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Research article

# Wildfire connectivity under drought-induced impacts and landscape management strategies in a Mediterranean region

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ABSTRACT

Global warming and land-use changes have increased wildfire risk in Mediterranean regions. Landscape management strategies (LMS) potentially can reduce extreme wildfire behavior through the maintenance and recovery of traditional agroforestry mosaics. However, we still have limited knowledge about LMS viability regarding their interaction with the ongoing escalation 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 drought intensity levels. Then, we analyzed differences in wildfire connectivity patterns arising from the interaction between drought events and three alternative LMS co-designed with local stakeholders: recovering former croplands, increasing wood harvesting and logging drought-affected stands. 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 average fire connectivity reduction occurred under a higher incidence of extreme-drought events, although this scenario was also associated with annual peaks of extreme fire connectivity events. *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 most spatially uniform reduction in fire connectivity when simulated under high-drought intensity, due to the elimination of annual peaks following drought episodes. According to our results, there is room for combining drought-induced impacts with LMS to reduce wildfire connectivity at regional scales in fire-prone Mediterranean areas.

## 1. Introduction

Climate change is increasing 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; Dupuy et al., 2020; Ellis et al., 2022). 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 promote 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 being 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

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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 "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 ladder fuels (Palmero-Iniesta et al., 2017; Piqué and Domènech, 2018). However, the current 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 further abandonment of rural activities (Perpiña Castillo et al., 2021).

Along with passive forest expansion after land abandonment, an increase in drought-induced forest mortality episodes has also occurred 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 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. Long-term 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 and the probability to develop mega-fires (Stephens et al., 2018). In this sense, landscape management should promote the development of more resilient forest stands that are less likely to support large wildfire events. 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. Given the negative effects of drought on annual-scale fire behavior, it would be interesting to assess to which extent dry fuel loads and connectivity can be reduced by salvage-logging in drought-affected stands. Thus, while keeping in mind potential negative outcomes derived from salvage-logging practices (Leverkus et al., 2021), partial logging activities could aid in reducing fire risk peaks arasing immediately after drought-induced forest mortality.

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 projected for the next decades. These uncertainties arise from little empirical evidences on regional-scale LMS applications 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 what 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) historical 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 historical 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: returning to active farming 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 historical (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 historical 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 what 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 inhabitants 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. 2020). 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 with 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). The relatively low percentage of total area burned (3 % of the BMR's total forest area over 20 years) could be explained by the region's effective firefighting, which is facilitated by early warnings and the rapid arrival of firefighting services, a feature typical of densely populated areas. However, this success in fire suppression, coupled to the traditionally low forest management intensity, has resulted in high fuel loads accumulations (*i.e.*

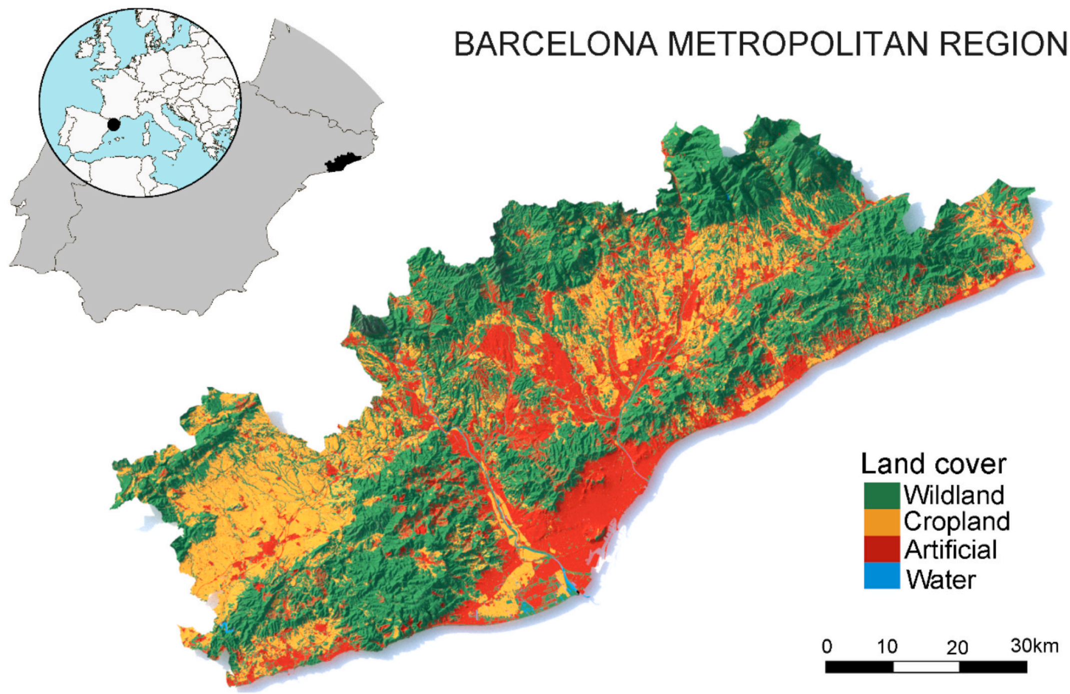


**Fig. 1.** Barcelona Metropolitan Region location, topography, and land cover types (ICGC, 2018).

the fire paradox) increasing the potential to develop extreme wildfire events beyond extinction capacities (Moreira et al., 2020).

### 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 with observed data from Spanish National Forest Inventory plots located within the 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), being the minimum available resolution due to computational limitations. Then, in each grid 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 (see 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, since model performance in shrubland areas has not yet been evaluated. 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, historical period). These simulations were run using meteorological input data daily interpolated from nearby weather stations (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 entails high risk of soil erosion and it rarely occurs owing to challenges for equipment and material transport (Neidermeier et al., 2023).

### 2.3. Business-as-usual landscape management strategy

We took the forest stands structures obtained at the end of the historical period (2024) 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 conducted using weather data from two different 26-year periods of the same projected climatic scenario (MPI-ESM-LR-RCA4-RCP8.5, EuroCordex). We first conducted forest dynamics simulations using the meteorological data projections from 2024 to 2050, hereafter referred to as "*low-drought*" climatic scenario. Then we run a second round of forest dynamics simulations starting again with forest stands structures at the end of the historical period (2024) but now using the meteorological data projections from 2054 to 2080. As the model projects more arid conditions and a higher incidence of extreme drought events for this period, hereafter it is referred to as "*high-drought*" climatic scenario. Drought events were defined as extreme when the annual averaged Aridity Index (AI) was lower than the median of the 1980–2023 period minus two times the median absolute deviance (Leys et al., 2013), that is an annual AI value lower than 0.3. While any year of the 2024–2050 period in the "low-drought" climatic scenario reached an AI lower than 0.3, the "high-drought" scenario recorded a total of four years that met the criteria for extreme drought events (Supplementary Information S3). We simulated forest dynamics from 2024 to 2050 under both climatic scenarios (*low-drought* and *high-drought*) applying the same demand-based management and silvicultural prescriptions applied for the historical period. Thus, as we maintained current wood harvesting rates and no changes in other land covers were simulated, hereafter we refer to this first future forest dynamics simulation round as the *Business-as-usual* landscape management strategy.

### 2.4. Alternative landscape management strategies

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 used the resulting forest dynamics simulations under the *Business-as-usual* scenario but changing in a single step the land cover type to "cropland" in those wildland cells that included more than 51 % of "recoverable-agricultural-land" areas. Accordingly, 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 and Vayreda, 2023), resulting in an annual rate of wood harvesting of 160,000 $m^3$ $yr^{-1}$. Finally, in the *Drought-stands-logging* LMS we modeled the yearly removal of dead vegetation from drought-affected stands. To this end, we used the yearly forest dynamics simulations from the *Business-as-usual* scenario but excluded the dead fine fuel loads (vegetation removed) in the annual wildfire modelling framework (described below). We selected forest stands as target for this scenario if they recorded a tree 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).

### 2.5. Wildfire connectivity modeling

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 fuel characteristics and the slope of the terrain to model local fire behavior in each wildland cell and year. To model fire behavior that is driven mainly by fuel characteristics and thus likely to be affected by landscape configuration, we used 24 km $h^{-1}$ wind speed (at 6 m over vegetation) and 97th percentile fuel moisture conditions (5 %–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. According to the Barcelona Provincial Council information most of the agricultural area of the BMR corresponds to wood and/or irrigated crops (vineyards, olive groves, orchards and corn crops). As these crops are unlikely to sustain fire activity we assumed a minimum ROS of 0.1 m $min^{-1}$ to all cropland cells. Finally, we assigned missing values to all artificial cells (*i.e.,* urban and infrastructure land cover types). Then, 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. The fire connectivity metric describes the spatial arrangement of areas with similar fire characteristics that could facilitate a contiguous fire spread across the landscape. OMNISCAPE estimated in each 4-ha grid cell the number of cumulative pathways for a fire to spread by modeling a fire spread from source cells with high ROS values to adjacent cells within a moving window of 4 km. Following Buchholtz et al. (2023), we established the source cell threshold parameter equal to the third quartile of the averaged ROS values for the historical period (ROS = 51.68 m $min^{-1}$), while the moving window value (4 km, *i.e.* 200 m × 20 cells) was established according to the maximum radius achieved historically by a wildfire in the study region from 2000 to 2023 (Omniscape initialization data input description and files in Supplementary Information S6).

### 2.6. Data analysis

We estimated average fire connectivity values per cell during the historical 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). Then we assessed fire connectivity patterns considering each climatic scenario and LMS combination for the decade 2040–2050, hereafter referred as the future period. For data analyses and visualization, we classified per-cell average fire connectivity values of the historical 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 (Table S7). We applied these 20 quantiles to classify all future average fire connectivity values and examine changes in the frequency of connectivity classes and the corresponding area affected. To assess individual events beyond average trends, we estimated the number of cells that recorded extreme fire connectivity values during the historical period (2020–2023) and for each year of the future period (2040–2050) for all LMS and climatic scenario combinations. Fire connectivity values were considered as extreme when they were higher than the median of the historical period plus three times the median absolute deviance (Leys et al., 2013). Finally, we assessed the changes in average fire connectivity frequency from the historical to 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. Historical fire connectivity (2020–2023)

The average fire connectivity modeled in the historical period (2020–2023) showed a spatial NE-SW 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 m $min^{-1}$ (Fig. S8). As we purposely 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. Areas with low fire connectivity matched with stands dominated by broadleaved species (mostly *Quercus* spp.), while areas with high fire connectivity matched with stands dominated by coniferous species (mostly *Pinus halepensis*, see Supplementary Information S2).

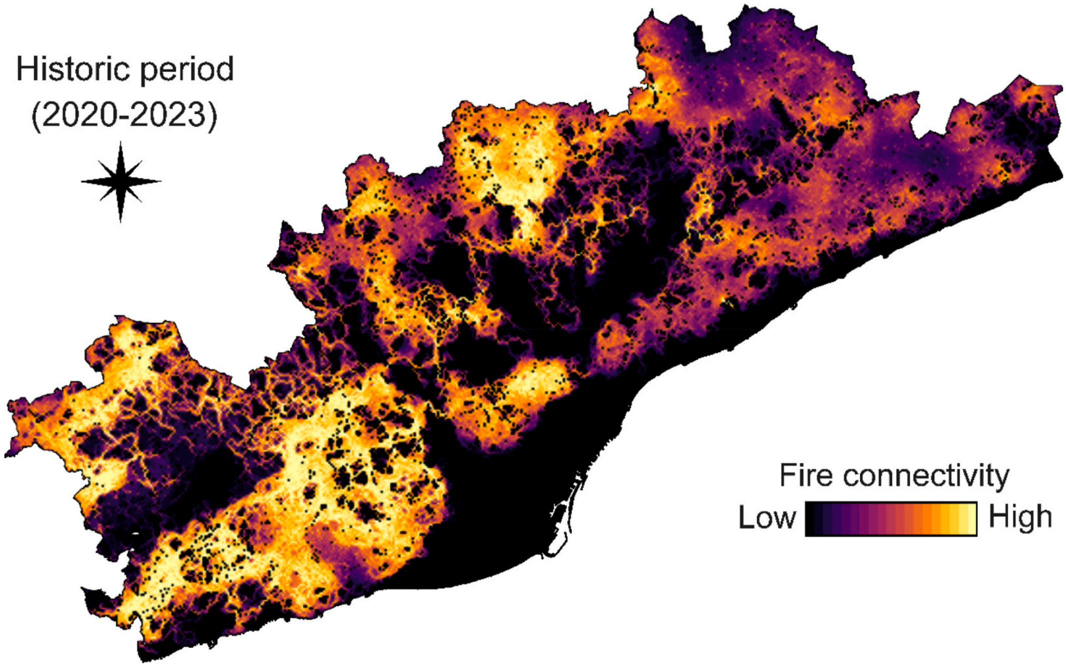


**Fig. 2.** Average fire connectivity values modeled in the historical period (2020–2023). Dark and light colors represent areas with lower and higher fire connectivity values, respectively. Fire connectivity values refer to the cumulative pathways for fire to spread and to connect areas with modeled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

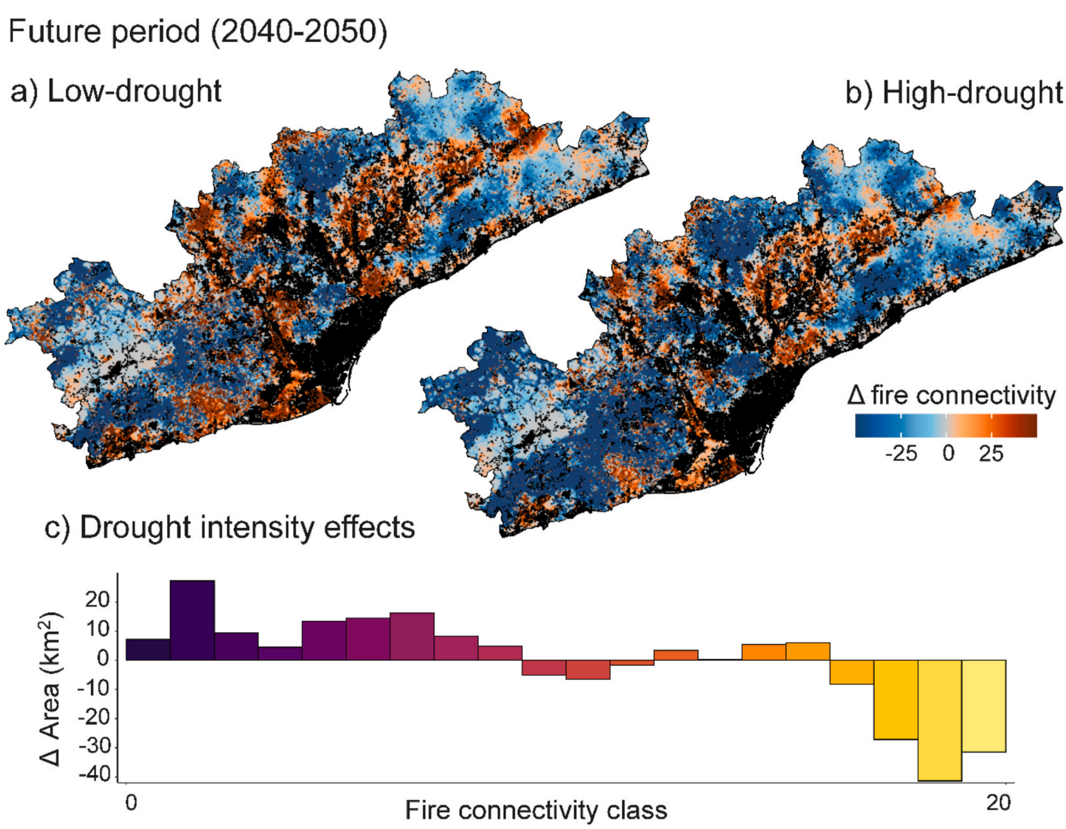


**Fig. 3.** Delta (Δ) fire connectivity estimated as the difference between historical (2020–2023) and future (2040–2050) fire connectivity values modeled considering the *Business-as-usual* (BAU) landscape management strategy under: a) *low-drought* and b) *high-drought* climatic scenarios. Orange and blue colors represent areas recording fire connectivity increases and decreases respectively. c) Effect of drought intensity on fire connectivity, estimated by subtracting *low-drought* fire connectivity values from the *high-drought* ones. 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.

### 3.2. Future fire connectivity (2040–2050) under the business-as-usual landscape management strategy

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). Average historical 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, Supplementary Information S9). In other words, higher drought intensities resulted in greater average fire connectivity reductions (6 % vs. 18.5 % for *low-drought* and *high-drought scenarios*). This was supported by delta values (the difference between the two drought scenarios), which 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). 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 historical to future periods under *low-* and *high-drought* conditions respectively (orange areas in Fig. 3a and b).

The number of individual events recording extreme fire connectivity (*i.e.* 4ha-grid-cells with values above 518.6) was also reduced (Fig. 4). Thus, while in the historical period the mean number of grid-cells that recorded extreme fire connectivity values was 4,909, it decreased to 2,988 and 1,565 in the *BAU low-drought* and *high-drought* scenarios (Fig. 4). Compared with the historical period, we recorded a lower incidence of extreme fire connectivity events across all years of the 2040–2050 period, expect one for each climatic scenario. Under the *low-drought* climatic conditions we recorded a peak in the number of extreme fire connectivity events (6,335) in the year 2044, while there were 7,696 extreme fire connectivity events in the year 2049 under the *high-drought* scenario (Fig. 4). This result highlights that drought-induced impacts result in fire connectivity peaks at annual scales. Thus, annual extreme drought events, such as the 2049 ones when the *high-drought* climatic scenario resulted in an aridity index (AI) value of 0.22 (1980–2023 mean AI = 0.55 ± 0.02), promotes the accumulation of dead fuel loads (FL) up to 0.3 kg $m^{-2}$ (2020–2023 mean dead FL = 0.1 ± 0.02 kg $m^{-2}$). This results in both the highest number of individual extreme events (Fig. 4) and the highest average fire connectivity recorded in any year of the complete series under both *low-* and *high-drought* scenarios (Fig. 5).

Finally, we observed a spatial matching between average fire connectivity increases and decreases from historical to future periods and fine fuel loading changes at the canopy, shrub and ground woody layers (Fig. S10). Overall, we observed that simulated dynamics in plant growth-mortality and forest succession processes modified stand structures resulting in a regional-level reduction of the fine fuel load by the 2040–2050 decade. Similarly, 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. S11).

### 3.3. Future fire connectivity (2040–2050) under 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, Fig. 6). *Crop-recovery* reduced average fire connectivity by the 2040–2050 period under both climatic scenarios (Fig. 6a and 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. S12c–d). Therefore, the annual and mean incidence of individual extreme fire connectivity events was similar between *Crop-recovery* and *Business-as-usual* LMS simulated under both climatic scenarios (Fig. 4). *Harvesting-increase* assumed 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 average fire connectivity changes in each climate scenario (Fig. 6c and d), both in terms of average-level effects (total decrease of 7 % and 19 % under *low-* and *high-drought* conditions, Table 1) and spatial patterns (Fig. S12e–f). However, it always resulted in a slight decrease in the number of annual and mean individual extreme fire connectivity events during the 2040–2050 period (Fig. 4). *Drought-stands-logging* LMS simulated under *high-drought* conditions resulted in the greatest effects (Fig. 6f), 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. S12h), resulting in the greatest annual and mean decrease (33 %) of individual extreme fire connectivity events in the future period (Fig. 4). An average of 7,500 ha 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. 6e), both in terms of the regional average connectivity (total decrease of 7.4 %, Table 1) and spatial connectivity patterns (Fig. S12g). The number of individual extreme fire connectivity events was also similar to the *Business-as-usual* ones (Fig. 4). 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.

## 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

**Table 1**
Distribution of fire connectivity values in the historical 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.

| | Historical (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 | 1870.3 | 1760.1 | 1748.7 | 1757.8 | 1722.7 | 1430.2 | 1446.4 | 1617.2 | 1287.6 |

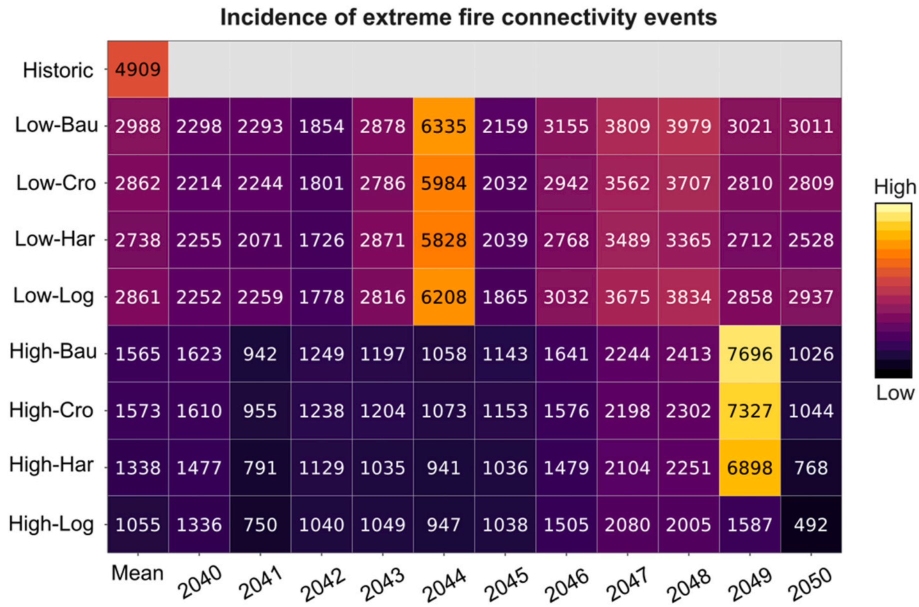


**Fig. 4.** Incidence of individual fire connectivity events that reached an extreme fire connectivity value (i.e. number of 4ha-grid-cells with values above 518.6). Numbers within colored squares refer to the mean number of extreme fire connectivity events recorded in the historical period (2020–2023; upper-left square) followed by the mean (first column) and the annual (remaining columns) number of extreme fire connectivity events recorded in the future period (2040–2050) predicted under *low-drought* (Low) and *high-drought* (High) climatic scenarios, considering the *Business-as-usual* (Bau), *Crop-recovery* (Cro), *Harvesting-increase* (Har) and *Drought-stands-logging* (Log) landscape management strategies.

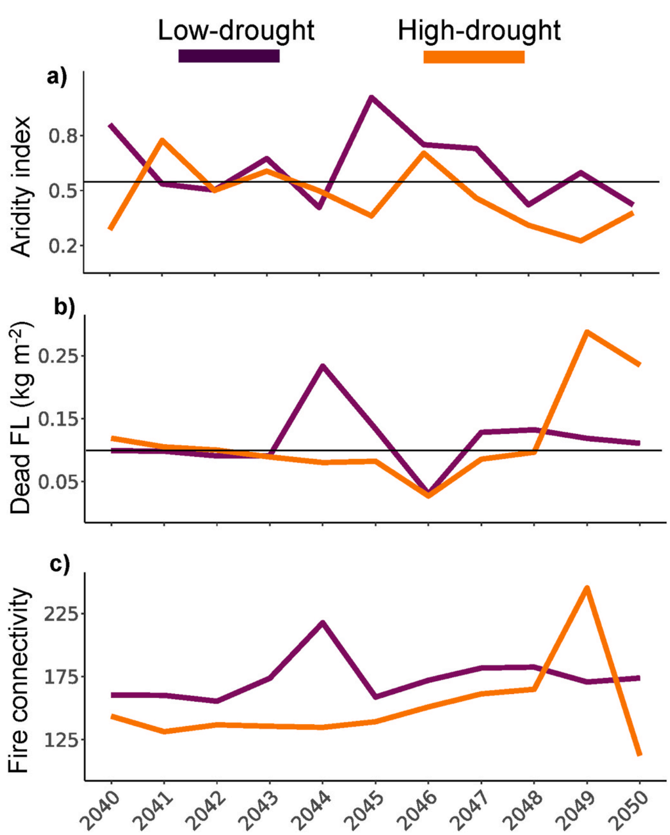


**Fig. 5.** Average annual trends in the 2040–2050 period of: a) aridity index, b) dead fuel load (kg m$^{-2}$), and c) fire connectivity. Values correspond to both climatic scenarios, *low-drought* in purple and *high-drought* in orange. Plots a) and b) include a horizontal line to show the average 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$^{-2}$).

structures resulting in a decrease in fine fuel loads ultimately reducing average fire connectivity and the incidence of individual extreme events by the 2040–2050 decade. In this regard, we observed larger fire connectivity reductions at decadal scales 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 the greatest annual 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 average 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 spatial and temporal uniform 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 annual and decadal scales.

In fire behavior assessments, we kept the values of fire weather components (*i.e.* wind speed and fuel moisture) constant to assume that variations in fire connectivity were mainly driven by changes in fuel characteristics caused by LMS and forest dynamics. Therefore, the spatial patterns of the areas with higher fire connectivity (Fig. 2) coincide with the distribution of conifer species (Fig. S2), due to 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 more extreme fire behavior (Balaguer-Romano et al., 2020). In this regard, the observed future fire connectivity trends (Fig. 3a and b) could be explained by plant growth, plant mortality and forest succession mechanisms that modified stand structure and fine fuel

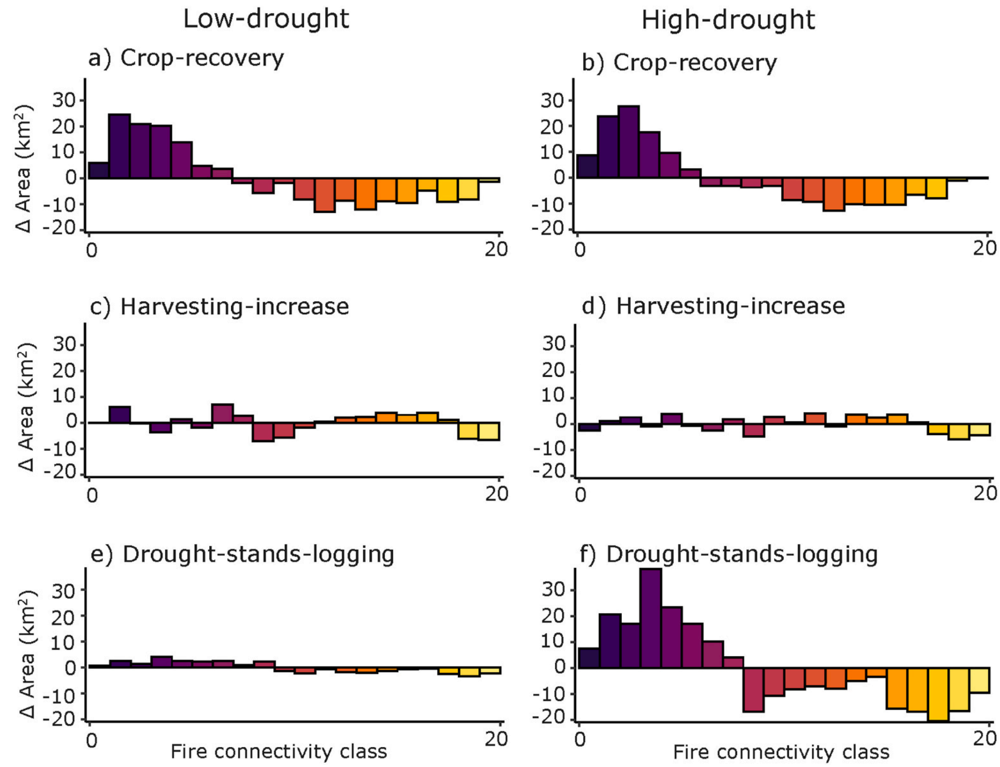


**Fig. 6.** Effects of landscape management strategies on fire connectivity, estimated as the difference between the *Business-as-usual* and the alternative LMS modeled under both climatic scenarios (*low-drought*: a-c-e; *high-drought:* b-d-f). a-b) *Crop-recovery*, c-d) *Harvesting-increase,* and e-f) *Drought-stands-logging.*

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. S10). In contrast, plant growth in more mature stands increased the development of the overstory stratum enhancing the separation among canopy and surface fuels and thus reducing the fuel ladder, while plant mortality and forest succession mechanisms self-thinned and self-pruned the understory in coniferous and broadleaf stands. 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 at a decadal scale (blue areas in Fig. 3a–b and Fig. S10). These results are consistent with hypotheses that 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 average fire connectivity at a decadal scale (Table 1, Fig. 3c). This was because drought periods reduce plant growth rates and increase plant mortality, leading to decadal scale reductions in forest stands basal area and fine fuel load (Fig. S11). However, our simulation results also showed that at an annual scale, extreme drought events induce forest mortality episodes that trigger dead fuel loads and thus alter fire behavior to reach the maximum number of individual extreme fire connectivity events (Fig. 4) and the greatest average fire connectivity value for a given period (Fig. 5). Taken together, these results highlight the complexity of the relationship between drought, wildfires and forest dynamics, which goes beyond the expectation of 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 average fire connectivity at landscape scales (Fig. 6a and b). Nonetheless, we observed that the implementation of this strategy also results in a similar number of individual extreme fire connectivity events compared with the *Business-as-usual* strategy (Fig. 4). This could be associated with the resultant narrower wildland corridors that concentrate the cumulative pathways for fire to spread and increase fire connectivity values at some locations (orange areas in Fig. S12c–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, average fire connectivity reductions were observed at regional scales 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 (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 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. 6c and 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 and Vayreda, 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 unexpectedly 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 annual and decadal scales. Indeed, under a higher incidence of extreme drought events as expected in the region (IPCC, 2023), the *Drought-stands-logging* resulted in the maximum average fire connectivity reduction (Fig. 6f–Table 1). This strategy not only could reduce fire connectivity at decadal scales but also could serve as a measure to control the incidence of annual extreme fire connectivity peaks by extracting the dead fuels resulting from drought-induced forest mortality episodes (Figs. 4 and 5). 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. S12h). 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. 6e–Table 1, Fig. S12g). In spite of these benefits, it is important to highlight that after the occurrence of wildfires 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. Firstly, with regard to the LMS, the models were based on a 'best-case' scenario without considering the associated costs and the economic viability of these practices. 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 future work. In line with this, potential tensions with carbon sequestration programs should also be considered when planning the implementation of the LMS proposed here. In addition, 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). Furthermore, a methodological limitation of this study relies on the assumption of a unique ROS value for all crop types, without accounting for crop structure variability at temporal and spatial scales. A practical implementation of a *Crop-recovery* strategy should carefully assess the fire behavior that could arise from the potential crop type selected to be recovered, as for example, previous studies have warned about high fire rates of spread within wheat crops (Cruz et al., 2020). Also, seed dispersal was not considered in forest dynamics simulations due to computational constraints. Despite these constraints, we highlight that 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, regarding the fire connectivity modeling framework, our 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). Also, this study does not incorporate in the forest dynamics simulations the potential effects of wildfire disturbances over forest structure, fuel loads and post-fire successional dynamics, which could also feedback on fire connectivity patterns. 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 explore to what extent landscape management strategies can help to reduce fire connectivity. Therefore, 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 decadal fire connectivity reductions at the landscape-scale. Fire connectivity declines modeled for 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 annual peaks of individual extreme fire connectivity events. 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 annual and decadal scales. 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 average 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 Maria Espelta:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lluís Brotons:** Writing – review & editing, Validation, Methodology. **Núria Aquilué:** Writing – review & editing, Validation, Methodology, Conceptualization. **Miquel De Cáceres:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127844.

## 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, products, and datasets used

## References

Alcasena, F.J., Ager, A.A., Bailey, J.D., Pineda, N., Vega-García, C., 2019. Towards a comprehensive wildfire management strategy for Mediterranean areas: framework development and implementation in Catalonia, Spain. J. Environ. Manag. 231, 303–320. https://doi.org/10.1016/j.jenvman.2018.10.027.

Aquilué, N., Fortin, M.J., Messier, C., Brotons, L., 2020. The potential of agricultural conversion to shape Forest fire regimes in Mediterranean Landscapes. Ecosystems 23, 34–51. https://doi.org/10.1007/s10021-019-00385-7.

Balaguer-Romano, R., De Cáceres, M., Espelta, J.M., 2025. Second-Growth forests exhibit higher sensitivity to dry and wet years than long-existing ones. Ecosystems 28, 6. https://doi.org/10.1007/s10021-024-00953-6.

Balaguer-Romano, R., Díaz-Sierra, R., De Cáceres, M., Voltas, J., Boer, M.M., Resco De Dios, V., 2023. Modeling fuel moisture dynamics under climate change in Spain's forests. fire ecol 19, 65. https://doi.org/10.1186/s42408-023-00224-0.

Balaguer-Romano, R., Díaz-Sierra, R., Madrigal, J., Voltas, J., de Dios, V.R., 2020. Needle senescence affects fire behavior in aleppo pine (Pinus halepensis mill.) stands: a simulation study. Forests. https://doi.org/10.3390/f11101054.

Banqué, M., Vayreda, J., 2023. DEBOSCAT. Resultats 2023. Seguiment De L'Estat Dels Boscos De Catalunya.

Bar-Massada, A., Alcasena, F., Schug, F., Radeloff, V.C., 2023. The wildland – urban interface in Europe: spatial patterns and associations with socioeconomic and demographic variables. Landsc. Urban Plann. 235, 104759. https://doi.org/10.1016/j.landurbplan.2023.104759.

Batllori, E., De Cáceres, M., Brotons, L., Ackerly, D.D., Moritz, M.A., Lloret, F., 2019. Compound fire-drought regimes promote ecosystem transitions in Mediterranean ecosystems. J. Ecol. 107, 1187–1198. https://doi.org/10.1111/1365-2745.13115.

Buchholtz, E.K., Kreitler, J., Shinneman, D.J., Crist, M., Heinrichs, J., 2023. Assessing large landscape patterns of potential fire connectivity using circuit methods. Landsc. Ecol. 38, 1663–1676. https://doi.org/10.1007/s10980-022-01581-y.

Callau-Berenguer, S., Roca-Torrent, A., Montasell-Dorda, J., Ricart, S., 2022. How to guarantee food supply during pandemics? Rethinking local food systems from peri-urban strategic agents' behaviour: the case study of the Barcelona Metropolitan Region. Ingeopres 363. https://doi.org/10.14198/INGEO.19554.

Cruz, M.G., Hurley, R.J., Bessell, R., Sullivan, A.L., 2020. Fire behaviour in wheat crops – effect of fuel structure on rate of fire spread. Int. J. Wildland Fire 29, 258. https://doi.org/10.1071/WF19139.

De Caceres, M., Améztegui, A., González, M., Aquilué, N., Caviedes-Voullième, D., Morales-Hernández, M., 2025. Medfateland: mediterranean landscape simulation. R package version, 2.6.0. Available in: https://github.com/emf-creaf/medfateland https://emf-creaf.github.io/medfateland/.

De Cáceres, M., Molowny-Horas, R., Cabon, A., Martínez-Vilalta, J., Mencuccini, M., García-Valdés, R., Nadal-Sala, D., Sabaté, S., Martin-StPaul, N., Morin, X., D'Adamo, F., Batllori, E., Améztegui, A., 2023. Medfate 2.9.3: a trait-enabled model to simulate Mediterranean forest function and dynamics at regional scales. Geosci. Model Dev. (GMD) 16, 3165–3201. https://doi.org/10.5194/gmd-16-3165-2023.

DIBA, 2023. Barcelona provincial council report on agricultural land recovery potential. https://bcnagraria.diba.cat/ca/investiga/potencial-de-recuperacio-de-terres.

Dickman, L.T., Jonko, A.K., Linn, R.R., Altintas, I., Atchley, A.L., Bär, A., Collins, A.D., Dupuy, J., Gallagher, M.R., Hiers, J.K., Hoffman, C.M., Hood, S.M., Hurteau, M.D., Jolly, W.M., Josephson, A., Loudermilk, E.L., Ma, W., Michaletz, S.T., Nolan, R.H., O'Brien, J.J., Parsons, R.A., Partelli-Feltrin, R., Pimont, F., de Dios, V.R., Restaino, J., Robbins, Z.J., Sartor, K.A., Schultz-Fellenz, E., Serbin, S.P., Sevanto, S., Shuman, J.K., Sieg, C.H., Skowronski, N.S., Weise, D.R., Wright, M., Xu, C., Yebra, M., Younes, N., 2023. Integrating plant physiology into simulation of fire behavior and effects. New Phytol. https://doi.org/10.1111/nph.18770.

Duane, A., Aquilué, N., Canelles, Q., Morán-Ordoñez, A., De Cáceres, M., Brotons, L., 2019. Adapting prescribed burns to future climate change in Mediterranean landscapes. Sci. Total Environ. 677, 68–83. https://doi.org/10.1016/j.scitotenv.2019.04.348.

Duane, A., Castellnou, M., Brotons, L., 2021a. Towards a comprehensive look at global drivers of novel extreme wildfire events. Clim. Change 165, 1–21. https://doi.org/10.1007/s10584-021-03066-4.

Duane, A., Miranda, M.D., Brotons, L., 2021b. Forest connectivity percolation thresholds for fire spread under different weather conditions. For. Ecol. Manag. 498, 119558. https://doi.org/10.1016/j.foreco.2021.119558.

Dupuy, J. luc, Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., Fernandes, P., 2020. Climate change impact on future wildfire danger and activity in southern Europe: a review. Ann. For. Sci. 77. https://doi.org/10.1007/s13595-020-00933-5.

Elia, M., Lovreglio, R., Ranieri, N., Sanesi, G., Lafortezza, R., 2016. Cost-Effectiveness of fuel removals in Mediterranean Wildland-Urban interfaces threatened by wildfires. Forests 7, 149. https://doi.org/10.3390/f7070149.

Ellis, T.M., Bowman, D.M.J.S., Jain, P., Flannigan, M.D., Williamson, G.J., 2022. Global increase in wildfire risk due to climate-driven declines in fuel moisture. Glob. Change Biol. 28, 1544–1559. https://doi.org/10.1111/gcb.16006.

GENCAT, 2024. Government of Catalonia. Department of Agriculture, Livestock, Fisheries and Food. Forest fires that occurred between 1986-2023. https://agricultura.gencat.cat/ca/serveis/cartografia-sig/bases-cartografiques/boscos/incendis-forestals/incendis-forestals-format-shp/.

Goussios, D., Gaki, D., Mardakis, P., Faraslis, I., 2024. New possibilities for planning the recovery of abandoned agricultural land in Mediterranean Mountain communities: the case of troodos in Cyprus. Land 14, 6. https://doi.org/10.3390/land14010006.

Hartmann, H., Bastos, A., Das, A.J., Esquivel-Muelbert, A., Hammond, W.M., Martínez-Vilalta, J., McDowell, N.G., Powers, J.S., Pugh, T.A.M., Ruthrof, K.X., Allen, C.D., 2022. Climate change risks to global Forest health: emergence of unexpected events of elevated tree mortality worldwide. Annu. Rev. Plant Biol. 73, 673–702. https://doi.org/10.1146/annurev-arplant-102820-012804.

Herrando, S., Brotons, L., Anton, M., Páramo, F., Villero, D., Titeux, N., Quesada, J., Stefanescu, C., 2016. Assessing impacts of land abandonment on Mediterranean biodiversity using indicators based on bird and butterfly monitoring data. Environ. Conserv. 43, 69–78. https://doi.org/10.1017/S0376892915000260.

ICGC, 2018. Cartographic and Geological Institute of Catalonia: Land Cover Map of Catalonia: icgc.cat/en/Sustainable-territory/Land-cover.

IPCC, 2023. Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental Panel on climate change. IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647. Geneva, Switzerland.

Keane, R.E., 2015. Wildland fuel fundamentals and applications, wildland Fuel Fundamentals and Applications. https://doi.org/10.1007/978-3-319-09015-3.

Landau, V., Shah, V., Anantharaman, R., Hall, K., 2021. Omniscape.jl: software to compute omnidirectional landscape connectivity. JOSS 6, 2829. https://doi.org/10.21105/joss.02829.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M.P., Lana-Renault, N., 2017. Space–time process and drivers of land abandonment in Europe. Catena 149, 810–823. https://doi.org/10.1016/j.catena.2016.02.024.

Lecina-Diaz, J., Chas-Amil, M.-L., Aquilué, N., Sil, Â., Brotons, L., Regos, A., Touza, J., 2023. Incorporating fire-smartness into agricultural policies reduces suppression costs and ecosystem services damages from wildfires. J. Environ. Manag. 337, 117707. https://doi.org/10.1016/j.jenvman.2023.117707.

Leverkus, A.B., Buma, B., Wagenbrenner, J., Burton, P.J., Lingua, E., Marzano, R., Thorn, S., 2021. Tamm review: does salvage logging mitigate subsequent forest disturbances? For. Ecol. Manag. 481, 118721. https://doi.org/10.1016/j.foreco.2020.118721.

Leys, C., Ley, C., Klein, O., Bernard, P., Licata, L., 2013. Detecting outliers: do not use standard deviation around the mean, use absolute deviation around the median. J. Exp. Soc. Psychol. 49, 764–766. https://doi.org/10.1016/j.jesp.2013.03.013.

Littell, J.S., Peterson, D.L., Riley, K.L., Liu, Y., Luce, C.H., 2016. A review of the relationships between drought and forest fire in the United States. Glob. Change Biol. 22, 2353–2369. https://doi.org/10.1111/gcb.13275.

Lloret, F., Batllori, E., 2021. Climate-Induced global Forest shifts due to heatwave-drought. In: Canadell, J.G., Jackson, R.B. (Eds.), Ecosystem Collapse and Climate Change. Springer International Publishing, Cham, pp. 155–186. https://doi.org/10.1007/978-3-030-71330-0_7.

Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M.C., Catry, F. X., Armesto, J., Bond, W., González, M.E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J.G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V.R., Van Wilgen, B. W., Xanthopoulos, G., Fernandes, P.M., 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15, 011001. https://doi.org/10.1088/1748-9326/ab541e.

Moreira, F., Pe'er, G., 2018. Agricultural policy can reduce wildfires. Science 359. https://doi.org/10.1126/science.aat1359, 1001–1001.

Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., Bilgili, E., 2011. Landscape – wildfire interactions in southern Europe: implications for landscape management. J. Environ. Manag. 92, 2389–2402. https://doi.org/10.1016/j.jenvman.2011.06.028.

Neidermeier, A.N., Zagaria, C., Pampanoni, V., West, T.A.P., Verburg, P.H., 2023. Mapping opportunities for the use of land management strategies to address fire risk in Europe. J. Environ. Manag. 346, 118941. https://doi.org/10.1016/j.jenvman.2023.118941.

Pais, S., Aquilué, N., Honrado, J.P., Fernandes, P.M., Regos, A., 2023. Optimizing wildfire prevention through the integration of prescribed burning into 'Fire-Smart' land-use policies. Fire 6, 457. https://doi.org/10.3390/fire6120457.

Palmero-Iniesta, M., Domènech, R., Molina-Terrén, D., Espelta, J.M., 2017. Fire behavior in Pinus halepensis thickets: effects of thinning and woody debris decomposition in two rainfall scenarios. For. Ecol. Manag. 404, 230–240. https://doi.org/10.1016/j.foreco.2017.08.043.

Palmero-Iniesta, M., Espelta, J.M., Gordillo, J., Pino, J., 2020. Changes in forest landscape patterns resulting from recent afforestation in Europe (1990–2012): defragmentation of pre-existing forest versus new patch proliferation. Ann. For. Sci. 77, 43. https://doi.org/10.1007/s13595-020-00946-0.

Penman, T.D., Clarke, H., Cirulis, B., Boer, M.M., Price, O.F., Bradstock, R.A., 2020. Cost-Effective prescribed burning solutions vary between landscapes in Eastern Australia. Front. For. Glob. Change 3, 79. https://doi.org/10.3389/ffgc.2020.00079.

Perpiña Castillo, C., Jacobs-Crisioni, C., Diogo, V., Lavalle, C., 2021. Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: an application for the EU. Environ. Model. Software 136, 104946. https://doi.org/10.1016/j.envsoft.2020.104946.

Piqué, M., Domènech, R., 2018. Effectiveness of mechanical thinning and prescribed burning on fire behavior in Pinus nigra forests in NE Spain. Sci. Total Environ. 618, 1539–1546. https://doi.org/10.1016/j.scitotenv.2017.09.316.

Prichard, S.J., Sandberg, D.V., Ottmar, R.D., Eberhardt, E., Andreu, A., Eagle, P., Swedin, Kjell, 2013. Fuel Characteristic Classification System Version 3.0: Technical Documentation (No. PNW-GTR-887). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. https://doi.org/10.2737/PNW-GTR-887.

Resco de Dios, V., Hedo, J., Cunill, À., Thapa, P., Martínez, E., Martínez, J., Aragón, D., Antonio, J., Balaguer-Romano, R., Díaz-sierra, R., Yebra, M., Boer, M.M., 2021. Climate change induced declines in fuel moisture may turn currently fi re-free Pyrenean mountain forests into fi re-prone ecosystems. Sci. Total Environ. 797, 149104. https://doi.org/10.1016/j.scitotenv.2021.149104.

Richardson, D., Black, A.S., Irving, D., Matear, R.J., Monselesan, D.P., Risbey, J.S., Squire, D.T., Tozer, C.R., 2022. Global increase in wildfire potential from compound fire weather and drought. npj Clim. Atmos. Sci. 5, 23. https://doi.org/10.1038/s41612-022-00248-4.

Roces-Díaz, J.V., Vayreda, J., De Cáceres, M., García-Valdés, R., Banqué-Casanovas, M., Morán-Ordóñez, A., Brotons, L., de-Miguel, S., Martínez-Vilalta, J., 2021. Temporal changes in Mediterranean forest ecosystem services are driven by stand development, rather than by climate-related disturbances. For. Ecol. Manag. 480, 118623. https://doi.org/10.1016/j.foreco.2020.118623.

Rodrigues, M., Cunill Camprubí, À., Balaguer-Romano, R., Coco Megía, C.J., Castañares, F., Ruffault, J., Fernandes, P.M., Resco de Dios, V., 2023. Drivers and implications of the extreme 2022 wildfire season in Southwest Europe. Sci. Total Environ. 859, 160320. https://doi.org/10.1016/j.scitotenv.2022.160320.

Ruffault, J., Curt, T., Martin-Stpaul, N.K., Moron, V., Trigo, R.M., 2018. Extreme wildfire events are linked to global-change-type droughts in the northern Mediterranean. Nat. Hazards Earth Syst. Sci. 18, 847–856. https://doi.org/10.5194/nhess-18-847-2018.

Salis, M., Del Giudice, L., Jahdi, R., Alcasena-Urdiroz, F., Scarpa, C., Pellizzaro, G., Bacciu, V., Schirru, M., Ventura, A., Casula, M., Pedes, F., Canu, A., Duce, P., Arca, B., 2022. Spatial patterns and intensity of land abandonment drive wildfire hazard and likelihood in Mediterranean agropastoral areas. Land 11, 1942. https://doi.org/10.3390/land11111942.

SIGPAC, 2022. Geographic information System for agricultural plots. https://agricultura.gencat.cat/ca/ambits/desenvolupament-rural/sigpac/informacio-general-sigpac.

Stephens, S.L., Collins, B.M., Fettig, C.J., Finney, M.A., Hoffman, C.M., Knapp, E.E., North, M.P., Safford, H., Wayman, R.B., 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience 68, 77–88. https://doi.org/10.1093/biosci/bix146.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C., Cobb, T., Donato, D.C., Durska, E., Fontaine, J.B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R.L., Lee, E., Leverkus, A.B., Lindenmayer, D.B., Obrist, M.K., Rost, J., Seibold, S., Seidl, R., Thom, D., Waldron, K., Wermelinger, B., Winter, M., Zmihorski, M., Müller, J., 2018. Impacts of salvage logging on biodiversity: a meta-analysis. J. Appl. Ecol. 55, 279–289. https://doi.org/10.1111/1365-2664.12945.

Torres-Ruiz, J.M., Cochard, H., Delzon, S., Boivin, T., Burlett, R., Cailleret, M., Corso, D., Delmas, C.E.L., De Caceres, M., Diaz-Espejo, A., Fernández-Conradi, P., Guillemot, J., Lamarque, L.J., Limousin, J.M., Mantova, M., Mencuccini, M., Morin, X., Pimont, F., De Dios, V.R., Ruffault, J., Trueba, S., Martin-StPaul, N.K., 2023. Plant hydraulics at the heart of plant, crops and ecosystem functions in the face of climate change. New Phytol. 241, 984–999. https://doi.org/10.1111/nph.19463.

Xu, C., Liu, H., Ciais, P., Hartmann, H., Camarero, J.J., Wu, X., Hammond, W.M., Allen, C.D., Chen, F., 2024. Enhanced drought exposure increasingly threatens more forests than observed. Earths Future 12, e2023EF003705. https://doi.org/10.1029/2023EF003705.

Zylstra, P., Wardell-Johnson, G., Falster, D., Howe, M., McQuoid, N., Neville, S., 2023. Mechanisms by which growth and succession limit the impact of fire in a south-western Australian forested ecosystem. Funct. Ecol. 37, 1350–1365. https://doi.org/10.1111/1365-2435.14305.

Zylstra, P.J., Bradshaw, S.D., Lindenmayer, D.B., 2022. Self-thinning forest understoreys reduce wildfire risk, even in a warming climate. Environ. Res. Lett. 17, 044022. https://doi.org/10.1088/1748-9326/ac5c10.