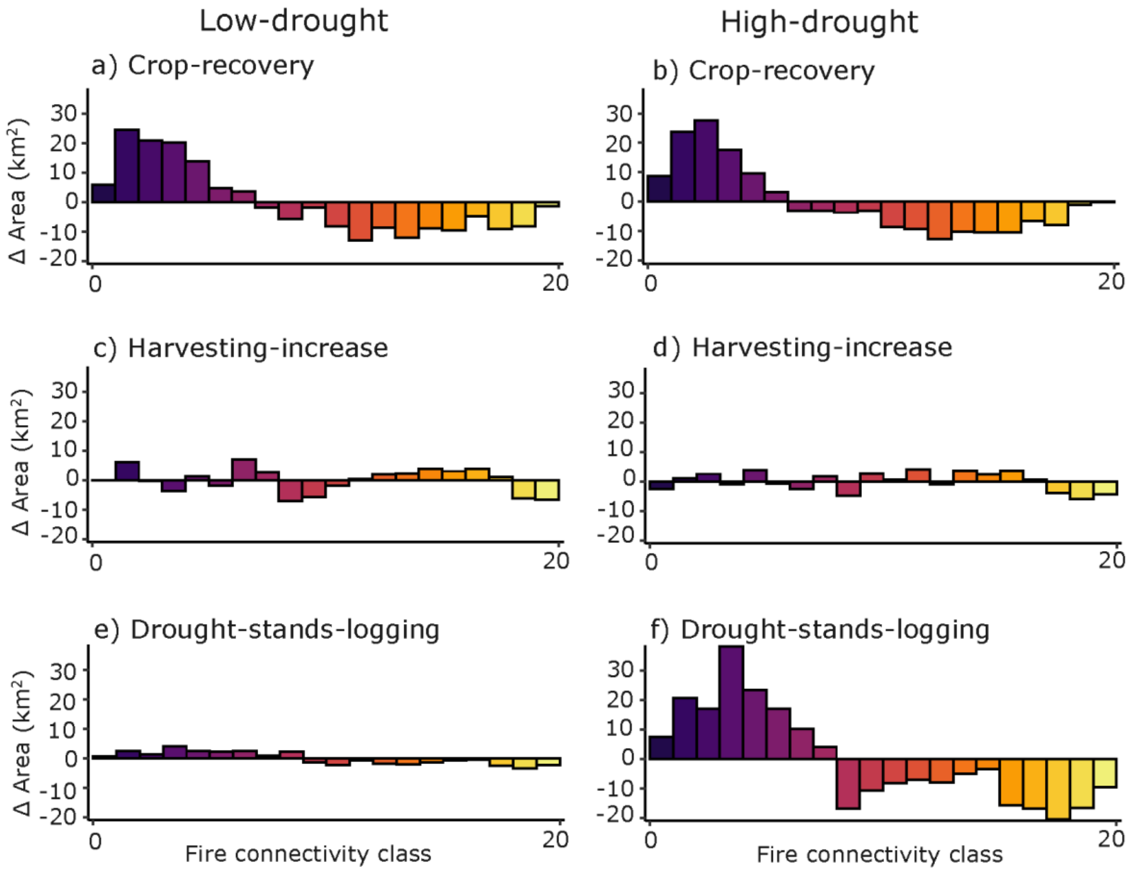

Figure 5. Effects of landscape management strategies on fire connectivity, estimated as the difference between the *Business-as-usual* and the alternative LMS modeled under both climatic scenarios (*low-drought*: a-c-e; *high-drought:* b-d-f). a-b) *Crop-recovery*, c-d) *Harvesting-increase,* and e-f) *Drought-stands-logging*.

4. Discussion

This study shows how drought-induced impacts can reduce wildfire connectivity and the interaction between these effects and landscape management strategies can further increase this reduction. We observed that forest succession processes, combined with drought-induced plant growth reductions and the increase in plant mortality, modified stand structures resulting in a decrease in fine fuel loads ultimately reducing fire connectivity by the 2040-2050 decade. In this regard, we observed larger fire connectivity reductions in the mid-term (decadal scale) when forest dynamics were simulated under a higher incidence of extreme drought events. However, higher drought intensities also triggered forest mortality episodes that resulted in short-term (annual scale) fire connectivity peaks. The three alternative LMS considered were shown to be adequate to reduce fire connectivity at regional scales yet to a different extent. *Crop-recovery* increased landscape heterogeneity and fuel discontinuity by providing open spaces among forest patches. Thus, the promotion of agroforestry mosaics resulted in fire connectivity reductions regardless of the degree of drought intensity, highlighting the crucial role of landscape configuration in shaping the risk of extreme wildfire events. Surprisingly, *Harvesting-increase* resulted in similar fire connectivity patterns to those observed in the *Business-as-usual* strategy in both climatic scenarios. These results contrast with the expectations of reducing wildfire risk through the promotion of a bio-economically oriented increase of silvicultural practices. Finally, *Drought-stands-logging* resulted in the greatest and more even fire connectivity reduction when simulated under a higher incidence of extreme drought events. This highlights the opportunity for managing the effects of increasing drought-induced forest mortality events to reduce wildfire connectivity in Mediterranean landscapes in both short and middle temporal scales.

Fine fuel characteristics were the primary driver of fire connectivity as we purposedly kept constant the values of the fire weather components (*i.e.* wind speed and fuel moisture) in fire behavior assessments. Thereby, the spatial patterns of the areas with higher fire connectivity (Fig. 2) coincide with the distribution of conifer species (Fig. S2), as the fuel properties (*i.e.* higher load) and structures (*i.e.* lower canopy base height) of *Pinus halepensis* stands (the main dominant species, Table. S2) usually lead to extremer fire behavior (Balaguer-Romano et al., 2020). In this regard, the observed future fire connectivity trends (Fig. 3a-b) could be explained by plant growth, plant mortality and forest succession mechanisms that modified stand structure and fine fuel loads during forest dynamics simulations (Zylstra et al., 2022). Therefore, in young forest stands (mostly recently established on former croplands), plant growth increased fine fuel load across all layers (canopy, shrub and ground woody) enhancing fire connectivity in the future periods (orange areas in Fig. 3a-b and Fig. S8). In contrast, plant growth in more mature stands increased the development of the overstory stratum enhancing the separation among canopy and surface fuels reducing the fuel ladder, while plant mortality and forest succession mechanisms self-thinned and self-pruned the understory. Although this process caused an increase in canopy fuels, it also decreased shrubs and ground woody fuels, resulting in an overall decline of fine fuel loads that reduced fire connectivity in the mid-term (blue areas in Fig. 3a-b and Fig. S8). These results are consistent with hypotheses that mid- and long-term forest dynamics would lead to fuel models with a lower potential of developing extreme fire behavior (Zylstra et al., 2023).

We found that drought-induced impacts on forest dynamics also played a crucial role in shaping future fire connectivity. The relationship between global warming and fire behavior has been widely addressed, showing that climate change escalates the incidence of extreme wildfire events by shifting fire weather components (Resco de Dios et al., 2021; Ruffault et al., 2018). However, it is more uncertain how an increasing occurrence of droughts and wildfire disturbances will interact with forest dynamics at different time scales (Littell et al., 2016). In the long term, the effects of fire-drought interactions could lead to forest stands resilience losses, driving species composition changes which ultimately could promote transitions to opposite situations: i.e. non-forest ecosystems or to even more fire-resistance ecosystems (Batllori et al., 2019). Nonetheless, our simulation results indicate that a higher incidence of extreme drought events interacts with forest dynamics reducing fire connectivity in the mid-term (Table 1, Fig. 3c). This was because drought periods reduce plant growth rates and increase plant mortality, leading to mid-term (decade scale) reductions in forest stands basal area and fine fuel load (Fig. S9). However, our simulation results also showed that in the short-term (annual scale), extreme drought events induce forest mortality episodes that trigger dead fuel loads and thus alter fire behavior to reach maximum fire connectivity values for a given period (Fig. 4). Taken together, these results highlight the complexity of the relationship between drought, wildfires and forest dynamics, which goes beyond the assumed generalized increase of fire occurrence after drought events (Ellis et al., 2022; Richardson et al., 2022).

We observed that different alternative LMS could reduce fire connectivity compared with the *Business-as-usual* strategy. *Crop-recovery* increased fuel discontinuity by providing open spaces among forest patches which reduced fire spread rates and thus fire connectivity at landscape scales (Fig. 5a-b). Nonetheless, we observed that the implementation of this strategy could also lead to narrower wildland corridors that concentrate the cumulative pathways for fire to spread, increasing fire connectivity values at some locations (orange areas in Fig. S10c-d). However, this side effect could be viewed as an opportunity for wildfire management as the concentration of fire activity to these corridors could serve to focus firefighting operations and resources. In any case regional fire connectivity reductions were observed after simulating this LMS regardless of the intensity and frequency of drought events (Table 1), highlighting the potential of agroforestry mosaics to contribute to the development of fire-adapted landscapes with a lower occurrence of extreme wildfire events (Aquilué et al., 2020). Also, this strategy has the potential to yield associated benefits, such as reversing the marked decline in Mediterranean open-habitat species (*e.g.* birds and butterflies species) that has resulted from the abandonment of traditional land-use practices and forest encroachment (Herrando et al., 2016). Moreover, from a socio-economic perspective, the recovery of former croplands could moderate rural depopulation by providing development opportunities to the local communities (Goussios et al., 2024), as well as increase the local food supply in peri-urban areas (Callau-Berenguer et al., 2022). Finally, secondary-growth forest established on former croplands have been shown to exhibit higher climate sensitivity than forests with a longer and more continuous land-use history being more at risk under uncertain climate change scenarios (Balaguer-Romano et al., 2025). Thus, the *Crop-recovery* LMS could additionally serve as climate change adaptation measure, by reducing the surface covered by forest stands which exhibit a higher vulnerability to climatic disturbances.

Conversely to the paramount effects of cropland recovery, the implementation of the *Harvesting-increase* LMS resulted in surprisingly similar fire connectivity patterns to those observed in the *Business-as-usual* one (Fig. 5c-d). This may be because the average wood volumes harvested currently or under the *Business-as-usual* strategy (Table S4) are so extremely low (the yearly extraction rate represents 8.5% of all stands growth), that a 60% increase in these rates does not have a major impact under any climatic scenario (Table 1). Larger percentages in wood extraction rates could result in greater differences between the two LMS, yet it must be highlighted that the 60% increase was established following a bio-economically oriented strategy ensuring a minimum feasibility of this LMS (Banqué et al., 2023). Thus, larger increases in current wood harvest volumes would require a greater demand in the market to dispose of stocks and provide economic incentives to forest owners (Neidermeier et al., 2023).

According to our results the occurrence of drought disturbances could be surprisingly viewed as an opportunity for combining drought-induced impacts with moderate active management strategies to further reduce fire connectivity at the landscape scale in both the short- and the mid-term. Indeed, under a higher incidence of extreme drought events as expected in the region (IPCC, 2023), the *Drought-stands-*

logging resulted in the maximum fire connectivity reduction (Fig. 5f, Table 1). This strategy not only could reduce fire connectivity at a decadal scale but also could serve as a measure to control annual fire connectivity peaks by extracting the dead fuels resulting from drought-induced forest mortality episodes (Fig. 4). Moreover, as the application of this strategy did not modify land uses (unlike *Crop-recovery*) nor interacted with forest dynamics (unlike *Harvesting-increase*), it was the only LMS that resulted in a spatially uniform fire connectivity reduction across the whole study area (Fig. S10h). This highlights the opportunity to shape wildfire behavior at the landscape-scale by combining drought-induced impacts with novel management strategies beyond the assumed benefits from recovering traditional agricultural and silvicultural practices. However, the application of the *Drought-stands-logging* LMS is only feasible after drought-induced forest mortality episodes as minimum improvements were achieved under a low incidence of extreme drought events compared to the *Business-as-usual* results (Fig. 5e, Table 1, Fig. S10g). In spite of these benefits, it is important to highlight that after the occurrence of wilfires extensive salvage logging activities have been pointed out to increase the impact of subsequent disturbances by magnifying erosion and flood impacts, enhancing susceptibility to windthrow and increasing microclimatic stress due to greater radiation and temperature fluctuations (Leverkus et al., 2021). Similarly, removal of dead trees and ground deadwood in naturally disturbed forests can result in biodiversity losses, especially of saproxylic organisms (Thorn et al., 2018). Notwithstanding these potential negative outcomes, the application of a reduced *Drought-stands-logging* such as the one modeled in this study (under *high*-drought conditions an extraction of 2% over all fuels on an average of 7,500 ha yr^{-1}), emerges as feasible LMS to control the potential cascading effects derived from the increased incidence of drought-induced forest mortality episodes, which otherwise pave the way for the occurrence of extreme wildfire events (Lloret and Batllori, 2021).

Notwithstanding the contribution of the results obtained, this study has some methodological limitations that must be also acknowledged. First, the LMS were modeled under a “best-case” scenario without considering the associated costs and the economic viability of these practices. In this regard, the feasibility in terms of costs and benefits (Elia et al., 2016; Penman et al., 2020) of implementing these alternative LMS compared to the *Business-as-usual* strategy will have to be assessed in the future. Also, the alternative LMS have been simulated independently without considering possible combinations or including other fuel treatments such as prescribed burns (Duane et al., 2019; Pais et al., 2023). In addition, seed dispersal was not considered in forest dynamics simulations due to computational constraints. However, our main objective was to assess to which extent the impacts of extreme drought events interact with different LMS to reduce fire connectivity at the regional scale, with the aim of providing stakeholders and planners with a priori evaluation of the efficiency of these strategies. Second, the fire connectivity analysis did not model fire probabilities or assess cumulative fire risk. Our approach did not explicitly incorporate the likelihood of ignition or simulated dynamic fire weather components such as wind speed and fuel moisture (Duane et al., 2021b). However, our objective was to model the spatial arrangement of areas with similar fire properties that could facilitate a contiguous fire spread across the landscape, and not to assess changes in the wildfire regime. Considering that the Barcelona Metropolitan Region is a peri-urban area with an ongoing expansion of the wildland-urban interface, preventative actions such as the ones modeled in this study may be appropriate in those areas with higher potential fire connectivity to minimize wildfire impacts on the population.

5. Conclusions

Overall, our results indicate that forest dynamics mechanisms (*i.e.* plant growth-mortality and forest succession) and drought-induced impacts on stands structure and composition may shape mid-term fire connectivity reductions at the landscape-scale. Overall fire connectivity declines in the decade 2040-2050 were greater when forest dynamics were simulated under a higher incidence of extreme drought events. However, fine fuel load increases resulting from drought-induced forest mortality episodes also drive fire connectivity peaks at annual scales. Therefore, these results indicate that there is room for combining drought-induced impacts with landscape management strategies (LMS) to reduce wildfire connectivity at regional scales in both the short (annual) and the middle (decadal) term. Widely proposed, but difficult to implement strategies based on the recovery of agricultural and silvicultural practices resulted in contrasting effects. While the *Crop-recovery* strategy enhanced fire connectivity reductions regardless of the drought intensity, the *Harvesting-increase* strategy resulted in similar fire connectivity patterns to those observed in the *Business-as-usual* LMS under both climatic scenarios. The alternative and more novel *Drought-stands logging* strategy resulted in the greatest and evenly fire connectivity reductions when simulated under a higher incidence of extreme drought events. This brings to the table the consideration of drought-induced impacts and LMS interactions as an opportunity to adapt Mediterranean landscapes to climate change-driven disturbances such as extreme wildfire events.

CRediT authorship contribution statement

Rodrigo Balaguer-Romano: Writing-original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Josep María Espelta**: Writing-review & editing, Validation, Methodology, Supervision, Resources, Investigation, Formal analysis, Data curation, Conceptualization, Founding acquisition, Project Administration. **Lluís Brotons**: Writing-review & editing, Validation, Methodology. **Núria Aquilué**: Writing-review & editing, Validation, Methodology, Conceptualization. **Miquel de Cáceres**: Writing-review & editing, Validation, Methodology, Supervision, Resources, Investigation, Formal analysis, Software, Data curation, Conceptualization.

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

All data that supports this study were obtained from publicly available resources. See Supplementary Information for a description, sources and links of all data layers, data products, and datasets used.

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Declaration of interests

☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: