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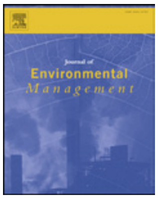

Research article

Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain

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ABSTRACT

Southern European countries rely largely on fire suppression and ignition prevention to manage a growing wildfire problem. We explored a more wholistic, long-term approach based on priority maps for the implementation of diverse management options aimed at creating fire resilient landscapes, restoring cultural fire regimes, facilitating safe and efficient fire response, and creating fire-adapted communities. To illustrate this new comprehensive strategy for fire-prone Mediterranean areas, we developed and implemented the framework in Catalonia (northeastern Spain). We first used advanced simulation modeling methods to assess various wildfire exposure metrics across spatially changing fire-regime conditions, and these outputs were then combined with land use maps and historical fire occurrence data to prioritize different fuel and fire management options at the municipality level. Priority sites for fuel management programs concentrated in the central and northeastern high-hazard forestlands. The suitable areas for reintroducing fires in natural ecosystems located in scattered municipalities with ample lightning ignitions and minimal human presence. Priority areas for ignition prevention programs were mapped to populated coastal municipalities and main transportation corridors. Landscapes where fire suppression is the principal long-term strategy concentrated in agricultural plains with a high density of ignitions. Localized programs to build defensible space and improve self-protection on communities could be emphasized in the coastal wildland-urban interface and inner intermix areas from Barcelona and Gerona. We discuss how the results of this study can facilitate collaborative landscape planning and identify the constraints that prevent a longer term and more effective solution to better coexist with fire in southern European regions.

1. Introduction

Wildfires continue to cause substantial losses to socio-economic and natural values in Mediterranean areas where human activities both drive fire regimes and simultaneously incur highest negative impacts (Díaz-Delgado et al., 2004; Martínez et al., 2009). In the southern EU countries (Portugal, Spain, France, Italy, and Greece) some 48,600 fires burn every year on average 447,800 ha (1980–2015), and a small number of large fires ($<15\%$) account for the bulk of burned area (San-Miguel-Ayanz et al., 2017). These fires spread for long distances (>10 km), exhibit active crown fire that showers large amounts of embers into the wildland-urban interface (WUI) areas, and typically occur during simultaneous episodes associated to heat waves (Cardil et al., 2014; Castellnou and Miralles, 2009; San-Miguel-Ayanz et al., 2013). Currently, stand-replacing fires in unmanaged forest ecosystems, fatalities during extreme episodes, and increasing losses to human communities represent the major threats from large fires in southern European regions (Cardil et al., 2017; Costa et al., 2011). Such “mega-fires” are projected to increase due to climate change and increasing amounts and continuity of fuels (Barrera, 2011; Cardil et al., 2014; Kuemmerle et al., 2016; Moreira et al., 2011; Piñol et al., 1998).

The main strategy to reduce losses from large fires is suppression, which has been shown to be largely ineffective during extreme fire weather conditions, represent a significant financial outlay in countries like Spain (15–20 million € yr^{-1}), and result in human injuries and loss of life (56.3 injured yr^{-1} and 3.5 fatalities yr^{-1} on average from 1996 to

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2010) (ADCIF, 2012). These catastrophic events also burn through many land tenures, communities, and jurisdictional boundaries on landscapes highly fragmented in terms of ownership, fuels loadings, and land management objectives (Alcasena et al., 2017; Palaiologou et al., 2018). Thus, fires are increasingly becoming an issue that needs to be addressed collectively by the various organizations responsible for fire suppression, as well as rural inhabitants managing landscape fuels and institutions ruling territorial policies concerning wildfire (Acacio et al., 2010; Gazzard et al., 2016; Marino et al., 2014). Building a risk governance system in these Mediterranean cultural landscapes where human communities, multi-objective mosaics of pastures with forested lands and intensively managed numerous smallholdings intermingle has not progressed much beyond additional investments in suppression (Garrido et al., 2017; Oliveira et al., 2017; Senf et al., 2015). If no measures are taken, many rural communities and urban areas that depend on multifunctional forest systems for their livelihood will likely continue to face catastrophic wildfire events.

In the US, where similar concerns challenge to land managers in fire-prone areas, a new wildland fire cohesive strategy has been developed that partitions the problem into three objectives: fire-resilient landscapes, fire-adapted human communities, and a safe and efficient wildfire response (USDA Forest Service, 2014). Fire-resilient forest ecosystems have the adaptations needed to withstand and recover from fire with minimal restoration treatments, and are often characterized by low-density open stands of single-storied dominant trees with small patches of saplings and multiple discontinuities of surface, ladder and crown fuels (Fernandes et al., 2015; Hessburg et al., 2015). While mixed-severity lightning fires have been the main landscape disturbance agent maintaining low fuel loads and persistent openings in pre-settlement western US forests, the intensive anthropic management on Mediterranean cultural landscapes (i.e., agriculture, livestock, firewood and cultural use of fire) was historically responsible for preserving sharp-transition small-unit mosaics of low-fuel-load land covers (Cervera et al., 2016; Seijo et al., 2016). Although human communities in the Mediterranean have been historically less susceptible to losses from fire compared to the western US, the limited management surrounding rural communities and newly developed residential areas in the WUI has substantially reduced the capacity for firefighters and local residents to defend these communities during large-scale events (Costa et al., 2011; Sirca et al., 2017; Viedma et al., 2015).

There has been a minimal discussion in the literature on a broader, integrated approach to the fire problem for southern European Union (EU) countries, and fire exclusion and ignition prevention programs continue to be the main pillars of wildfire management (Corona et al., 2015; Fernandes, 2013; Silva et al., 2010). Nonetheless, a fire exclusion policy in fire-adapted ecosystems is not a viable long-term policy as demonstrated by the current situation in the EU countries and elsewhere (Otero and Nielsen, 2017; Seijo and Gray, 2012). Developing a broader mix of fire management objectives that are tailored to particular landscapes based on fire regimes, human values, and land use could potentially highlight where alternative and integrated strategies provide a long-term solution to better coexist with fire (Moritz et al., 2014). For instance, suppression efforts should be prioritized on areas where these interventions can efficiently prevent property loss without exposing firefighters to entrapment in hazardous environments (Cardil et al., 2017). On the other hand, fuel management should be prioritized where potential property loss is high (Alcasena et al., 2015; Salis et al., 2013). Where that is not the case, management could be directed at the re-introduction of fire in fire-dependent ecosystems, using unplanned fire as a means to manage fuels on protected natural sites and regulating traditional fire uses for pasture clearing and conservation when feasible (Barnett et al., 2016; Coughlan, 2015; Regos et al., 2014).

The current fire policy in European countries is failing to protect human communities and natural values from devastating events and this study proposes a new approach and long-term solution to deal with the growing large-fire problem in Mediterranean cultural landscapes. To explore how the current approach to wildfire could be broadened to consider other fire management strategies we combined outputs from simulation modeling with land use patterns, valued assets, and historical ignition data to map specific fire and fuel management goals including fire resiliency in forests, restoration of the cultural fire regime, safe and efficient fire response, and creating fire-adapted human communities. To illustrate our framework we implemented this study in Catalonia (northeastern Spain), a fire-prone Mediterranean region where extreme events caused very substantial losses during the last decades. Our study presents an innovative methodological framework to model historical fire size distributions and burn patterns on diverse fire-regime macro-areas while accounting for spatially changing weather scenarios across the study area. The maps obtained in this paper can be used to advance discussions about alternative management strategies and help resolve fire-related socioecological conflicts. Specifically, the results can be also used to locally prioritize specific management options as part of the landscape and urban planning within the study area. This study can represent the baseline for the development of a broader wildfire management strategy encompassing the entire fire-prone southern European regions.

2. Material and methods

2.1. Overview of the proposed wildland fire management strategy

We identified four wildfire management primary goals for southern European regions, while considering the US cohesive strategy (USDA Forest Service, 2015) as a referent, that each rely on specific management options (Fig. 1). We used these goals to prioritize and rank management options at municipality level (i.e., administrative division units) according to spatially-explicit quantitative metrics. The results were a set of maps that can be used to prioritize local fuels management projects, ignition prevention programs, suppression resource pre-positioning, community action projects or any other public or private risk mitigation initiatives. Human communities refer to development areas containing most residential housing structures within municipalities. See Appendix A in the supplementary material for further details about each goal, respective management options and the metrics used to assess priorities.

2.2. Study area

The study area was located in the northeastern extremity of the Iberian Peninsula and encompassed the 32,113 km^2 autonomous community of Catalonia (northeastern Spain). Catalonia is administratively divided into 948 municipalities, which are jurisdictionally aggregated into 42 counties and 4 provinces. Most of the 7.5 million inhabitants ($> 90\%$) concentrate in the highly-developed metropolitan area of Barcelona and a few cities close to the coastline. The climate is predominantly Mediterranean with increasing rainfall on pre-littoral mountain ranges (precipitation $> 500\,\text{mm yr}^{-1}$) and milder winters closer to the coastline to the east (average temperatures for January $> 7\,^{\circ}\text{C}$). The transition to high-mountain climate (precipitation $> 750\,\text{mm yr}^{-1}$ and average temperatures for January $< 3\,^{\circ}\text{C}$) is associated with the altitudinal gradient moving northwards to the Pyrenees mountain range above the 1500 m. Irrigated agricultural lands, mosaics of shrublands (*Solsona vermiculata* L.) and herbaceous xerophytic vegetation edges cover the central depression of Lleida's plain below 450 m. Increasing elevations and rough reliefs to the north confine cultivated plots to valley bottoms, with forested areas dominated by Mediterranean oaks (e.g., *Quercus ilex* L.) and low shrublands on slopes (*Lavandula angustifolia* Mill., *Rosmarinus officinalis* L. and *Quercus coccifera* L.). These shrublands and forests are gradually replaced by tall-shrubland species (*Buxus sempervirens* L. and *Juniperus communis* L.), mid-mountain oak (*Quercus pubescens* Willd.) and conifer species (*Pinus nigra* Arn. and *Pinus sylvestris* L.) first on north-facing

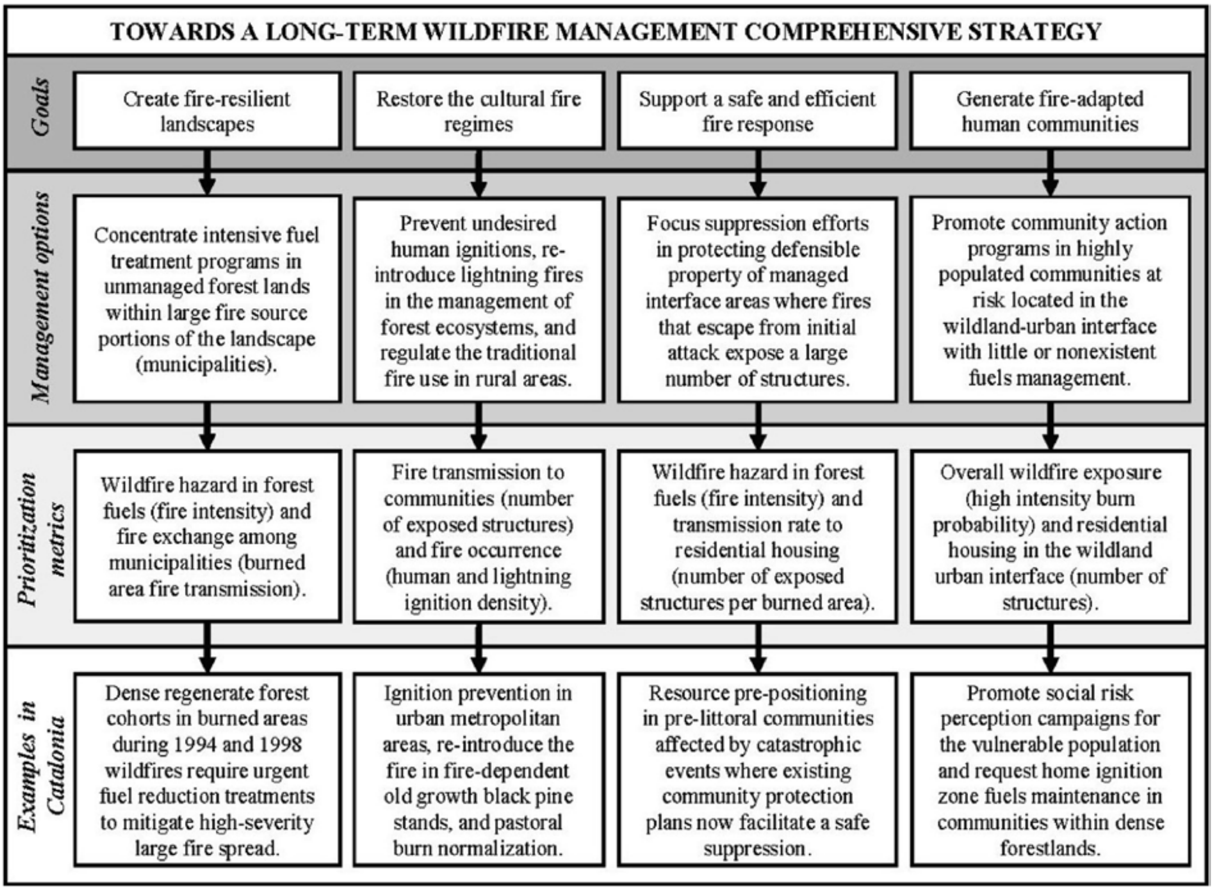


Fig. 1. General framework of the wildfire management comprehensive strategy baseline proposed for the southern European fire-prone regions. We identified four major objectives and, respectively, the most feasible management options. Wildfire occurrence, hazard, exposure, and large fire transmission metrics were used to rank priorities in the different management options at the municipality level. To illustrate the potential applicability of the framework we present some examples for its implementation in Catalonia (northeastern Spain).

slopes, and then all across on higher elevations (*Pinus uncinata* Ram.). The presence of broadleaved forests (*Fagus sylvatica* L.) and fir woods (*Abies alba* Mill.) is very limited. Mosaics of rocky outcrops, low shrublands (*Genista balansae* Boiss.) and pastures cover the high mountain tops above the 1400 m. On the pre-littoral mountain ranges, the Mediterranean maquis (*Pistacia lentiscus* L. and *Arbutus unedo* L.) appear in combinations with densely regenerated young Aleppo pine cohorts (*Pinus halepensis* Mill.). Silicicolous shrublands (*Cistus* ssp. and *Erica* ssp.) are frequently found in coastal lowlands sometimes with presence of stone pine (*Pinus pinea* L.). Cork oak (*Quercus suber* L.) is confined to the northeastern lowlands of the study area. Protected natural sites of special interest occupy about one-third of the study area and occasionally can represent a wildfire management constraint for the implementation of fuel reduction programs (Appendix B).

2.3. *Historical fire activity*

Catalonia is one of the largest fire-prone areas in the Mediterranean basin and encompasses a wide variety of landscapes, vegetation types, physiographic gradients, climates, and fire ignition patterns. On average some 650 fires burn about 11.5 thousand ha yr^{-1}, from which a low number ($< 2\%$) of large fires (> 100 ha) account for more than the 88% of the burned area, and a few extreme events (> 1.000 ha fire of 1986, 1994, 1998, 2003 and 2012) concentrate the bulk ($> 65\%$) of the burned area. Most fire ignitions ($> 90\%$) are caused by humans (1983–2014) (MAAyMA, 2015). Lightning activity is concentrated from June to August, and most natural fires start from cloud-to-ground flashes between 12:00 and 18:00 UTC (Pineda et al., 2014).

The climatic factors in the study area controlling large fire weather conditions are associated with spatial and temporal atmospheric circulation patterns presenting substantial region-wide differences (Duane and Brotons, 2018; Rasilla et al., 2010). Therefore, we divided the study area into five zones that capture changing fire activity gradients across Catalonia, coincidental with major fire regime macro-areas (Fig. 2a; Appendix C): the Pyrenees, pre-Pyrenees, Western plain, Northern coast, and the Mediterranean coast. The delimitation of the fire regime areas was based on climatic and physiographical zone land divisions of Catalonia (Bolòs, 1975) using municipality boundary polygons. Analyzing fire activity separately on these areas facilitated the segmentation of the study area into blocks with a different wildfire season duration and very particular burn patterns associated with the local weather conditions. The wildfire season was considered as the annual period concentrating 90% of the burned area from fires > 100 ha (Fig. 2b; Table 1). Apart from the typical summer wildfire season corresponding to the Mediterranean dry period, the Pyrenees also have a secondary winter fire season (Costafreda-Aumedes et al., 2018). We can observe wide differences in fire activity between the macro-areas in terms of large fire number and mean annual burn probability (fire database from 1983 to 2014) (Table 1). For instance, large fire number and mean annual burn probability in the northern coast are, respectively, 5 and 20 times higher than in the Pyrenees.

2.4. *Wildfire modeling*

We used input data for fire modeling corresponding to the landscape grid (topography, surface fuels, and forest canopy metrics), fire weather

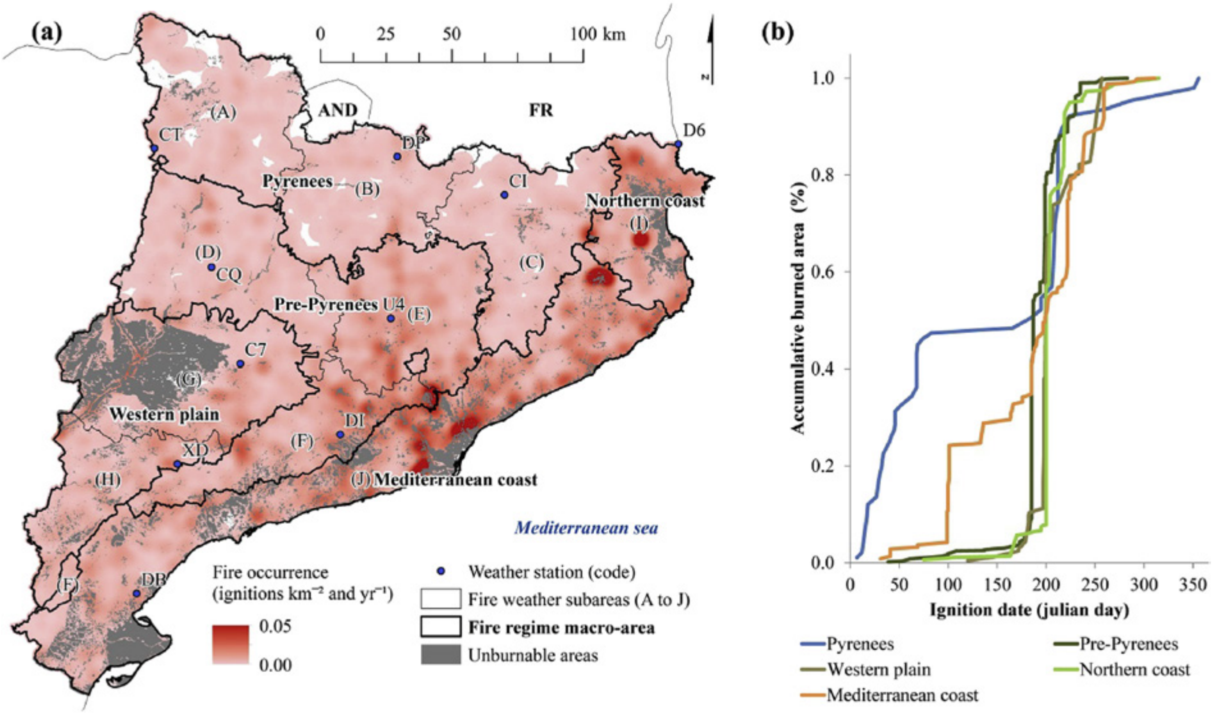


Fig. 2. Spatial extent (a) and historic fire activity (b) for the major fire regime macro-areas in Catalonia (northeastern Spain; Table 1). The fire occurrence grid (a) was generated with kernel geostatistical methods using historical ignition locations from 1998 to 2014. The fire regime macro-areas were further divided into 10 fire-weather subareas to consider the changing conditions on local wind scenarios (a; A to J; Table 2).

conditions (wildfire season wind and fuel moisture content scenarios), and an ignition probability grid derived from historical ignition locations. Topography, surface fuel, and canopy metric raster grids were assembled into the landscape file at 150-m resolution. In order to account for incoming fires, especially from the western side, and avoid edge effects on modeling outputs, the landscape file was extended with a 10 km buffer encompassing a total fire modeling domain area of 3.84 million ha. Topographic data grids (elevation, aspect, and slope) were generated from the 25-m resolution digital terrain model (ign.es), canopy metrics (canopy height, canopy cover, canopy base height, and canopy bulk density) were obtained from LiDAR-derived 20-m resolution woodland biophysical variable grids for Catalonia (ICGC, 2016), and surface fuels were obtained by assigning standard fuel models (Scott and Burgan, 2005) to the 1:5000-scale land use land-cover polygons (GENCAT, 2016). For the fuel model assignment to the different land cover polygons, we considered the vegetation characteristics such as species composition, cover, thickness, and shrubs and herbaceous fuels heights detailed in the 2012 map of habitats of Catalonia (GENCAT, 2012).

The fire modeling domain was divided in 10 subareas in order to capture the fire-weather variability across Catalonia (see A to J subareas in Fig. 2a). Some fire regime macro-areas were internally subdivided due to differences in the local wind scenarios. For every subarea, we identified a representative automatic weather station with a long data series. We used hourly temperature, rainfall, wind speed, wind direction, relative humidity, and solar radiation records to characterize the wildfire season weather conditions using Fire Family Plus (Bradshaw and McCormick, 2000). Specifically, we considered extreme weather reference conditions (i.e., 97th percentile) in terms of wind speed for most frequent wind directions and ERC-G fuel moisture content (Nelson, 2000) to obtain the fire modeling weather scenarios (Table 2). Containment efforts are very effective under mild weather conditions and thus most of the area is burned by a few extreme fires overwhelming suppression capabilities (Castellnou and Miralles, 2009; Finney, 2005).

In Catalonia, most historical fire ignitions are geospatially related to urban development and transportation corridors in highly-populated sites, and concentrate in high-density hot-spots with a sharp transition to non-ignition poor access remote areas (Costafreda-Aumedes et al., 2016; Gonzalez-Olabarria et al., 2015). In order to capture this pattern in the fire occurrence input grid required to display the ignitions within the fire modeling domain, we used fixed kernel density methods with a 2000 m bandwidth to generate a 150-m resolution ignition probability grid (Fig. 2a) considering all fire ignition coordinates for the 1998-2014 period (Gonzalez-Olabarria et al., 2012).

We used the FConstMTT command line version of FlamMap to

Table 1
Wildfire history on the main fire regime macro-areas of Catalonia (northeastern Spain; Fig. 2a). We considered a 100 ha large fire threshold to calculate the large fire frequency and define the wildfire season from the historical fire activity chart (Fig. 2b). The mean annual burn probability in Catalonia is 0.0036.

Fire regime macro-area	Wildfire season	Area (ha)	Large fire number (per 10^6 ha and yr^{-1})	Burned area (ha yr^{-1})	Mean annual burn probability
Pyrenees	Jan 7 to March 9, and July 13 to October 12	881,035	1.5	488	0.0006
Pre-Pyrenees	Jun 26 to August 27	837,776	5.1	5,234	0.0062
Western plain	July 10 to September 13	418,626	2.8	1,261	0.0030
Northern coast	Jun 18 to August 11	157,226	7.8	1,911	0.0122
Mediterranean coast	April 8 to September 10	531,950	5.6	2,604	0.0049

Table 2

Fire-weather modeling input scenarios in the different subareas (Fig. 2a). Every fire was modeled under constant extreme fuel moisture and wind conditions (97th percentile), those corresponding to the ignition location fire weather subarea. We modeled a burned area equivalent to 10,000 wildfire seasons at 150-m resolution while considering the historical fire occurrence grid (Fig. 2a) to display the fire ignitions within the modeling domain. The fire duration scenario was determined from fire size distribution replicates (Appendix D).

Fire weather subarea	Weather station (Code)	97th perc. fuel moisture content (%)					97th perc. wind speed (km h^{-1}) and frequency (%)								Duration (min) and probability (%)
		1 h	10 h	100 h	LH	LW	45^0	90^0	135^0	180^0	225^0	270^0	315^0	360^0	
Central (A)	El Pont de Suert (CT)	9	10	14	25	60	–	–	8 (15)	10 (50)	6 (5)	11 (5)	14 (15)	8 (10)	150 min (100)
Oriental meridional (B)	Das (DP)	9	10	14	25	60	23 (15)	16 (20)	11 (10)	14 (15)	14 (25)	17 (15)	–	–	
Transverse mountain system (C)	Sant Pau de Segúries (CI)	10	11	18	30	60	9 (15)	6 (30)	7 (20)	6 (10)	11 (25)	–	–	–	
Meridional central (D)	Vilanova de Meià (CQ)	8	8	11	20	60	–	–	6 (10)	8 (55)	9 (20)	7 (5)	10 (10)	–	145 min (70), 270 min (20) and 840 min (10)
Oriental (E)	Castellnou de Bages (U4)	8	9	13	20	60	–	–	7 (5)	10 (65)	11 (20)	13 (10)	–	–	
Pre-coastal mountain range (F)	Font-rubí (DI)	7	8	10	20	50	–	–	9 (10)	15 (65)	15 (25)	–	–	–	
Plain of Lleida (G)	Tàrrega (C7)	7	8	10	20	50	–	–	16 (20)	14 (20)	15 (20)	19 (40)		–	105min (90) and 215 min (10)
Southern plain (H)	Ulldemolins (XD)	6	7	9	15	50	–	–	13 (35)	19 (20)	9 (10)	13 (25)	20 (10)	–	
L'Empordà coastal plain (I)	Portbou (D6)	6	7	9	20	60	32 (15)	–	31 (20)	35 (25)	37 (5)	–	–	44 (35)	70min (70), 85 min (20) and 540 min (10)
Coastal range (J)	El Perello (DB)	7	8	11	20	50	–	15 (10)	12 (25)	19 (30)	18 (20)	–	34 (10)	28 (5)	85 min (70), 250 min (20) and 500 min (10)

model wildfire spread and behavior with the minimum travel time (MTT) algorithm (Finney, 2006). The MTT algorithm calculates a two-dimensional fire growth by searching for the set of pathways with minimum fire spread times from the cell corners at an arbitrary resolution set by the user (Finney, 2002). The algorithm has been widely used in previous studies assessing wildfire exposure and transmission in complex terrains worldwide (Jahdi et al., 2016; Kalabokidis et al., 2016; Oliveira et al., 2016; Palaiologou et al., 2018; Salis et al., 2013). Fire spread is predicted using Rothermel's surface fire spread model (Rothermel, 1972), fire intensity (kW m^{-1}) is converted to flame length (FL) using Byram's equation (Byram, 1959), and crown fire initiation is predicted according to Scott and Reinhardt (2001).

In order to calibrate the surface fire spread model, we replicated historical large fire size ($>$ 100 ha) distribution in every macro-area separately (Appendix D). In each case, we obtained the fire spread duration that better replicated the historical fire size distribution under extreme weather conditions (Table 2). Fire ignitions were first distributed within the modeling domain according to the ignition probability grid, and then every fire was independently modeled considering the weather scenario (Table 2) in the ignition location subarea (Fig. 2a). During fire modeling, weather conditions were held constant, and fire suppression efforts were not considered due to their limited containment capabilities during extreme fire events. In total 160,000 fires were simulated at 150 m resolution, which accounted for an accumulated burned area equivalent to some 10,000 seasons. Modeled fires saturated the study area and burned each pixel more than 30 times on average. We obtained conditional burn probability (BP), fire intensity, fire size, and fire perimeter polygon outputs from fire modeling. Conditional BP is a pixel-level wildfire likelihood estimate obtained from the proportion of fires that burned each pixel given a fire occurs under extreme weather conditions within the modeling domain. FConstMTT generates the fire intensity result as flame length probability (FLP) where pixel-level outputs are expressed for 20 bin 0.5 m fire-intensity levels (FIL_1 to FIL_{20}, $FIL_{20} \geq 9.5$ m). The fire size (FS) output assigned a value (ha) to every fire ignition coordinates on a fire list file.

2.5. *Analyses*

We used fire modeling outputs (i.e., burn probability, fire intensity, fire size, and fire perimeters) and valued asset geospatial locations to assess wildfire hazard, overall exposure, and fire transmission. In addition, historic fire ignition data were used not only to generate the ignition probability grid required in fire modeling (Fig. 2a) but also to assess anthropogenic and lightning ignition density. Results were provided at the municipality level these because administrative boundaries delineate reference planning areas for landscape and urban planning, and represent the smallest division with management competencies. This allows transferring the core findings from this study to stakeholder and landscape managers dealing with policy-making and strategic planning. All results were annualized considering historical fire activity and normalized for a 10^3 ha area to facilitate the comparison between variable size and distant planning areas.

2.5.1. *Historical fire ignitions and the cultural use of the fire*

Fire records were used to calculate ignition densities for human-caused and lightning fires at the municipality level considering data from the last 32 years (1983–2014) (MAAyMA, 2015). Although early records before 1998 did not have ignition location coordinates, fire ignitions after 1983 were attributed to the municipality. The former 40 fire causes recognized in the national fire database were first grouped into natural (NAT) and 16 more major anthropic (ANT) classes. Then we calculated all anthropic (ANT) and lightning fire (NAT) densities as the number of ignitions yr^{-1} per 10^3 ha municipality area. We also calculated the incidence of the principal human causes associated with the traditional fire use. Major fire ignition causes related to the traditional use include grassland or shrub burns to improve pasture quality, silvicultural or pile burnings to eliminate thinning residue, agricultural edge property burning for multiple purposes (e.g., weed and pest control), and post-harvesting agricultural waste burnings.

2.5.2. Wildfire hazard

We used fire modeling outputs that describe flame length probability classes for each pixel to calculate conditional flame length (CFL):

$$\mathrm{CFL} = \sum_{i=1}^{20} \mathrm{FLP_i} \times \mathrm{FL_i} \tag{1}$$

where *CFL* is the conditional flame length (m), FLP_i is the flame length probability of a fire at the *i*-th flame length category, and FL_i is the flame length (m) midpoint of the *i*-th category fire intensity level (*FIL*). The CFL is the probability-weighted fire intensity accounting for all the possible fire front spreading directions at a given pixel (i.e., heading, flanking and backing) and is an estimate of wildfire hazard. Hazard refers to the potential for loss given a fire event, allows for the interpretation of fire suppression capabilities and facilitates the estimation of conditional losses on natural values (e.g., tree mortality and habitat loss) (Alcasena et al., 2016a; Andrews et al., 2011; Miller and Ager, 2013). At low intensities (< 1.2 m of flame length), fire can easily be contained by ground crews and those areas do not usually represent a priority in fuel treatment implementation. Intermediate fire intensity levels (1.2–2.5 m of flame length) are too intense for direct attack and can cause a significant mortality on young forests. On these areas treatments such as prescribed fires and mastication are frequently used to reduce fuels. High fire intensities (> 2.5 m of flame length) overwhelm fire suppression capabilities and easily torch dense unmanaged forests and cause massive mortalities. Here, thinning is usually required in addition to the surface fuel treatments to eliminate laddered structures and tree crown continuity.

2.5.3. Overall wildfire exposure

We used flame length probability and burn probability outputs to assess wildfire exposure as the high-intensity burn probability (HIBP) as follows (Lozano et al., 2017):

$$\mathrm{HIBP} = \sum_{i=6}^{20} \mathrm{FLP_i}\cdot\mathrm{BP} \tag{2}$$

where *HIBP* is the pixel level high-intensity burn probability, *FLP* is the flame length probability of a fire at the *i*-th flame length category above 2.5 m of flame length threshold, and *BP* is the conditional burn probability modeling output. Therefore, integrates both likelihood and intensity results in a unique exposure metric. Although exposure itself does not reflect fire effects, flame lengths above 2.5 m produce stand-replacing effects in conifer forests and high losses on residential houses (Alcasena et al., 2017). In this study, we used HIBP to assess exposure in the different wildand-urban interface, intermix, and disperse rural communities across Catalonia (Alcasena et al., 2018a).

2.5.4. Large fire transmission

We used a fire transmission analysis to assess the fire exchange across Catalonia and identify risk-source municipalities (i.e., planning areas). To assess burned area fire transmission, we used the following equation (Ager et al., 2014):

$$T_{ij} = \frac{BA_j}{N_i} \tag{3}$$

where T_{ij} measures the average fire transmission in terms of the *BA* burned area (ha) from large fires (> 100 ha) ignited in the *i*-th municipality and burning into the *j*-th neighboring municipality (i.e., $j = i$ for self-burning). Therefore, the study area was considered as a continuous cover polygon mosaic where the ignition location was assigned at the municipality in the origin and the fire exchange was estimated on every municipality (n = 948, with an average area of ~3400 ha) in terms of self-burning (SB), incoming fire (T_IN) and the outgoing fire (T_OUT) burned area (mean annual ha yr^{-1}, per a normalized municipality area of 10^3 ha). Thus, for the entire fire modeling domain area encompassing Catalonia and the expanding 10 km buffer, ΣT_IN = ΣT_OUT.

In addition, we calculated fire transmission to structures (number of exposed structures yr^{-1}) separately for residential housing (T_RES) and industrial structures (T_IND) at the municipality level using equation [3], where *BA* burned area (ha) was replaced with the number of exposed structures in all municipalities (*SN*). To assess the transmission to structures, we intersected large fire perimeter outputs with structure geospatial locations (Appendix E) and then assigned the number of intersected structures to the ignition location (Alcasena et al., 2017, 2018c). Then, using the transmission to structures, we calculated the rates (TR) per burned area to have a better estimate of potential losses per burned ha. The latter represents a better metric to prioritize first attack and ground force pre-positioning because smaller fires burning several structures on the wildland-urban interface represent a higher priority with respect to the very large fires burning uninhabited remote areas.

2.6. Management priorities

Results from these efforts were presented in a set of priority maps in order to transfer our findings into straightforward meaningful outcomes for the implementation of a wildfire management strategy. We first designated a pair of metrics to prioritize each wildfire management option (Table 3). In particular, transmission and hazard metrics were used to prioritize fuels management in forest lands, fire occurrence and transmission to communities were used to target human ignition prevention areas, wildfire exposure and the number of structures on the WUI were considered to identify the communities requiring a protection plan, and transmission rates in combination with wildfire hazard were used to identify best opportunities for a safe efficient response. Then, we cross-tabulated the values from the two factors to set four priority levels: I-high, II-moderate, III-low and IV-very low (Table 4). Except for wildfire hazard, we considered quartile values to set the four categories in each metric. Fire-intensity classes associated with fire behavior were used for the interpretation of wildfire hazard: 0–1.2 m; 1.2–2.4 m; 2.4–3.4 m; > 3.4 m (Andrews et al., 2011). While the highest intensity categories present a higher priority for fuel treatment location, lower intensities represent a better opportunity for fire containment. Finally, we also generated a set of scatter-plots to explore the variation in average values among high-priority municipalities (Appendix F).

3. Results

3.1. Historical fire ignitions and the traditional fire use

Our results showed different annual ignition density results in terms of spatial patterns and density values for anthropic (ANT) and lightning (NAT) fires (Fig. 3a and b). While ANT ignitions concentrated at densities above 0.26 ignitions yr^{-1} per 10^3 ha in coastal municipalities and metropolitan areas of Barcelona, municipalities in central Catalonia reached the highest NAT density values (> 0.12 ignitions yr^{-1} per 10^3 ha). Anthropic ignitions showed clustered spatial patterns in areas where the human activity is especially intense (e.g. close to the communication corridors and highly populated urban areas). On the other hand, the spatial patterns of natural fire ignitions were associated with spatiotemporal atmospheric conditions, altitudinal gradients and lightning strike densities (Pineda and Rigo, 2017).

Overall, ANT ignitions resulted in much higher densities than NAT (i.e., on average ANT values were six times higher than NAT), and only very few municipalities in central Catalonia presented NAT > ANT. Among human-caused fires, ignitions related to the cultural fire use

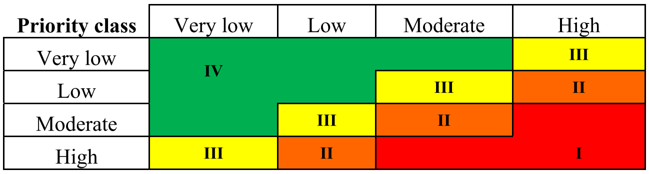
Table 3

Assignment of metric pairs (i.e, fire occurrence, hazard, exposure, and transmission results) to the different objectives of the wildfire management strategy (Fig. 1). These metrics were cross-tabulated to obtain 4 priority classes (Table 2). The final results were presented at the municipality level (n = 948) in a set of spatial priority maps.

Goal	Management options	Prioritization metrics	Priority map
Create fire resilient landscapes	Fuel treatments	We used fire transmission (T_OUT quartiles; Fig. 5a) and wildfire hazard (CFL levels; Fig. 4a) to assess the priority classes. The classes were ranked from the highest transmission and hazard values to the lowest. Protected areas (Appendix B) were overlaid on the map to delineate areas with potential treatment constraints.	Fig. 7
Restore the cultural fire regime	Human ignition prevention	Annual anthropic fire ignition density (ANT quartiles; Fig. 3a) and transmission to residential houses (T_RES quartiles; Fig. 6a) were used to assess the priority classes. The classes were ranked from the highest ignition density and transmission to the lowest.	Fig. 8
	Natural fire re-introduction	Lightning ignition density (NAT quartiles; Fig. 5b) and transmission to residential houses (T_RES quartiles; Fig. 6a) were used to assess the classes. The classes were ranked from the highest lightning fire ignition densities to the lowest and from the lowest transmission values to the highest.	Fig. 9
Support a safe and efficient response	Fire suppression	Fire transmission rates to residential houses (TR_RES; Fig. 6c) and wildfire hazard (CFL levels; Fig. 4a) was used to set the classes. The classes were ranked from the highest transmission rates to the lowest and from the lowest hazard levels to the highest.	Fig. 10
Generate fire-adapted communities	Community action	High overall exposure levels (annual HIBP quartiles;Fig. 4b) and number of residential houses on the wildland-urban interface (Alcasena et al., 2018a) were used to set the classes. The classes were ranked from the highest exposure values and the highest number of structures to the lowest.	Fig. 11

Table 4

Metric pair cross-tabulation on the generation of management priority classes. First, we used quartile values to set 4 classes on the metrics, except for wildfire hazard where we considered interpretation charts (Andrews et al., 2011). The metric pairs were then cross-tabulated to generate 4 priority classes. These priorities were ranked from I (highest) to IV (lowest) and depicted on result maps using the color ramp of this table.



Priority class	Very low	Low	Moderate	High
Very low	🟩 IV	🟩	🟩	🟨 III
Low	🟩	🟩	🟨 III	🟧 II
Moderate	🟩	🟨 III	🟧 II	🟥
High	🟨 III	🟧 II	🟥	🟥 I

required a separate consideration from those of accidental or arson origin (Fig. 3c and d). From all ANT ignitions, 29% were attributed to the cultural use, which locally represented the most important cause in some northern portions of the landscape. Fire was systematically used in the past for pasture and shrub clearing in the conservation of extensive grazing mountainous areas of the northwestern Pyrenees, and this was reflected in the results (> 0.2614 ignitions yr^{-1} per 10^3 ha). Likewise, using fire in agricultural post-harvesting waste elimination or edge clearing represented a widely extended practice, and our results highlighted this fact in many areas dominated by dryland herbaceous crops. Very similar site-specific spatial patterns for the main ignition causes were also observed in previous studies conducted in Catalonia (Gonzalez-Olabarria et al., 2015).

3.2. Wildfire hazard and exposure

Fire intensity in terms of conditional flame length (CFL, Fig. 4a) showed widely variable results across Catalonia, which were mainly related to the dominant vegetation types and fire season extreme weather conditions. Highest CFL values (> 2.4 m) concentrated in transition areas between open plains and Mediterranean shrubby or forest type vegetation edges (i.e., northeastern L'Empordà coastal plain and western plain of Lleida), except for some valleys in central Catalonia and some conifer forests on pre-littoral mountain portions where fast spreading heading fires were frequently impacting unmanaged forested lands. Conversely, high elevation mountainous areas ($> 1,500$ m) showed the lowest values due to milder weather conditions during fire season and multiple fuel discontinuities with low load patches on mosaics with rocky outcrops. Here, CFL values in temperate broadleaved forests and high-elevation conifer forests were overall very low (< 1.2 m). Agricultural irrigation lands and densely developed areas represented unburnable barriers to fire spread and showed the sharpest transitions in CFL.

Areas with high overall exposure values, as represented by the annual high-intensity burn probability (aHIBP; Fig. 4b) concentrated in the valleys of central Catalonia (i.e., Anoia, Barberà basin, Bages and southern Berguedà), where a mosaic of dense and laddered conifer forests with dryland agricultural patches dominated the landscape. In fact, one of the most devastating historical fire episodes in 1994 burned some 46,000 ha there within a week (GENCAT, 2014). Northeastern areas of Alt Empordà also had high values (> 0.06 aHIBP), where the frequency of historical high-intensity (> 2.4 m of flame length) fire is among the highest of Catalonia. For instance, “La Jonquera” large fire event on 2012 burned about 13,000 ha at flame lengths above 3 m with spread rates > 5 km h^{-1}. In all these areas wildfire risk is high since substantial losses can be expected to most valued resources at these intensities (Alcasena et al., 2017). Overall, highest HIBP values concentrated in open land to forested fuel transition areas because substantial numbers of fires ignited close to urban development areas and spread towards forested lands. Predictably, all the mountainous areas of the Pyrenees showed the lowest values (< 0.02 aHIBP), where forest fuels are only partially cured during wildfire season and fire spreading is limited to short distance upslope (< 5 km) heading runs.

3.3. Fire exchange between municipalities and transmission to communities

Fire exchange between municipalities in terms of the burned area revealed a high spatial variability (Fig. 5) that was related to historical ignition patterns, complex fire weather conditions, and dominant vegetation types. In total, all outgoing fires (T_OUT; Fig. 5a) represented the same amount as (T_IN; Fig. 5b) incoming fires, and varied from the low of 0 to the high of 46.21 ha yr^{-1} per 10^3 ha municipality area. Self-burning (SB; Fig. 5c) ranged between 0 to the high of 13.19 ha yr^{-1} per 10^3 ha municipality area (SB; Fig. 5a). On average, the 37% of the burned area in the municipalities (i.e., > 4000 ha yr^{-1}) corresponded to fires ignited in the vicinities (i.e., SB × 1.5 = T_IN, being T_IN = T_OUT). This is not a surprising result since the average municipality area (3400 ha) is 2.5 times smaller than the largest historic fire size in the macro areas with the highest activity. While some municipalities were net recipients of fire (T_OUT < T_IN), others resulted in net contributors (T_OUT > T_IN) (Fig. 5d). The net exchange map allowed for the interpretation of dominant fire flow directions across Catalonia, as evidenced in transitions among neighboring blocks from high fire contributors to high recipients (Fig. 5d). Locally, prevailing wind direction scenarios drove these gradients and resulted in clear

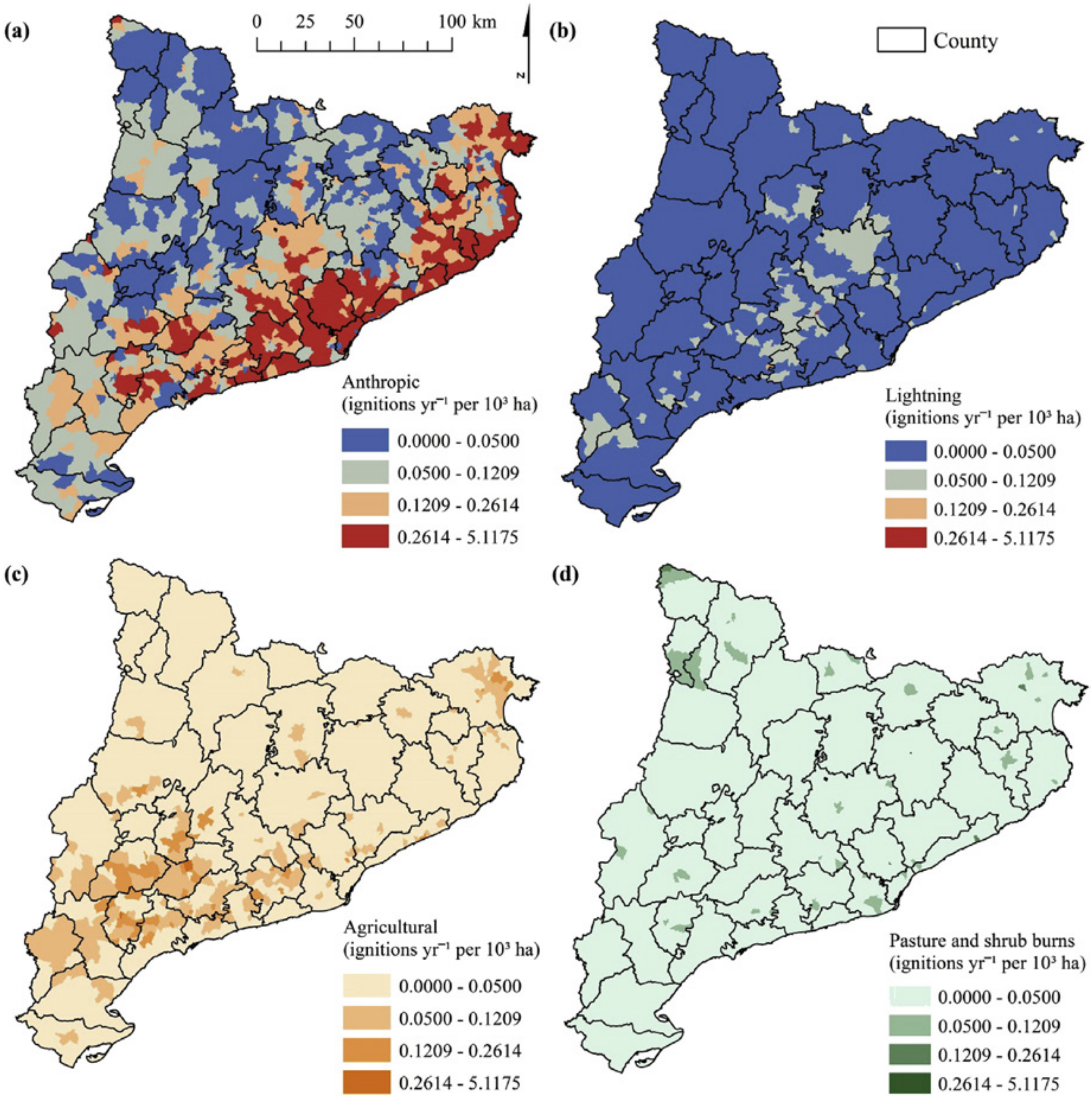


Fig. 3. Municipality level anthropic (a) and lightning (a) fire ignition densities in Catalonia for the period 1983–2014. The boundaries delineate the County level administrative division. We considered the anthropic ignition density quartile value intervals to set the classes. The cultural fire use is mainly associated to agricultural waste and edge cleaning (c), and pasture or shrub clearing (d).

trends where herbaceous fuel types covered relevant portions of the landscape. The lowest fire exchange occurred in northern mountainous areas and irrigation lands of the southwest, where SB, T_OUT, and T_IN hardy surpassed 1 ha yr^{-1} per 10^3 ha municipality area.

While high burned-area transmission was observed in Central and northeast Catalonia, transmission to structures (Fig. 6a and b) was substantially higher in coastal areas due to the very high concentration of residential houses in the wildland-urban interface (Alcasena et al., 2018a). Intensive-breeding farms were considered as industrial structures in the analysis and explained why the highest values located in certain central municipalities (Fig. 6b), while the bulk of industrial assets concentrate in highly-developed unburnable metropolitan areas of Barcelona and Tarragona. On average, transmission to housing and industrial sites at the municipality level resulted respectively in 0.45 and 0.07 structures yr^{-1} in Catalonia. Housing transmission rates (exposed structures ha^{-1}) revealed different patterns on the blocks where fires $<$ 1.000 ha affected a high number of structures (Fig. 6c and d). This was the case for some Pyrenean municipalities where large fires ($>$ 100 ha) were rare events and fire transmission were low ($<$ 0.20 structures yr^{-1}; Fig. 6a), but transmission rates were high ($>$ 0.15 structures ha^{-1}; Fig. 6c) because major fire runs affected valley bottoms and lower slopes where most structures concentrate.

3.4. Spatial prioritization

Municipality blocks with a high priority for fuels management concentrated in northeastern and several areas of central Catalonia, and represented 13% of the land in the study area (Fig. 7). Here, environmental protection land designations occupy 5.6% (23,339 ha; Appendix B) and this might represent a constraint for fuels management in some portions of the region. More specifically, treatments were not allowed on 2,822 ha (e.g., The National Park of Aigüestortes y Estany de Sant Maurici), interventions are restricted to habitat restoration on 423 ha, and fuel treatments are conditioned to traditional uses on another 2,360 ha. The highest concentrations of protected lands (i.e., Integral Natural Reserves) were located in northwestern Catalonia where fuels management priority was very low. On the other hand, active management land designations on high priority areas covered 17,735 ha

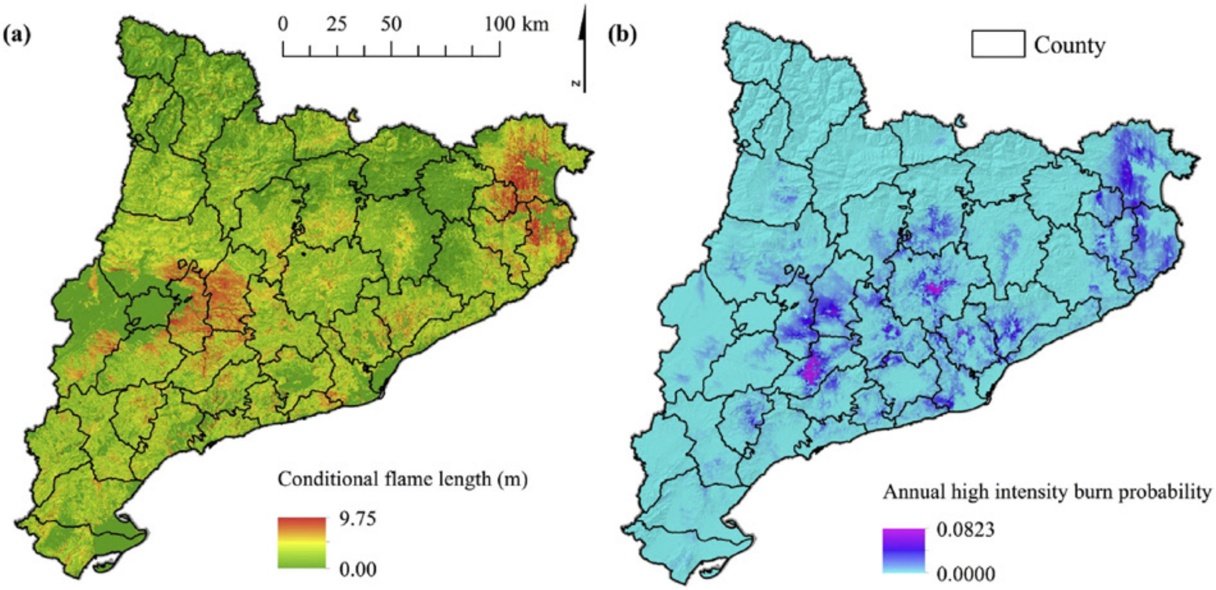


Fig. 4. Conditional flame length (CFL; a) and annual high intensity burn probability (HIBP; b) maps of Catalonia. We used them respectively as hazard and exposure metrics. The maps were generated at 150 m resolution from fire simulation modeling.

where the strong spatial collocation between timber production and risk mitigation objectives would facilitate the implementation of fuel treatment projects (Ager et al., 2017). In the municipalities with high fuels management spatial priority (n = 192 municipalities), the average wildfire hazard varied between 2.4 and 4.9 m CFL, and outgoing fire transmission varied between 3.9 and 42.66 ha yr^{-1} per 10^3 ha municipality area (Appendix F). Overall, the average CFL was higher in the municipalities with the lowest transmission values ($<$ 15 ha yr^{-1} per 10^3 ha municipality area).

We identified the suitable areas for the cultural fire regime restoration in separate maps for anthropic fire ignition prevention (Fig. 8) and lightning fire reintroduction (Fig. 9). Coastal and metropolitan areas showed the highest priority for anthropic fire ignition prevention due to high ignition densities and transmission values to residential houses. Indeed, the bulk of municipalities in these areas had densities of 0.26–1.00 ignitions yr^{-1} per 10^3 ha and transmission values of 0.2–2.5 structures yr^{-1} (Appendix F). Conversely, high priority municipalities for natural fire re-introduction were located in the Pyrenees and remote mountainous areas of central Catalonia (Fig. 9). Instead of using high transmission values to residential houses, we used the lowest values to identify areas with high lightning ignition densities ($>$ 0.016 ignitions yr^{-1} per 10^3 ha) but a low potential of exposing human communities ($<$ 0.06 exposed structures yr^{-1}). Lightning ignitions densities rarely exceeded values of 0.1 ignitions yr^{-1} per 10^3 ha (Appendix F). Somehow, ignition prevention and fire reintroduction strategies showed antagonistic spatial gradients and presented a complementary basis to discern when the contribution of unplanned fire might be damaging or beneficial.

Most appropriate areas to promote safe and efficient fire response were located in some coastal municipalities and open mountainous valleys where fires affecting residential houses were surrounded by predominantly herbaceous vegetation (Fig. 10). In those areas, the numbers of exposed housing structures were high and average fire intensity was below firefighting capabilities. Many of the municipalities that showed high transmission rates were excluded as a high priority due to very high CFL values ($>$ 3.4 m). Despite the wide variation on the average CFL, which ranged from the low of 0.75 m to the high of 2.4 m (maximum value for an effective fire suppression), most transmission rate values concentrated between 0.2 and 0.4 residential houses (Appendix F). In total, 218 municipalities covering 641,605 ha were classified as highly suitable for a full suppression strategy.

Community action can especially contribute to mitigating losses on human communities of the metropolitan area of Barcelona and densely populated municipalities of the northwest (Fig. 11). In fact, among the top 25 municipalities presenting the highest number of residential houses in the WUI, 64% were located in Barcelona and 36% in Gerona (Table 5). Although some human communities also presented high exposure values in central Catalonia, the number of residential structures there in the wildland-urban interface was much lower ($<$ 100 structures) (Alcasena et al., 2018a) and therefore those areas were excluded from the high priority class. The bulk of human communities had less than 1500 residential houses and annual HIBP $<$ 0.015 (Appendix F), and overall the exposure was lower as the number of residential houses in the wildland-urban interface increased. Community action represented the strategy with the highest number of municipalities in the high priority class (n = 219), which covered the 22% of the land in Catalonia.

4. Discussion and conclusions

This study advances ideas and a reference framework for a cohesive strategy founded on core themes of fire-resilient landscapes, cultural fire regime restoration, safe and efficient fire response, and fire-adapted human communities. These concepts parallel efforts in the US (USDA Forest Service, 2014), and can help facilitate a broader fire management strategy in fire-prone southern European regions (Appendix A). The cultural landscapes in the Mediterranean basin represent one of the most intensively-managed areas worldwide, where humans have been driving fire regimes for millennia (Seijo and Gray, 2012). However, losses from uncharacteristic high-severity fires and increasing suppression costs during the last decades emphasized the need for a new and wider comprehensive strategy beyond the fire exclusion policy (i.e. ignition prevention and firefighting) (Bovio et al., 2017; Curt and Frejaville, 2017). Our strategy used simulation modeling outputs to decompose the wildfire risk in a sequence of the major causative factors: (a) fire ignition source municipalities (Fig. 3), (b) large fire exchange among municipalities (Fig. 5), (c) forestland wildfire hazard in dominant fire trajectories (Fig. 4a), and (d) a pixel-based overall exposure on densely developed communities (Fig. 4b). Form these outputs we generated a consistent set of spatial priority maps for Catalonia (northeastern Spain) (Figs. 7–11) concerning specific strategies (Fig. 1). These strategies provide broad range of solutions for addressing the

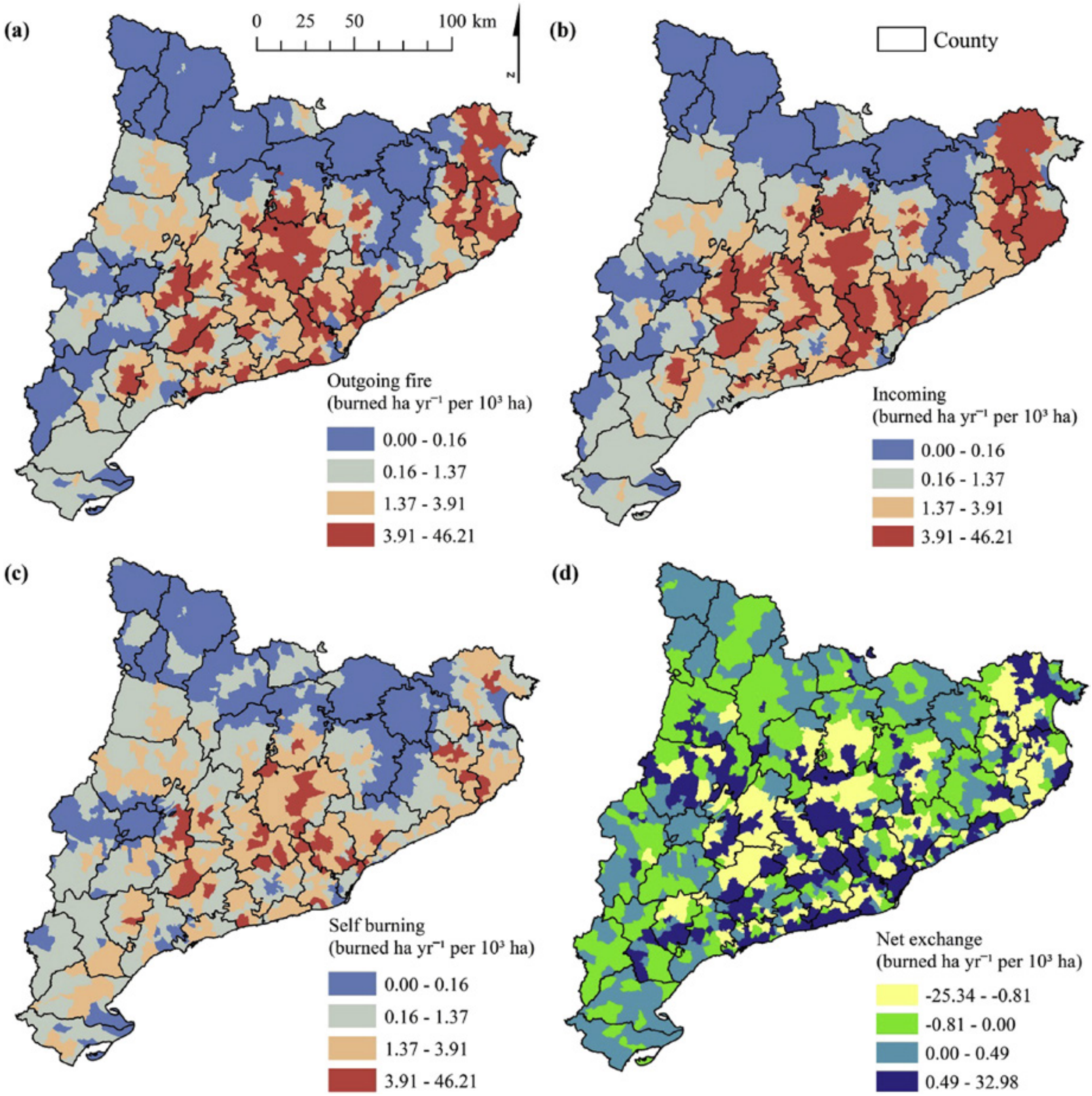


Fig. 5. Fire exchange across Catalonia at the municipality level (n = 948) in terms of incoming (T_IN; a), outgoing (T_OUT; b), self-burning (SB; b) and net exchange (Net exchange = T_OUT – T_IN; d) in terms of burned ha yr^{-1} per a normalized municipality area of 10^3 ha. On average wildfires in Catalonia burn about 11.5 thousand ha yr^{-1} (n = 650 fires yr^{-1}; 1983 to 2014), from which the 37% of the burned area came from fires initiated on the neighboring municipalities (ΣT_IN = ΣT_OUT = ~1.5 × ΣSB).

uncharacteristic fire problem that leverage the institutional capabilities to prevent ignitions, disrupt major fire movements or promote fire-adaptation strategies both in forest ecosystems and in human communities. The results also highlight the need for collaborative planning among neighboring communities at scales beyond jurisdictional boundaries since municipalities were highly interconnected by cross-boundary fire networks and local management actions can affect neighbors (Ager et al., 2016; Alcasena et al., 2017; Scott et al., 2016). Wildfire and landscape managers of Catalonia can benefit from these results to prioritize budgetary allocations in prevention and mitigation programs, in addition to urban planning and policy making.

There are only a few studies that have applied simulation modeling to examine wildfire risk and exposure at large scales in the fire-prone southern European regions (Oliveira et al., 2016; Palaiologou et al., 2018; Salis et al., 2013). Most previous fire modeling assessed wildfire exposure, and risk on smaller study areas and attempted to provide management prescriptions to local fire managers (Alcasena et al., 2016b; Elia et al., 2016; González-Olabarria et al., 2012; Molina et al., 2017). We added substantially more detail in our simulations compared to previous studies in order to capture the fire weather, ignition pattern, and fuel moisture changing gradients across the study area. The result was a 150-m resolution set of maps of key risk causative factors that previously have not been available for the fire prevention and mitigation purposes in Catalonia. Specifically, we generated consistent hazard, exposure and transmission quantitative results which facilitated comparisons and spatial prioritization between very distant areas (> 100 km) within the study area (Figs. 4 and 5). Previous studies in Catalonia characterized the dominant spread patterns from historic fire perimeters and principal synoptic fire weather conditions, to then prioritize fuel treatment allocation on strategic management points (ridges, ravines, changes in slope and buffering road infrastructure) according to expert criteria (Costa et al., 2011; Duane et al., 2015, 2016).

Extreme fires impacting populated communities represent a major concern in Mediterranean areas and many previous efforts accurately mapped the WUI types considering urban development structure

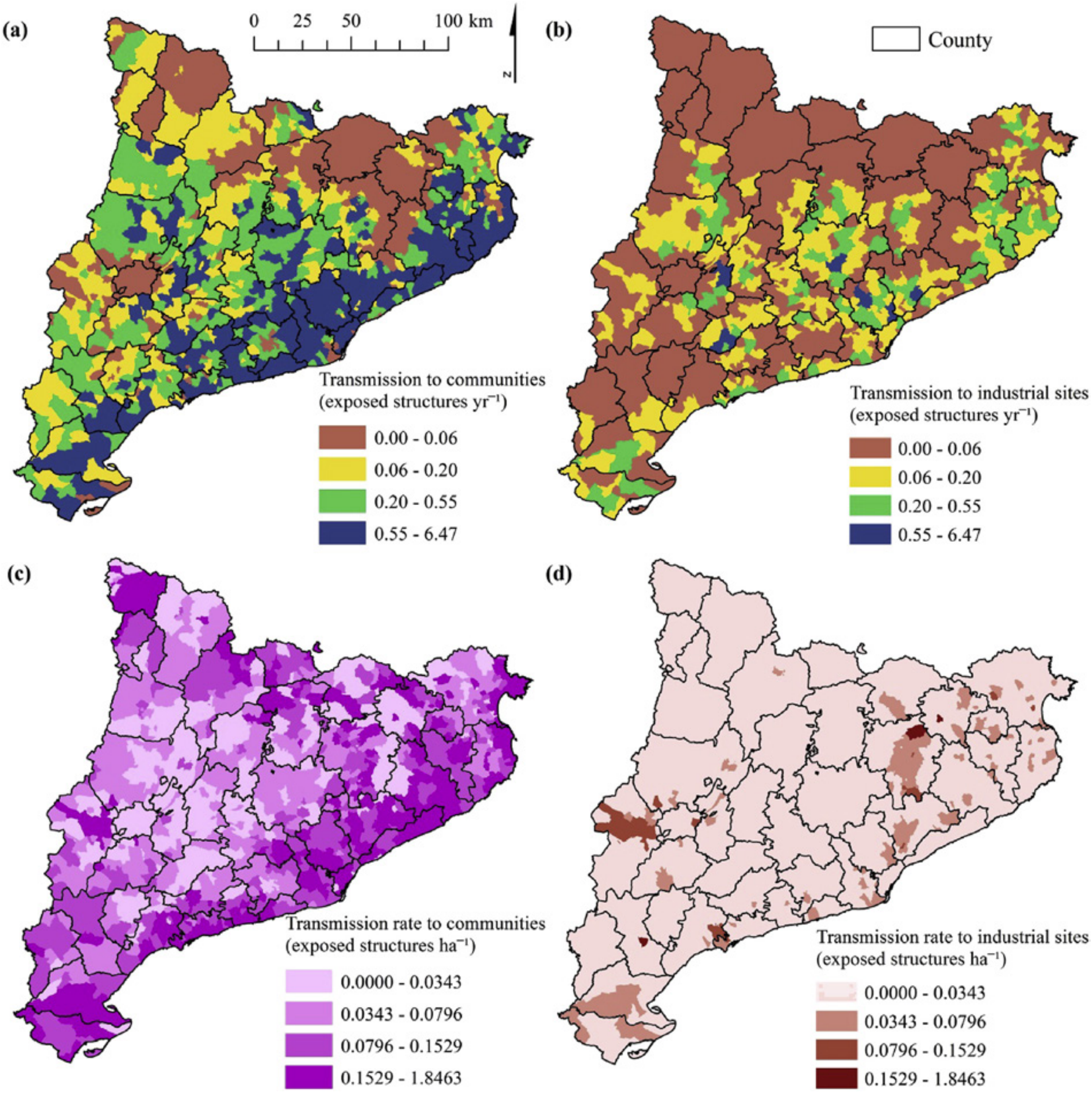


Fig. 6. Annual fire transmission and transmission rate per burned area (ha) for structures in communities (a and c) and industrial sites (b and d) at the municipality level. The analysis was conducted intersecting modeling output large fire perimeters (> 100 ha) with structure centroid locations (Appendix E).

aggregation degree, fuel types, and fire occurrence in the vicinities (Badia et al., 2011; Herrero-Corral et al., 2012; Lampin-Maillet et al., 2010; Madrigal et al., 2013; Pellizzaro et al., 2012; Sirca et al., 2017). Nonetheless, these studies did not assess wildfire exposure to large and catastrophic events, and only a few considered the potential fire effects (Alcasena et al., 2017; Mitsopoulos et al., 2015). On the other hand, previous studies in the US widely used fire modeling to estimate wildfire likelihood on populated areas, and assumed structure loss given a fire reaches a residential house (Bar Massada et al., 2009; Haas et al., 2013), or alternatively integrated structure susceptibility relations to assess the effects (Thompson et al., 2011, 2013). In our study, we first identified the number of individual structures in the wildland-urban interface (Alcasena et al., 2018a) to then use the annual high intensity (> 2.4 m flame length) burn probability as the structure potential for loss metric. We considered that fire suppression efforts can efficiently protect residential houses exposed to low intensities (i.e., in Catalonia major fire spread duration is limited to few days and structure loss is usually associated at high intensities on the home ignition zone).

Forest fuel management priority maps (Fig. 7) identified the municipalities where treatments (i.e., prescribed fire, thinning and mastication) on strategic locations above certain intensities (> 15–20% of the area) can effectively slow large fire spread and mitigate risk (Finney, 2007; Salis et al., 2016, 2018). In the context of current budgetary constraints treating the entire study area at effective intensities is impossible, and thus we proposed treating hazardous fuels (CFL > 2.4 m) on the specific high transmission planning areas that contributed the most to the burned area in neighboring municipalities. Wildfire management strategies based on fire suppression in these areas would have a low probability of success during extreme events (Andrews et al., 2011). Municipalities with lowest intensity values (CFL < 1.2 m) were classified as a very low priority for treatment implementation regardless of a high fire transmission, since managing flashy herbaceous fuels would require other options such as livestock grazing (Casasús et al., 2007; Riedel et al., 2013).

In order to restore the cultural fire regime, we identified the priority areas for anthropic ignition prevention program implementation and

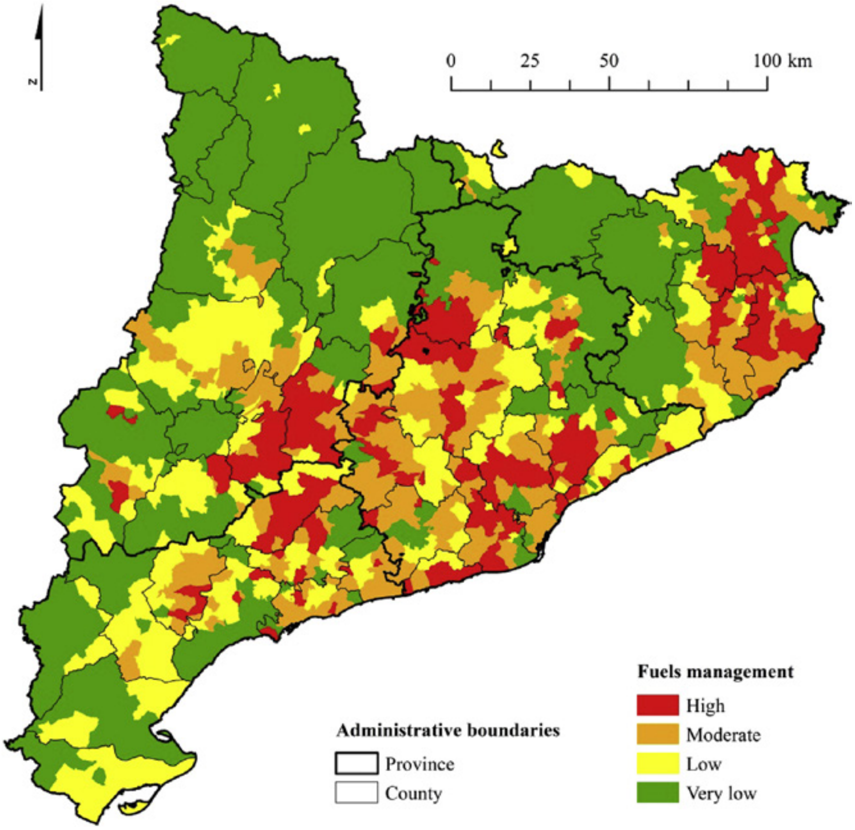


Fig. 7. Spatial prioritization map for fuel reduction programs in Catalonia. We cross-tabulated wildfire hazard on forest fuels (CFL levels; Fig. 4a) and burned area transmission (T_OUT quartiles; Fig. 5a) to prioritize fuel treatment program implementation. The highest priorities located on central and northeastern portions of the study area. In some planning areas, the protected lands might present a constraint in fuels management program implementation (Appendix B).

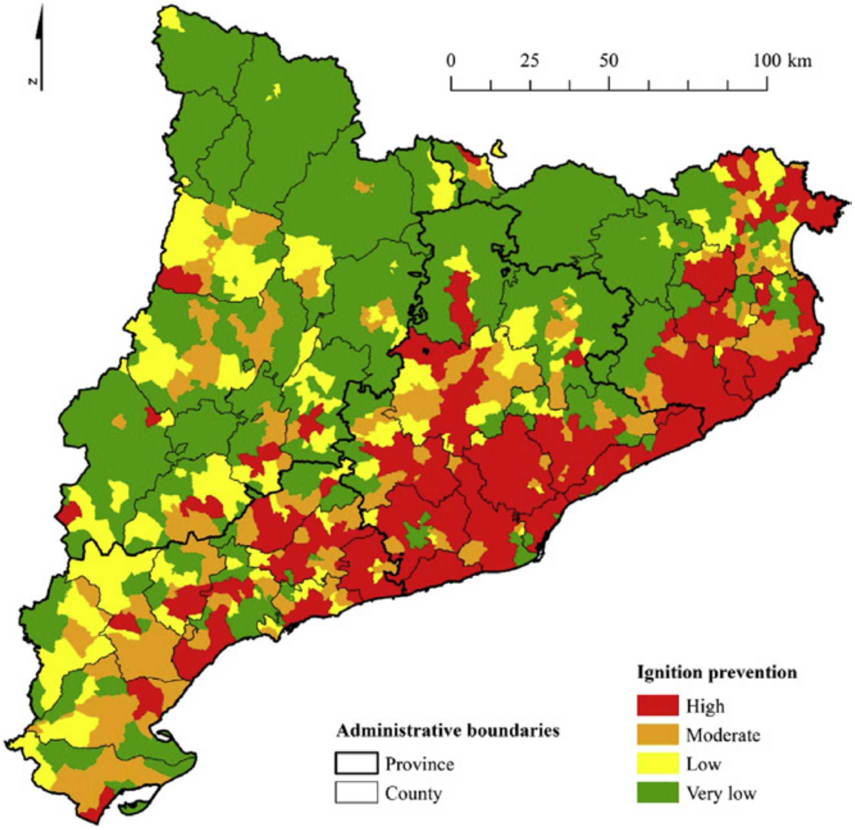


Fig. 8. Spatial prioritization map for human ignition prevention in Catalonia. We cross tabulated anthropic fire ignition densities (ANT quartiles; Fig. 3a) and transmission to residential houses (TF_RES quartiles; Fig. 6a) to prioritize ignition prevention program implementation. Coastal and metropolitan areas of Barcelona showed the highest priority.

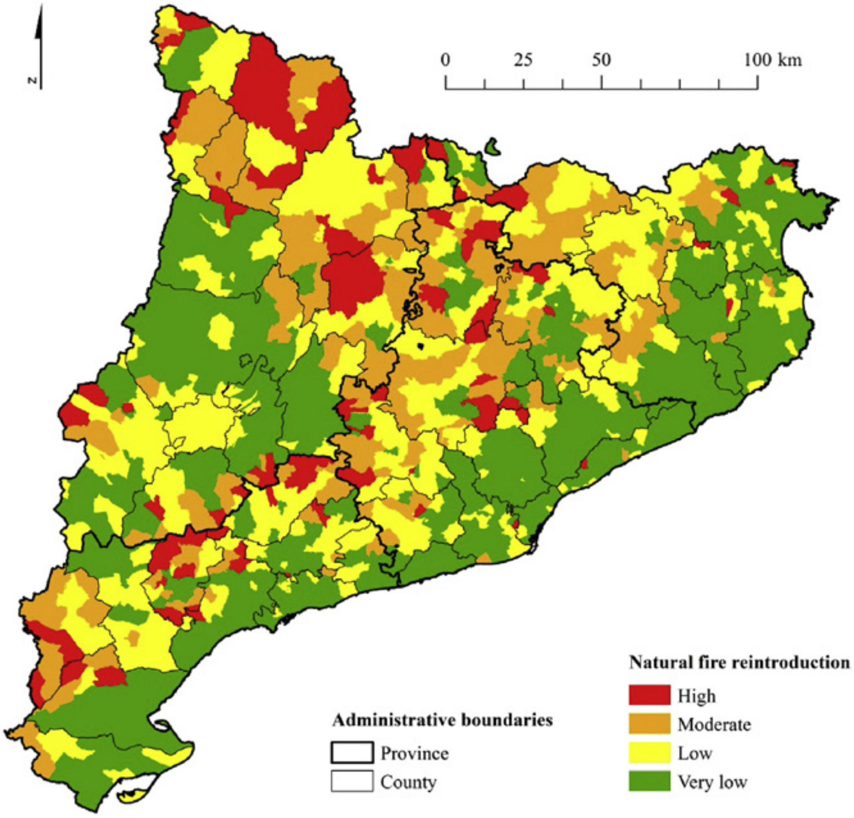


Fig. 9. Spatial prioritization map for natural fire reintroduction in forest ecosystems. We cross tabulated lightning fire ignition densities (NAT quartiles; Fig. 3b) and transmission to residential houses (TF_RES quartiles; Fig. 6a) to identify the most suitable areas for unplanned fire reintroduction. The municipalities with a highest potential located on remote mountainous areas were lightning fire reintroduction would not pose a risk to communities.

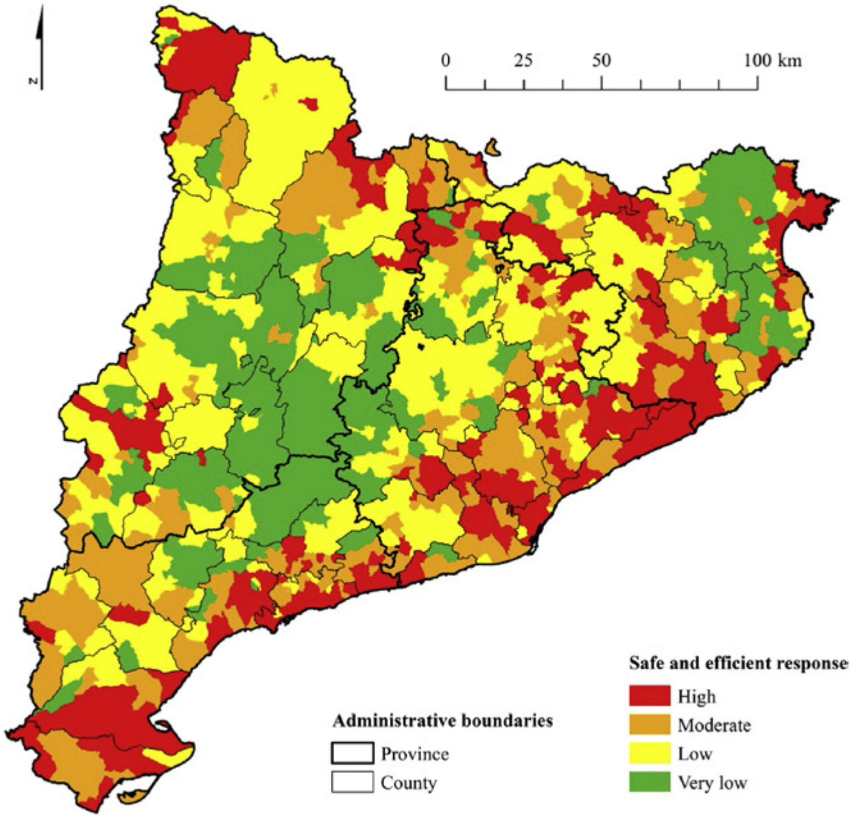


Fig. 10. Spatial prioritization map for a safe and efficient response in Catalonia. We cross-tabulated wildfire hazard on forest fuels (CFL levels; Fig. 4a) and transmission rate to communities (TR_RES; Fig. 6c) to identify the most suitable areas for an aggressive full suppression policy. Wildland-urban interface areas surrounded by managed fuels, predominantly agricultural plains and narrow valleys of the Pyrenees presented the highest priority.

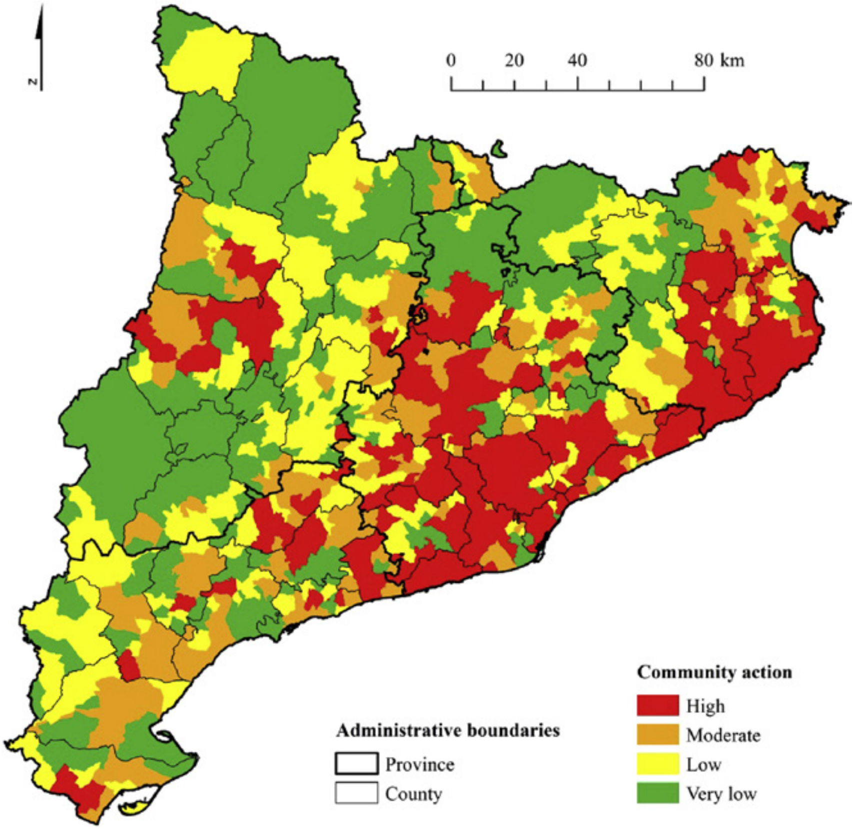


Fig. 11. Spatial prioritization map for community action program implementation in Catalonia. We cross-tabulated wildfire exposure values on the home ignition zone (annual HIBP quartiles; Fig. 4b) and the number dwellings on the WUI (quartiles; Alcasena et al., 2018) to identify the municipalities requiring a community action plan. The top priorities located on populated littoral and pre-littoral areas of Barcelona and Girona (Table 5).

Table 5

Community action (Fig. 11) priority municipalities (n = 25) in Catalonia, ranked by the highest number of structures on the wildland-urban interface (Alcasena et al., 2018a). The number of structures and the average overall exposure is detailed by wildland-urban interface classes. Largest human communities with the highest overall exposure values (annual HIBP > 0.0045) located on friction areas between the urban development and forestedlands of Barcelona and Gerona.

Municipality	Province	WUI class						Total	
		Disperse rural		Intermix		Interface			
		structures	avg. aHIBP	structures	avg. aHIBP	structures	avg. aHIBP	structures	avg. aHIBP
Rubí	Barcelona	1	0.0004	410	0.0053	3089	0.0044	3500	0.0046
Lliçà d'Amunt	Barcelona	1	0.0009	272	0.0040	2612	0.0055	2885	0.0051
Terrasa	Barcelona	7	0.0047	409	0.0090	2056	0.0113	2472	0.0106
Calonge	Girona	8	0.0047	469	0.0047	1944	0.0089	2421	0.0074
Mançanet de la Selva	Gerona	14	0.0008	415	0.0034	1992	0.0061	2421	0.0051
Begur	Gerona	4	0.0054	269	0.0050	1935	0.0050	2208	0.0050
Girona	Gerona	12	0.0081	322	0.0084	1833	0.0073	2167	0.0076
Cervelló	Barcelona	5	0.0031	170	0.0036	1957	0.0057	2132	0.0052
Palafrugell	Gerona	7	0.0068	261	0.0068	1855	0.0093	2123	0.0087
Santa Cristina d'Aro	Gerona	23	0.0050	359	0.0087	1682	0.0085	2064	0.0084
Caldes de Montbui	Barcelona	12	0.0022	316	0.0047	1507	0.0108	1835	0.0088
Santa Eulàlia de Ronçana	Barcelona	1	0.0047	158	0.0047	1653	0.0067	1812	0.0063
Castell-Platja d'Aro	Gerona	5	0.0084	385	0.0067	1316	0.0077	1706	0.0073
l'Amatlla del Vallès	Barcelona	1	0.0134	210	0.0055	1396	0.0065	1607	0.0062
Pals	Gerona	6	0.0079	187	0.0080	1335	0.0099	1528	0.0095
Castellbisbal	Barcelona	9	0.0029	172	0.0057	1335	0.0057	1516	0.0056
Esparreguera	Barcelona	5	0.0108	132	0.0081	1357	0.0071	1494	0.0075
Llagostera	Gerona	18	0.0028	194	0.0041	1280	0.0079	1492	0.0070
Palau-solità i Plegamans	Barcelona	0	0.0000	69	0.0051	1294	0.0073	1363	0.0071
Vilanova del Vallès	Barcelona	2	0.0065	208	0.0055	1067	0.0082	1277	0.0074
Sentmenat	Barcelona	8	0.0034	209	0.0036	984	0.0097	1201	0.0080
Olesa de Montserrat	Barcelona	6	0.0065	141	0.0065	1021	0.0072	1168	0.0070
Montcada i Reixac	Barcelona	2	0.0049	283	0.0071	878	0.0092	1163	0.0085
Sant Vicenç dels Horts	Barcelona	0	0.0000	194	0.0051	957	0.0045	1151	0.0047
la Roca del Vallès	Barcelona	7	0.0104	159	0.0037	962	0.0098	1128	0.0083

the suitable municipalities for fire re-introduction in forest systems (Figs. 8 and 9). Previous studies also showed that most ignitions in Catalonia were caused by humans, and suggested the implementation of ignition-cause-specific prevention measures on high ignition density areas to mitigate wildfire risk (Gonzalez-Olabarria et al., 2012, 2015). For instance, temporary bans to recreational uses on protected areas and public forests (Appendix B) during wildfire season could help reduce the number of unintended human ignitions. Since not all ignitions can potentially pose a threat to communities, we also considered fire transmission to residential houses (Fig. 6c). This way, we directed the implementation of prevention measures on areas with a high anthropic fire ignition density and a high transmission to communities. On the other hand, municipalities with high lightning ignition densities and low transmission to residential houses were a priori identified for reintroducing managed fire in the forest ecosystems, in parallel with pasture burning. Some sub-Mediterranean forest ecosystems are well adapted to low-intensity frequent fires and lightning fires could positively contribute to maintaining a fire-resilient forest structure with a minimal human intervention. For instance, endemic black pine old growth forests in central areas and pre-Pyrenees of Catalonia represent a good example of well adapted species to frequent surface fires (Fulé et al., 2008; Tíscar and Lucas-Borja, 2016). However, fire exclusion policies, poor forest-management practices (i.e., diametric cuts by just thinning the largest and the suitable trees for electric poles), and depletion of livestock transformed those forests into laddered fuel dense structures where high severity stand-replacing fires caused very substantial losses on past events (Martín-Alcón and Coll, 2016; Ordóñez et al., 2005). Thus, previous mechanical treatments and prescribed fires might be required to favor the resistance of remaining dominant seed trees before re-introducing the lightning fires.

We also identified the priority areas where fires spreading under extreme weather conditions might present some opportunities to safely and efficiently protect property (Fig. 10). In this study we considered wildfire hazard and transmission rate to residential housing metrics to rank priorities and other important factors that may compromise suppression efforts (e.g., rate of spread and spotting) were excluded from this first approach. Since burned area fire transmission might not always represent an effective exposure metric to communities, we considered the transmission rate to structures to demonstrate that a high transmission in terms of the burned area does not necessarily connote high potential for loss. This is the case for central Catalonia where fire transmission to neighboring communities is high (> 3.91 ha yr^{-1}; Fig. 6a), but the number of structures on the WUI is much lower than in coastal areas (Alcasena et al., 2018a), and therefore transmission rates are overall much lower (< 0.08 structures ha^{-1}; Fig. 6c and d). Specifically, our results could be used to strengthen ground crew and terrestrial resource allocation on high priority areas during wildfire season. Similarly, the development of an efficient transportation system and the increasing water pond density on these areas would allow a rapid response and a more effective aircraft work by reducing the time between discharges (Rodríguez y Silva et al., 2014). Even if aggressive full suppression alone is not the most effective way to mitigate structure loss in most fire-prone areas, it can exceptionally represent the main strategy for the municipalities located on intensively managed agricultural plains.

Lastly, we identified priority municipalities in Catalonia for the promotion of community action programs aimed at preventing wildfire disasters in the WUI (Fig. 11). In addition to annual high-intensity burn probability, we also considered the number of residential structures on the WUI matrix as a criterion to prioritize interventions on municipalities presenting a large number of dwellings surrounded by forest lands. In fact, more than 25 municipalities in Catalonia had more than 1 thousand residential houses on the WUI (Table 4). Community action measures on priority municipalities should consider treating fuels on the home ignition zone, using fire-resistant design and ignitable materials on structures, and reducing social vulnerability (Calkin et al., 2014; Paveglio et al., 2015; Penman et al., 2015). Currently the existing legislation in Catalonia requires homeowner and communities to manage fuels on the WUI (i.e., fuels treatment and maintenance in parcels within communities and a 25 m buffer), and our results could be used to technically justify and support the implementation of auto-protection plans on priority areas. Beyond ownership, local authorities can use ordinances on urban planning to exclude hazardous forestlands and prioritize the development in the safest areas within municipalities.

There are many socioeconomic and legal constraints to implement many of the management activities discussed in this research. Land ownership and environmental protection can especially constrain the implementation of fuel treatments programs. In Catalonia very large portions in forestlands are private, and public forests mostly concentrate in the northwestern side, where treatment priority is overall low (Appendix B; Fig. 7). While landowner risk perception on private properties is crucial for risk mitigation, management on public lands is strongly conditioned by social demands for multiple competing objectives (Fischer et al., 2014; Olsen et al., 2017; Paveglio et al., 2016). These include intensive timber management to supply local mills, pastures for extensive livestock breeding, leisure areas for urban citizens, and environmental conservation. Specific legislation regulates the protection degree (with direct implications in manageability) and establishes management restrictions to protect sensitive species habitat and the natural sites of special interest from negative human impacts. On the other hand, the spatial co-location between ongoing habitat restoration works and required risk mitigation treatments can provide an opportunity for conducting fuel treatment programs on many protected areas (Ager et al., 2017).

While economic and operational constraints can limit the extent and reach to required minimum treatment intensities on fire-prone landscapes (North et al., 2015), potential timber revenues from thinning can help overcome budgetary constraints on temperate forest ecosystems (Ager et al., 2017). However, economic opportunities from timber production are limited or nonexistent in Mediterranean landscapes, and thus subsidies continue to be necessary to implement large-scale fuel treatment programs. Accordingly, the annual budget to subsidize forest work attempts to compensate costs in fuel treatments. In particular, fuel treatment with a total cost up to a maximum base of 2000 € ha^{-1} is subsidized on public and private lands with the 75–100%, depending on the protected area designation (Appendix B) while requiring a forest management plan approved by the Forest Administration. Dense Aleppo pine regenerate cohorts ($> 10{,}000$ trees ha^{-1}) in central Catalonia from 1994 to 1998 large fire events ($> 20{,}000$ ha) represent a clear example of high priority areas where noncommercial treatments are required to convert hazardous forests into fire resilient landscapes (Verkaik and Espelta, 2006). In the longer term, the promotion of a circular economy where rural communities provide high-quality bio-based products to closer customers on densely populated urban areas may represent a promising solution to obtain required revenues for preserving fire resilient cultural landscapes (Lindner and Suominen, 2017; Verkerk et al., 2018).

Future efforts should be directed to downscaling within high priority planning areas or municipalities. On the one hand, fuel management programs would require an optimization analysis to design a cost-effective stand-level treatment mosaic while considering all the previous economic and environmental constraints (Alcasena et al., 2018b). Similarly, highly exposed communities should develop their own protection and management plans from higher-resolution and structure-level exposure and risk estimates (Alcasena et al., 2017). Concerning a fire response aimed at reintroducing lightning fires into natural acosystems, our approach represented a preliminary step and a more detailed study is required to accurately delineate the extent of the areas on remote municipalities areas where lightning fires pose a minimal risk to property and could positively contribute to fire-adapted ecosystem conservation (Barnett et al., 2016; Riley et al., 2018). Assessing fire containment probability at high-resolution on suitable municipalities for a full suppression policy would help identify the strategic locations where opportunistic firefighting efforts would likely result effective in controlling fires (O'Connor et al., 2017). Additionally, exploring the landscape management complexity using algebraic and topological methods, the analysis of fire transmission networks, and the implementation of human community clustering techniques would result useful in future research to complement our geospatial priority maps and help develop the most convenient fire policy at the municipality level (Evers et al., In press; Palaiologou et al., 2018; Papadimitriou, 2012, 2013).

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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.2018.10.027.

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