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Application of simulation modeling for wildfire exposure and transmission assessment in Sardinia, Italy

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ABSTRACT

The development of comprehensive fire management and risk assessment strategies is of prominent concern in Southern Europe, due to the expanding scale of wildfire risk. In this work, we applied simulation modeling to analyze fine-scale (100-m resolution) wildfire exposure and risk transmission in the 24,000 km^2 island of Sardinia (Italy). Sardinia contains a variety of ecological, cultural, anthropic and touristic resources that each summer are threatened by wildfires, and represents well the Mediterranean Basin environments and conditions. Wildfire simulations based on the minimum travel time algorithm were used to characterize wildfire exposure and risk transmission in terms of annual burn probability, flame length, structures exposed and type and amount of transmission. We focused on the historical conditions associated with large (>50 ha) and very large (>200 ha) wildfires that occurred in Sardinia in the period 1998–2016, and combined outputs from wildfire simulation modeling with land uses, building footprint locations, weather, and historical ignition data. The outputs were summarized for weather zones, main wind scenarios and land uses. Our study characterized spatial variations in wildfire spread, exposure and risk transmission among and within weather zones and the main winds associated with large events. This work provides a novel quantitative approach to inform wildfire risk management and planning in Mediterranean areas. The proposed methodology can serve as reference for wildfire risk assessment and can be replicated elsewhere. Findings can be used to better understand the spatial dynamics and patterns of wildfire risk and evaluate expected wildfire behavior or transmission potential in Sardinia and neighboring regions.

1. Introduction

Wildfires are one of the most relevant threats to European forest and rural areas, particularly in fire-prone southern Countries [1]. In the 2000–2018 period, about 0.92 million wildfires in the southern European Union (Portugal, Spain, France, Italy and Greece) affected approximately 7.4 million hectares, with large spatial and temporal fluctuations in the annual area burned [2]. Despite the decreasing trends of the number of fires and total area burned at the EU level [3–5], there is evidence that a limited number of wildfire events with extreme spread and behavior has become progressively large and devastating [6–8]. A number of previous studies analyzed extreme wildfire events, which typically present very high spread rates and intensity, long-range travelling firebrands with high ignitability, variable and unpredictable behaviors, and are responsible for dire impacts on the social and natural systems [9–11]. Potential threats by extreme wildfires to ecological, social and economic values in the Mediterranean basin are amplified by several converging and intercorrelated drivers, while the inherent complexity in wildfire management cannot guarantee the protection of values at risk. These drivers include forest fuel accumulation, land abandonment, WUI expansion into fire-prone areas, climate change, and fire exclusion policies [12–21].

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Developing adequate and effective strategies to reduce the ecological and social impacts of wildfires remains challenging, especially when considering long-term perspectives and the spatial diversity in wildfire regime and socio-environmental driving factors [22–25]. Within this context, several solutions have been recently proposed, and include strengthening programs to treat and limit wildland fuels [26–29], changing fire management and suppression policies [30–33], promoting the creation of fire-wise communities and landscapes [34–36], and increasing public awareness of wildfire risk and safety [37–39]. The application of quantitative risk-based tools and assessments to analyze potential wildfire impacts and to inform a comprehensive array of fire and fuel management and planning in fire prone regions around the world can substantially support land managers and policy makers [40–43]. Promising results have been obtained by new wildfire spread simulation systems that can help estimate wildfire propagation likelihood and intensity for large landscapes (e.g., million hectares) by considering historical weather, fuels, fire ignition patterns and regime, and socio-economic features associated to the most significant wildfire events of fire prone Mediterranean areas [23,44–50]. For example, the use of burn probability modeling to inform wildfire risk assessment progressively increased in the Euro-Mediterranean area and allowed spatial and temporal variations in wildfire exposure and risk to be captured, to identify hot-spot areas and the potential to manage fuels and landscapes, or to estimate wildfire spread and risk transmission potential [23,27,51-58,136]. Apart from Northern America and Mediterranean areas, wildfire propagation simulations to characterize and map wildfire risk was also successfully applied in a range of other regions and ecosystem types [59–63].

In this study, we advance the application of wildfire simulation modeling to analyze wildfire exposure and risk transmission in Sardinia (Italy), using an innovative methodological simulation framework that allows the modeling of wildfire exposure and transmission after calibrating historical fire size distributions and burn patterns on the diverse weather zones of the island, while accounting for spatial weather scenarios across the modeling domain. By focusing on the historical conditions associated with large (>50 ha) and very large (>200 ha) wildfire events over the period 1998–2016, we combined the outputs from wildfire spread and behavior simulation modeling with land uses, building footprint locations, weather, and historical ignition data to map wildfire exposure and risk transmission. This methodology will serve as reference for the application of a common wildfire risk assessment approach that will be replicated in neighboring Italian and French regions (Corsica, Tuscany, Liguria and PACA Region) to characterize wildfire exposure and risk transmission in the context of the ongoing cross-border "Med-Star" project (Programma IT-FR Marittimo 2014–2020).

2. Methods

2.1. Study area

Sardinia, Italy, is located in the western part of the Mediterranean Basin and encompasses about 24,000 km^2 (Fig. 1). Sardinia is the second largest island of the Mediterranean Basin and one of the most relevant fire-prone areas at the national level. Approximately 1.7 million people live in the area year-round, mostly nearby the main towns of Cagliari and Sassari, but this number grows from April to October due to the touristic fluxes towards the coastal areas. The island topography consists of rolling hills and low mountains, mainly located on the eastern side. The average elevation is about 350 m above sea level (a.s.l.), while the highest peak is 1850 m a.s.l. The largest plains, i.e., Campidano in the South, and Nurra in the North, are located in the western part of the island.

According to the 2008 Sardinia Land Use Map (www.sardegnageoportale.it), approximately half of the island is covered by forest fuels. Broadleaf forests (~23%) are mostly represented by *Quercus ilex* L., *Q. suber* L., *Q. pubescens* Willd. and *Q. congesta* Presl. (Fig. 1*a*). At higher elevations, *Q. pubescens* Willd. is the most representative oak formation, and *Castanea sativa* Mill., *Taxus bacata* L. and *Ilex aquifolium* L. are also present. Mediterranean shrubs and garrigue (~27%) comprised primarily of *Pistacia lentiscus* L., *Arbutus unedo* L., *Erica arborea* L., *Myrtus communis* L., *Olea europea* L. var. *sylvestris* Brot., Phyllirea spp., Juniperus spp., Cistus spp. and Euphorbia spp.. With the progressive abandonment of forest and rural areas, the shrubland vegetation type is gradually evolving towards high-fuel load shrublands and broadleaf forests. Conifer stands (~2%) are primarily concentrated in the coastal areas and mostly include plantations of *Pinus pinea* L. and *P. halepensis* Mill.. A significant portion of Sardinia, particularly in the western part, is covered by grasslands, mixed agricultural areas and herbaceous pastures (~40%) (Fig. 1*a*). Permanent crops include olive groves, vineyards and orchards, and cover about 3% of the territory. Urban and anthropic areas, which were mapped from high-resolution data (www.sardegnageoportale.it) and [65], cover approximately 4% of Sardinia.

The climate consists of mild and rainy winters, dry hot summers and drought conditions from late May until September [66]. From a bio-climatic standpoint, approximately 2/3 of the island is characterized by mesomediterranean conditions [64] (Fig. 1*b*). Thermomediterranean bio-climate covers limited areas and is mostly concentrated in southern Sardinia and across the coastal zones, while supramediterranean, mesotemperate and supratemperate conditions can be found at high-elevation hills and in the mountains [64]. In broad terms, climate conditions vary from north to south and from mountainous areas to coastal areas. Annual precipitation ranges from about 400 mm in the southern coastlines to about 1100 mm in the mountains [67]. Most annual rainfall occurs in fall and winter, with November and December being the rainiest months of the year. Mean annual temperatures range from 7 to 17 °C, while maximum temperatures are often higher than 30 °C during the summer. The most frequent wind directions are west and northwest.

2.2. Wildfire history

To determine historical patterns of wildfire ignitions and spread in Sardinia, we used data provided by the Sardinia Forest Service from 1998 to 2016. The wildfire database contains date and municipality of ignition, ignition coordinates, and fire size; since 2003, wildfire perimeters are also available. For the study period, Sardinia experienced ~ 2900 fire ignitions year^{-1} (~ 0.121 fire ignitions km^{-2} year^{-1}), which burned approximately 18,500 ha year^{-1} (0.77% of Sardinia per year). About 60% of Sardinian wildfire ignitions are concentrated in Campidano, the large plain located in southern Sardinia (Figs. 1*a* and 2*a*).

The years with annual burned area greater than 30,000 ha (i.e., 1998, 2007, 2009) were associated with prolonged drought conditions, intense heat waves and strong winds, and fine dead fuels accumulation [57]. On the contrary, three years (i.e., 2006, 2008 and 2015) had annual area burned lower than 9000 ha. Wildfires largely (>90%) occurred from June to September, with an evident peak of ignitions and area burned in July. Most wildfires have anthropogenic causes (>95%) and approximately 93% of all fires burned less than 10 ha, accounting for only 16% of the total area burned. Half of the area burned occurred in a relatively low number of days (153 over the study period, on average 8 days per fire season), characterized by very large wildfire occurrence (>200 ha). To capture differences in wildfire regime and weather patterns, we divided the study area into nine weather zones (WZ) (Fig. 1*b*) that were broadly based on a classification proposed by the Sardinia Environmental Protection Agency and adopted for weather and environmental risk alerts [68]. The delimitation of these WZs was based on municipality boundary polygons. Exploring historical wildfire activity for each individual WZ allowed to better discriminate wildfire regimes and burning patterns associated with the main atmospheric circulation and weather conditions observed during the days when large events occurred. A summary of the major wildfire activity indicators for the different WZ is provided in the Supplementary Data (SD-T1 and SD-T2).

2.3. Input data

To meet wildfire modeling requirements, we prepared a set of input data that include spatial layers to describe the landscape (LCP file), fire weather conditions, fuel moisture content and wildfire ignition probability grids. Regarding the LCP file, we assembled spatial data on topography, surface fuels, and forest canopy metrics, which were processed with Arcfuels [69] to derive a 100-m resolution gridded file as required by FlamMap [70]. Topography layers were obtained from 10-m digital elevation data of the island (www.sardegnageoportale.it). Surface fuels were derived from the 2008 Sardinia Land Use Map (www.sardegnageoportale.it) by first stratifying the original 70 land use classes into 12 fuel types, and then assigning to each fuel type a fuel model, either standard [71,72] or custom developed for Sardinia and Corsica [73,74] (Table 1). We used slightly different fuel models to describe forest fuels depending on the bio-climatic conditions of the different zones of the island (Table 1). Forest canopy cover classes were determined by intersecting the 2008 Sardinia Land Use Map with tree cover density data from the Copernicus Programme (reference year 2012; https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps). Canopy characteristics, i.e., stand height, canopy base height and canopy bulk density, were defined using the data reported by the National Inventory of Forests and Forest Carbon Sinks [75] and already tested in previous research (e.g., [50,76]) (Table 1).

Regarding weather conditions, we gathered hourly meteorological data from the weather stations of the Sardinia Environmental Protection Agency for the study period 1998–2016. As previously reported, the modeling domain was divided into nine WZs (Fig. 1*b*). For each WZ, we identified a representative weather station with consistent data series. A second weather station was added to account for colder and wetter conditions observed in five WZs (NW, NE, E, C, SE), in which more than 15% of the area is characterized by bio-climates ranging from upper mesomediterranean to supratemperate.

We focused on the days during which wildfires above 200 ha occurred (Very Large Wildfire Days, VLWD), and for wind conditions observed in those days from 2 to 3 p.m.. This timeframe commonly represents the hottest and windiest moment of the day, which is also a critical period for wildfire ignitions with high propensity to spread. We then derived eight main dominant wind direction scenarios based on the historical wind data observed in the selected weather stations. The dominant wind directions mostly related to VLWD (about 80% of the total) were 315°, 270°, 225° and 180°. These four wind directions correspond to about 85% of the total area burned by very large wildfires (Table 2, Fig. 2*b-e*, and SD-T2), the remaining 15% represented by other

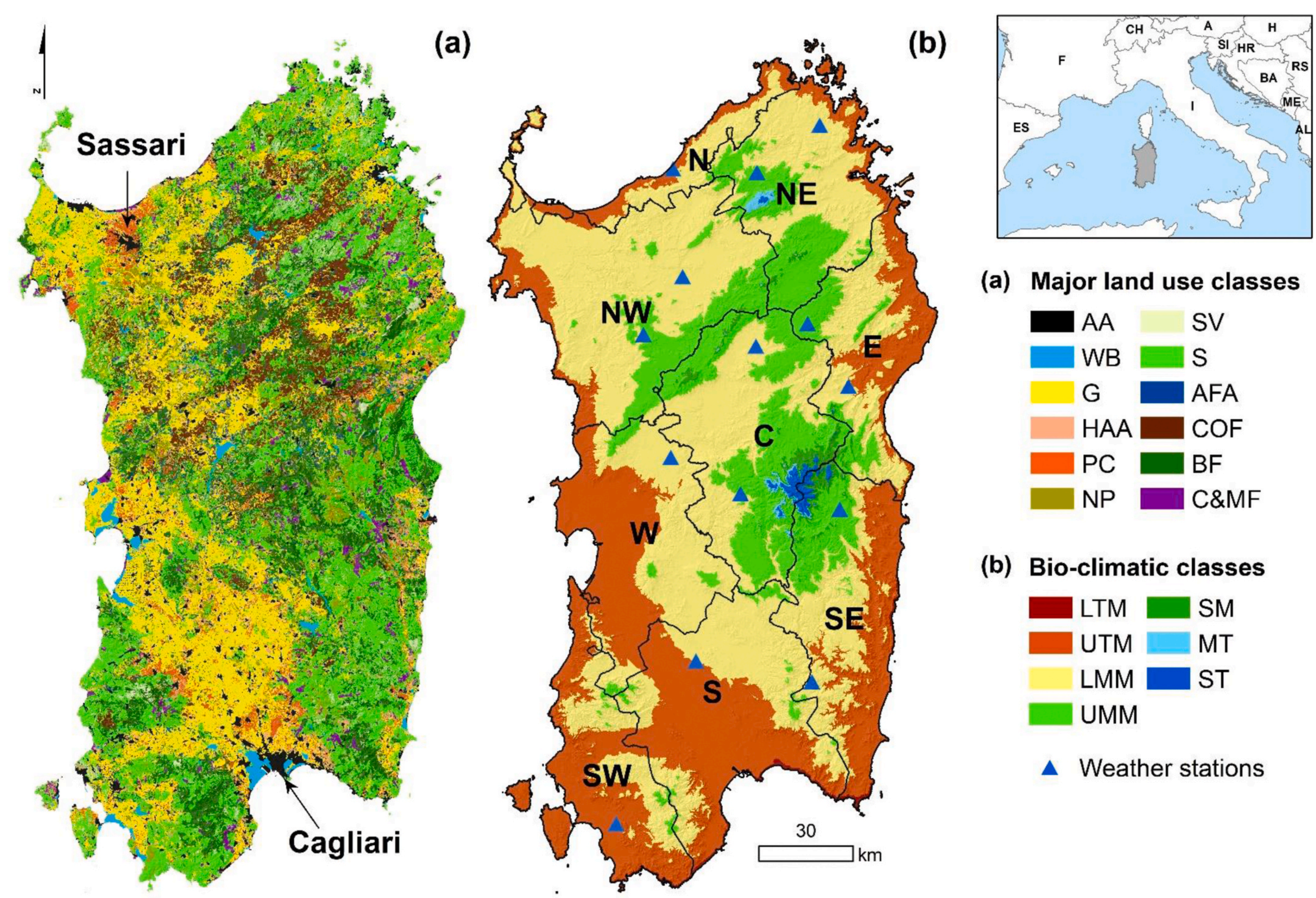

Fig. 1. (a) Major land use classes of Sardinia, Italy, according to the 2008 Sardinia Land Use Map (www.sardegnageoportale.it), along with the main towns. (b) Weather zones (adapted from Sardinia Environmental Protection Agency) and bio-climatic classification [64] of Sardinia, along with the meteorological stations used for the definition of the dominant wind direction scenarios. The study area has about 24,000 km^2 of land and is the second largest island of the Mediterranean Basin. AA= anthropic areas; WB = water bodies; G = grasslands; HAA = heterogeneous agricultural areas; PC = permanent crops; NP = natural pastures; SV = sparse vegetation; S = shrublands; AFA = agro-forestry areas; COF = cork oak forests, BF = broadleaf forests; C&MF = conifer and mixed forests. LTM = lower thermomediterranean; UTM = upper thermomediterranean; LMM = lower mesomediterranean; UMM = upper mesomediterranean; SM = supramediterranean; MT = mesotemperate; ST = supratemperate.

Table 1
Fuel model data used for the wildfire simulations. A different combination of fuel models was used depending on bio-climatic conditions of the island, as described in the methods. CH = canopy height; CBD = canopy bulk density; CBH = canopy base height. LTM = lower thermomediterranean; UTM = upper thermomediterranean; LMM = lower mesomediterranean; UMM = upper mesomediterranean; SM = supramediterranean; MT = mesotemperate; ST = supratemperate

Fuel Model Code	Dead Fuel Load ($t\ ha^{-1}$)	Live Fuel Load ($t\ ha^{-1}$)	Fuel Depth (cm)	Description	Bio-climatic Conditions	CH (m)	CBD ($kg\ m^{-3}$)	CBH (m)
FM25	1.2	0.0	20	Grasslands	LTM, UTM, LMM, UMM	0	0	0
FM26	1.2	0.0	30	Het. Agricultural Areas		0	0	0
FM27	1.0	2.0	80	Permanent Crops		10	0.11	1
FM28	2.5	0.0	35	Natural Pastures		0	0	0
FM29	5.3	4.1	45	Sparse Vegetation		0	0	0
FM30	15.0	12.5	135	Shrublands		12	0.14	1
FM31	10.0	1.0	25	Conifer		14	0.11	2
FM32	12.0	2.0	70	Broadleaf		12	0.14	2
FM33	12.0	2.0	70	Mixed Forests		14	0.13	2
FM45	1.2	0.0	20	Grasslands	SM, MT, ST	0	0	0
FM46	1.2	0.0	30	Het. Agricultural Areas		0	0	0
FM47	1.0	2.0	80	Permanent Crops		10	0.11	1
FM48	3.0	0.0	35	Natural Pastures		0	0	0
FM49	6.4	4.9	70	Sparse Vegetation		0	0	0
FM50	18.0	15.0	160	Shrublands		12	0.14	1
FM51	12.0	1.2	25	Conifer		15	0.11	4
FM52	14.4	2.4	70	Broadleaf		14	0.14	3
FM53	14.4	2.4	70	Mixed Forests		15	0.13	4

Table 2
Overview of the dominant wind directions at the regional scale and their influence on the observed burning patterns in days characterized by the occurrence of very large wildfires (>200 ha, VLWD) for the study period 1998–2016. VLW_{FN} = number of very large wildfires; VLW_{AB} = area burned by very large wildfires; VLW_{AFS} = average size of a very large wildfire. Numbers in brackets represent the percent value for each wind direction category.

DOMINANT WIND DIRECTION	WIND DIRECTION RANGE (degrees)	VLWD (#) (%)	VLW_{AB} (ha) (%)	VLW_{FN} (#) (%)	VLW_{AFS} (ha)
0°	337.50 ÷ 22.49	2 (1.3%)	790 (0.5%)	2 (0.9%)	395
45°	22.50 ÷ 67.49	2 (1.3%)	2550 (1.6%)	3 (1.3%)	850
90°	67.50 ÷ 112.49	11 (7.2%)	6920 (4.3%)	16 (6.8%)	430
135°	112.50 ÷ 157.49	18 (11.8%)	11,930 (7.4%)	27 (11.5%)	440
180°	157.50 ÷ 202.49	13 (8.5%)	22,090 (13.7%)	29 (12.3%)	760
225°	202.50 ÷ 247.49	23 (15.0%)	60,990 (37.9%)	53 (22.6%)	1150
270°	247.50 ÷ 292.49	54 (35.3%)	36,815 (22.9%)	64 (27.2%)	575
315°	292.50 ÷ 337.49	30 (19.6%)	18,930 (11.8%)	41 (17.4%)	460
		153	**161,015**	**235**	**685**

wind directions (Fig. 2*f*). For each dominant wind direction scenario, we derived spatial wind input files for wildfire modeling as described in Supplementary Data (SD-T2). Finally, additional wind scenarios for the days with 50–200 ha wildfires (large wildfire days, LWD) were set, by varying wind directions drawing from their historical probability of occurrence in the reference weather stations of each WZ (SD-T3): this condition accounted for about 22% of the total area burned in Sardinia for the study period (Fig. 2*g* and SD-T2). The wind speed was set at 35 $km\ h^{-1}$ and kept constant for the entire duration of each wildfire simulation and across all wind direction scenarios.

Fuel moisture content (FMC) for the 1-h and 10-h time lag dead fuel was determined by the methods described by Pellizzaro et al. [77,78] and Salis et al. [79] using the fuel moisture data gathered in Sardinia by field observations and fuel moisture sticks ([80,81]; Pellizzaro, personal communication), focusing on values below the 3rd percentile, which reflect conditions commonly associated to large wildfire ignitions in Sardinia. Dead fuel moisture content values used for wildfire simulations ranged from 5 to 10% (1-h time lag dead fuels) to 9–13% (100-h time lag dead fuels), with a gradient from the driest to the moistest areas of the island (Fig. 1*b*). The live fuel moisture values were tuned to consider differences among weather zones (Fig. 1*b* and SD-T1). Shrubland and forest understory live fuel moisture was set using a time series of data collected in northern Sardinia from 2003 to 2019 and previous studies ([78,82]; Pellizzaro, personal communication; [79,83]), by accounting the driest periods of the fire season (July–August). Live fuel moisture content values ranged from 40% (xerophytic shrublands) to 100% (shrub-grass understory in broadleaf forests of the coldest bio-climatic areas).

Finally, we created a set of wildfire ignition probability grids (100-m resolution) from the historical 1998–2016 database by considering all ignitions observed for each wind direction scenario of the VLWD, as well as for LWD (Fig. 2), using fixed kernel density methods with a 10-km bandwidth that generated continuous ignition probability maps for burnable areas.

2.4. Wildfire simulations

Wildfire simulations were performed by using the minimum travel time (MTT) fire spread algorithm as implemented in its command line version called "FConstMTT" [84]. The MTT algorithm calculates a two-dimensional fire growth by searching for the pathways with minimum spread time from the cell corners at an arbitrary resolution set by the user [84]. Wildfire spread is predicted by the equation of Rothermel [85] and crown fire initiation is evaluated according to Van Wagner [86] as implemented by Scott and Reinhardt [87]. This algorithm has been extensively described and widely applied to several case studies related to wildfire management analyses worldwide [48]. Calibration and validation of fuel model assignments and of the Rothermel's fire spread model in Sardinia were carried out by previous studies (e.g., [29,88]). We used MTT to simulate a large number of wildfires (300,000 simulated ignitions) under extreme weather conditions and to characterize spatial patterns of burn probability, wildfire intensity, and risk transmission in the island. The primary concern for fire management and civil protection is the combination of escaped large wildfires with extreme fire-weather. So, simulations were stratified into six extreme fire-weather scenarios and were tuned for each weather zone, as described below. We replicated the spatial distribution of large and very large wildfire sizes at the weather zone level by assigning a distribution of burn periods that better matched historical records under extreme

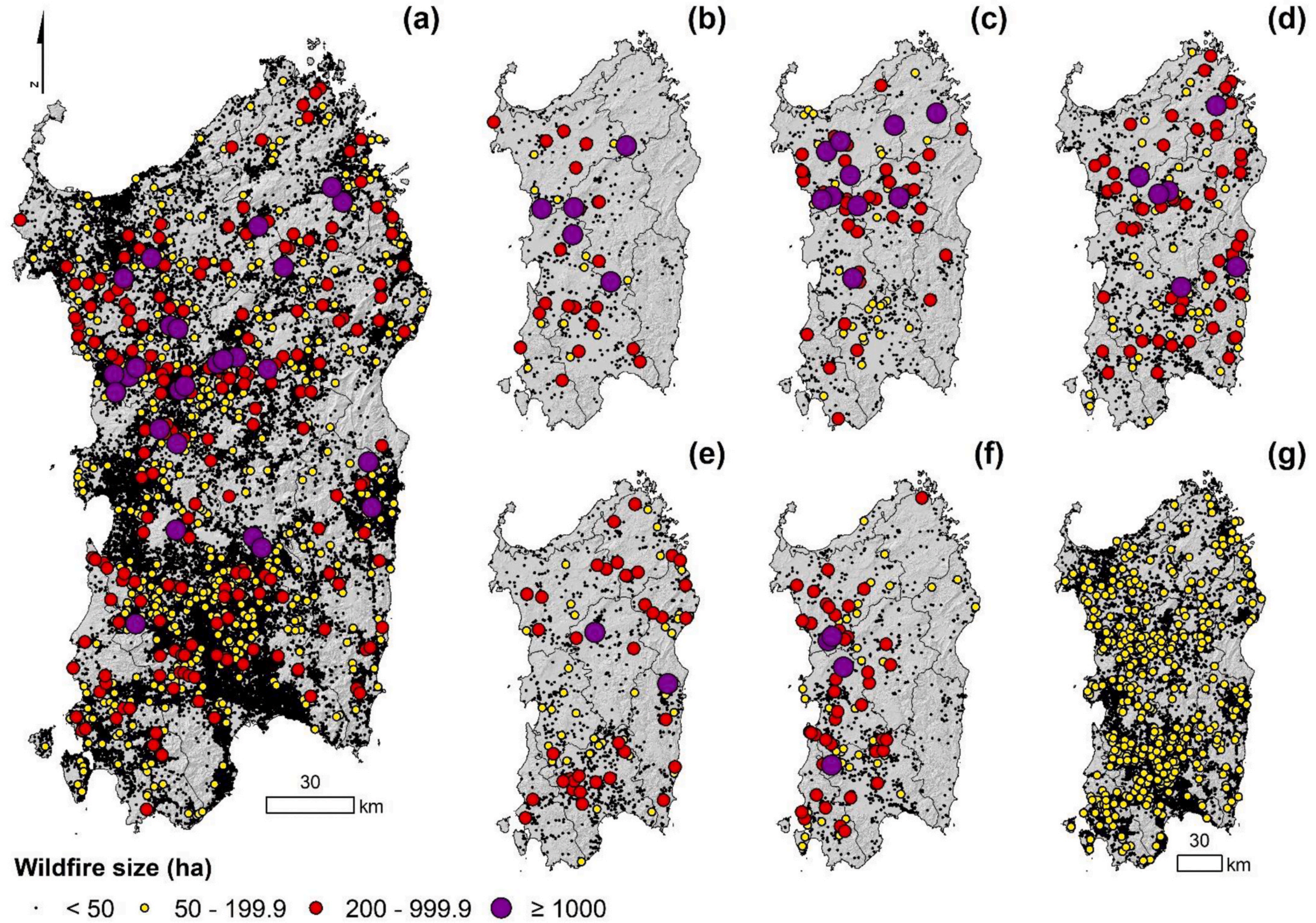

Fig. 2. (a) Historical wildfire ignitions in Sardinia for the study period (1998–2016) as a function of the final wildfire size. (b–g) Historical patterns of wildfire ignitions observed under very large wildfire days (VLWD, with at least a fire larger than 200 ha) and large wildfire days (LWD, with at least a fire in the range 50–200 ha) of the period 1998–2016. Wind conditions: (b) = VLWD, 180°; (c) = VLWD, 225°; (d) = VLWD, 270°; (e) = VLWD, 315°; (f) = VLWD, other wind directions; (g) = LWD.

conditions [50]. Wildfire ignitions were first distributed within the modeling domain according to the ignition probability grid associated with each fire-weather scenario. Each wildfire was independently modeled randomly drawing from the frequency distribution of fire-weather scenarios, burn periods and wind directions of the WZ where the fire was ignited. For each single fire simulation, weather conditions were held constant and fire suppression was not considered.

2.5. Wildfire exposure and transmission analysis

Simulations generated burn probability rasters (BP), frequency distributions of flame lengths (FL) in twenty 0.5-m intervals for each pixel, fire size lists (FS), and perimeter polygon outputs for the entire simulated landscape and for each scenario. The conditional burn probability is a relative measure that quantifies the chance that a pixel will burn given an ignition in the study area. The annual burn probability (aBP) represents the annual likelihood of burning given the current landscape and conditions, is estimated as the ratio between BP of a given pixel and the modeled wildfire seasons, and can range from 0 (the pixel never burns) to 1 (the pixel burns every wildfire seasons). The fire size output (FS) reports the fire size (in ha) and ignition coordinates of all simulated fires. The distribution of flame length (FL) values (in m) for each pixel was used to calculate the maximum flame length, as well as the high flame length probability (HFLP), which represents the probability that a pixel burns with flame length greater than 2.5 m considering only the fires that burned that pixel [89]. This flame length threshold was set to describe the required conditions for suppression forces to safely operate in the fire front area [90].

We then estimated wildfire exposure to human communities using the 100-m annual burn probability grid and individual building footprint locations. Specifically, we attributed the aBP values to each footprint polygon based on the structure centroid location. This structure footprint database provided accurate locations and contained all structures in Sardinia (n= 561,110 footprints) including residential housing, commercial buildings, farms, large stores, industrial buildings, and religious structures [65]. Finally, we summarized the results by municipality (n = 377 polygons) in terms of total number of exposed structures per year. The municipality represents the wildfire risk management unit dictating the local conditions for the definition of the wildfire risk and prevention plans as well as the preferential designation of urban development areas.

Wildfire transmission was calculated by intersecting simulated wildfire perimeters with land use boundaries (Fig. 1*a*), and by assigning the origin of each wildfire (i.e., source land use) based on the ignition location. The intersected perimeter fragments were then divided into self-burning (i.e.: areas burned within the same land use as the ignition) and outgoing (i.e.: areas burned outside of the land use of ignition). To derive the fire exchange values, we quantified, as a function of the land use of the ignition source, the total area burned in each land use: 1) incoming fire, i.e., area that burned in a given land use from wildfires ignited outside of this land use, 2) outgoing fire, i.e., area burned outside the land use where the fire was ignited, and 3) non-transmitted fire, i.e., area ignited in a land use and burned within it. We also created a transmission network to associate sources of wildfire exposure and given land uses. Land uses represent the nodes of the transmission network, while connections among nodes represent wildfire transmission. Finally, we mapped the percentage of incoming wildfires across the study area. For this purpose, we created a 100-m lattice of points over the modeling domain, and then summarized the amount of area burned from all fire perimeter fragments that intersected each point in the lattice and quantified the percentage that comes from the same land use type. These points were converted to 100-m pixels and were classified as a function of incoming fires. A hexnet of 1000-ha hexcells (n = 2364) was created to summarize for each hexcell the annual number of exposed structures, the annual number of structures exposed as percentage contribution to each hexcell, and the average percentage of incoming fires.

3. Results

Simulated wildfires under VLWD and LWD conditions burned about 16,000 ha yr^{-1} (weighted average), which is slightly higher than the observed value (14,500 ha yr^{-1}) for the period 1998–2016 (SD-T1). The annual burn probability (aBP) ranged from 0 to 0.0669, with pronounced spatial variations within the study area (Fig. 3*a* and 4*a*, and Table 3). The mean aBP value at the regional scale was 5.91 10^{-3} and ranged from a mean of 1.52 10^{-3} observed in the northern WZ to 9.54 10^{-3} in the northwestern one. Four WZs (S; W; C; NW) exhibited high mean aBP (above 7.00 10^{-3}); low aBP values (below 3.00 10^{-3}) were in N, NE and E weather zones. About 10% of Sardinia territory was characterized by aBP higher than 1.50 10^{-2} (Fig. 3*a*), with the most evident peaks observed in the NW, C, S, and W WZs (with 23.2%, 14.6%, 13.1% and 10.0% of the WZ area, respectively). In general, the above-mentioned high aBP areas were mostly characterized by fast-burning herbaceous surface fuel types and cork oaks, flat areas close to hills and complex topography, and moderate historical ignition density (Figs. 1*a* and 2). In addition, the above four WZs presented more than 1% of their relative area with aBP values above 3.50 10^{-2}, with the most relevant burn probability peaks observed in northwestern and central Sardinia (Figs. 3 and 4*a*).

Annual BP maps for VLWD and LWD wind direction scenarios also presented large differences for both spatial and absolute values (Fig. 3 and Table 3). As expected, LWD conditions were associated to the highest average aBP values (1.69 10^{-3}), due to the high probability of occurrence of this scenario. Regarding VLWD conditions, relevant average aBP values were associated to the 225° and 270° wind scenarios, with 1.46 10^{-3} and 1.00 10^{-3}, respectively. In both the above wind scenarios, aBP peaks above 7.00 10^{-3} were observed in several zones of NW and C WZs (225°) and of C and SE (270°). VLWDs with wind directions from 180° and from 315° exhibited the lowest aBP values (5.48 10^{-4} and 5.72 10^{-4}, respectively). These findings agree with the

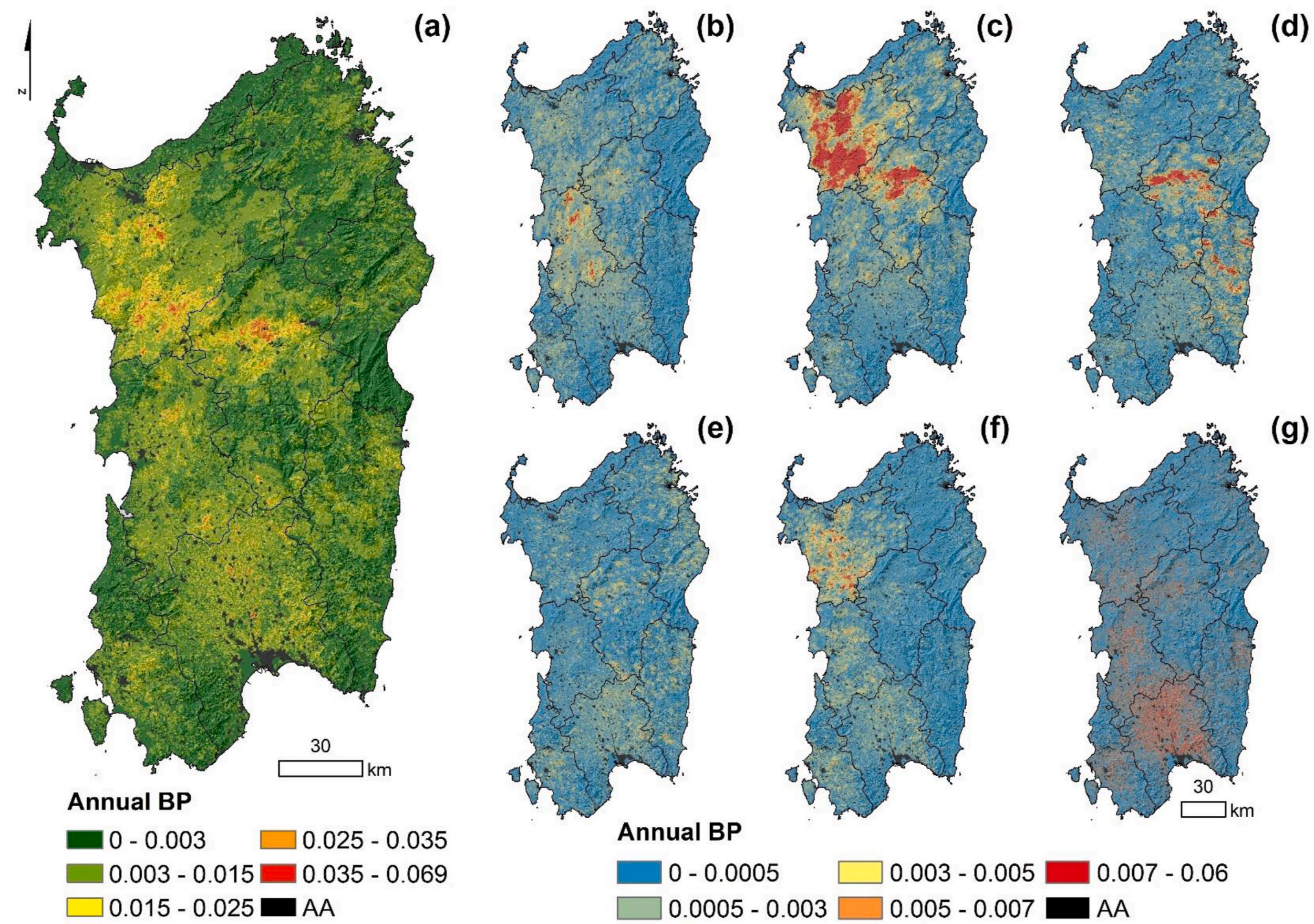

Fig. 3. Maps of the annual burn probability (aBP) of Sardinia, at 100-m resolution, derived from the combination of wildfire simulations, as described in the Methods. (a) Overall aBP; (b–g) aBPs under very large wildfire days (VLWD, with at least a fire larger than 200 ha) and large wildfire days (LWD, with at least a fire in the range 50–200 ha). Wind conditions: (b) = VLWD, 180°; (c) = VLWD, 225°; (d) = VLWD, 270°; (e) = VLWD, 315°; (f) = VLWD, other wind directions; (g) = LWD. AA = anthropic areas.

Table 3
Overview of the annual burn probability (aBP) values of the nine weather zones and the six wind direction scenarios associated to VLWD and LWD. The total annual burn probability was obtained as the sum of the six aBP values, as described in the methods.

WEATHER ZONE	VLWD – 180°	VLWD – 225°	VLWD – 270°	VLWD – 315°	VLWD – OWD	LWD	aBP
C	6.61 10^{-4}	2.48 10^{-3}	2.22 10^{-3}	6.26 10^{-4}	2.91 10^{-4}	1.35 10^{-3}	**7.62 10^{-3}**
E	4.90 10^{-5}	3.96 10^{-4}	6.89 10^{-4}	6.06 10^{-4}	1.90 10^{-4}	8.38 10^{-4}	**2.77 10^{-3}**
N	8.67 10^{-5}	4.72 10^{-4}	1.45 10^{-4}	1.17 10^{-4}	1.80 10^{-4}	5.19 10^{-4}	**1.52 10^{-3}**
NE	3.41 10^{-4}	7.08 10^{-4}	5.32 10^{-4}	5.59 10^{-4}	1.34 10^{-4}	6.79 10^{-4}	**2.95 10^{-3}**
NW	5.85 10^{-4}	4.63 10^{-3}	7.13 10^{-4}	4.13 10^{-4}	1.72 10^{-3}	1.47 10^{-3}	**9.54 10^{-3}**
S	4.22 10^{-4}	3.55 10^{-4}	8.83 10^{-4}	8.75 10^{-4}	6.92 10^{-4}	3.77 10^{-3}	**7.00 10^{-3}**
SE	1.11 10^{-4}	4.41 10^{-4}	2.01 10^{-3}	7.20 10^{-4}	1.86 10^{-4}	1.35 10^{-3}	**4.82 10^{-3}**
SW	3.44 10^{-4}	3.94 10^{-4}	4.85 10^{-4}	5.42 10^{-4}	6.70 10^{-4}	1.53 10^{-3}	**3.97 10^{-3}**
W	1.87 10^{-3}	8.02 10^{-4}	5.88 10^{-4}	4.31 10^{-4}	9.21 10^{-4}	2.43 10^{-3}	**7.04 10^{-3}**
SARDINIA	**5.48 10^{-4}**	**1.46 10^{-3}**	**1.00 10^{-3}**	**5.72 10^{-4}**	**6.53 10^{-4}**	**1.69 10^{-3}**	5.91 10^{-3}

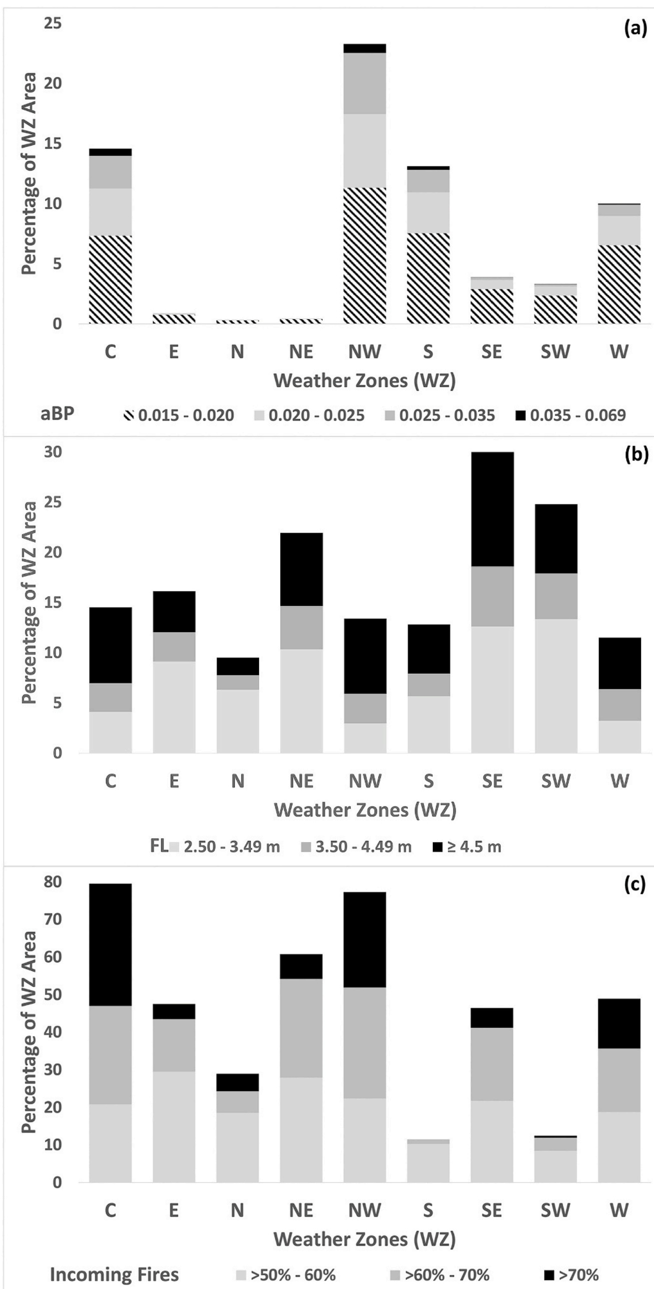

Fig. 4. Percentage of the relative area of each weather zone characterized by the highest values of conditional burn probability, flame length and percentage of incoming fires.

historical wildfire regime patterns, as shown in Fig. 2, SD-T1 and SD-T2.

The cumulative simulated ignition point densities (IPd) of the island derived from the historical data evidenced a clear concentration of wildfire ignitions in the southern plains, mostly located in S and W WZs (Fig. 5*a*): in these WZs, the relative area above 0.075 ignitions km^{-2} year^{-1} was about 52.4% and 12.6%, respectively. In contrast, the lowest incidence of wildfire ignitions was observed in N and E WZs, with 46.6% and 14.0% of their relative areas with ignition density below 0.008 wildfires km^{-2} year^{-1} (Fig. 5*a*). The major contribution to the total annual IPd was evidently exhibited by LWD conditions, while the other VLWD wind direction scenarios did not present values above 0.015 wildfires km^{-2} year^{-1}, with the highest ignition densities observed for 270° and 315° conditions and in the southern plains (Fig. 5*b-g*).

As far as the simulated fire size (FS) is concerned, values ranged from 1 ha to a maximum of about 19,000 ha, with the largest size observed for the 225° wind scenario. The FS maps allowed to identify the WZs with the highest potential to generate large wildfires (Fig. 6). Overall, the simulations reasonably replicated the wildfire size distribution and frequencies observed in Sardinia for the different WZs and for all six scenarios (see also Supplementary Data, SD-F1). However, the simulations were characterized by a general slight underestimation of the major wildfire size (200–1000 ha and >1000 ha) and an overestimation of the smallest size class for most of WZs and wind scenarios tested (Fig. 6). In general, small fires were generated from ignitions near the coastal zones and close to areas characterized by fragmented landscapes with a mosaic of low-fuel load vegetation and non-burnable fuels. On the contrary, large fires were generated from ignitions located upwind of large fuel fetches that permitted fire spread over long distances, and particularly in areas close to or with relatively complex topography, covered by a mixture of herbaceous pastures, cork oaks and shrublands. This explains why the major wildfire events were simulated in NW, W and C WZs, that is in accordance with the historical patterns of wildfire regime. In addition, Fig. 6, SD-F1 and Fig. 2 highlighted the relationship between large and very large wildfire occurrence and main wind directions, with downwind WZs more often exposed to large size events than upwind WZs.

Flame length (FL) outputs showed high (≥2.5 m) values for several locations around Sardinia (about 17% of the territory), mostly in steep areas and where fuel load and spatial continuity are high (Figs. 7 and 4*b*). For this reason, the WZs of eastern Sardinia presented FL values generally higher than those of southern and north-western parts of the island. As shown by Figs. 4*b* and 7, south-eastern Sardinia presented the highest relative area (about 12%) with FL values above 4.5 m, while the opposite pattern was showed by the northern WZ (about 2% of the relative area). Overall, the zones with the most significant peaks in fire intensity did not vary depending on wind direction scenarios. In addition, FL and aBP showed opposite patterns in a number of zones, with the highest FL values observed in areas with low aBP, and vice versa (Figs. 3, Figs. 4 and 6).

Wildfire exposure to communities varied very substantially across the study area (Fig. 8*a* and 8*b*). In terms of overall exposure, the highest

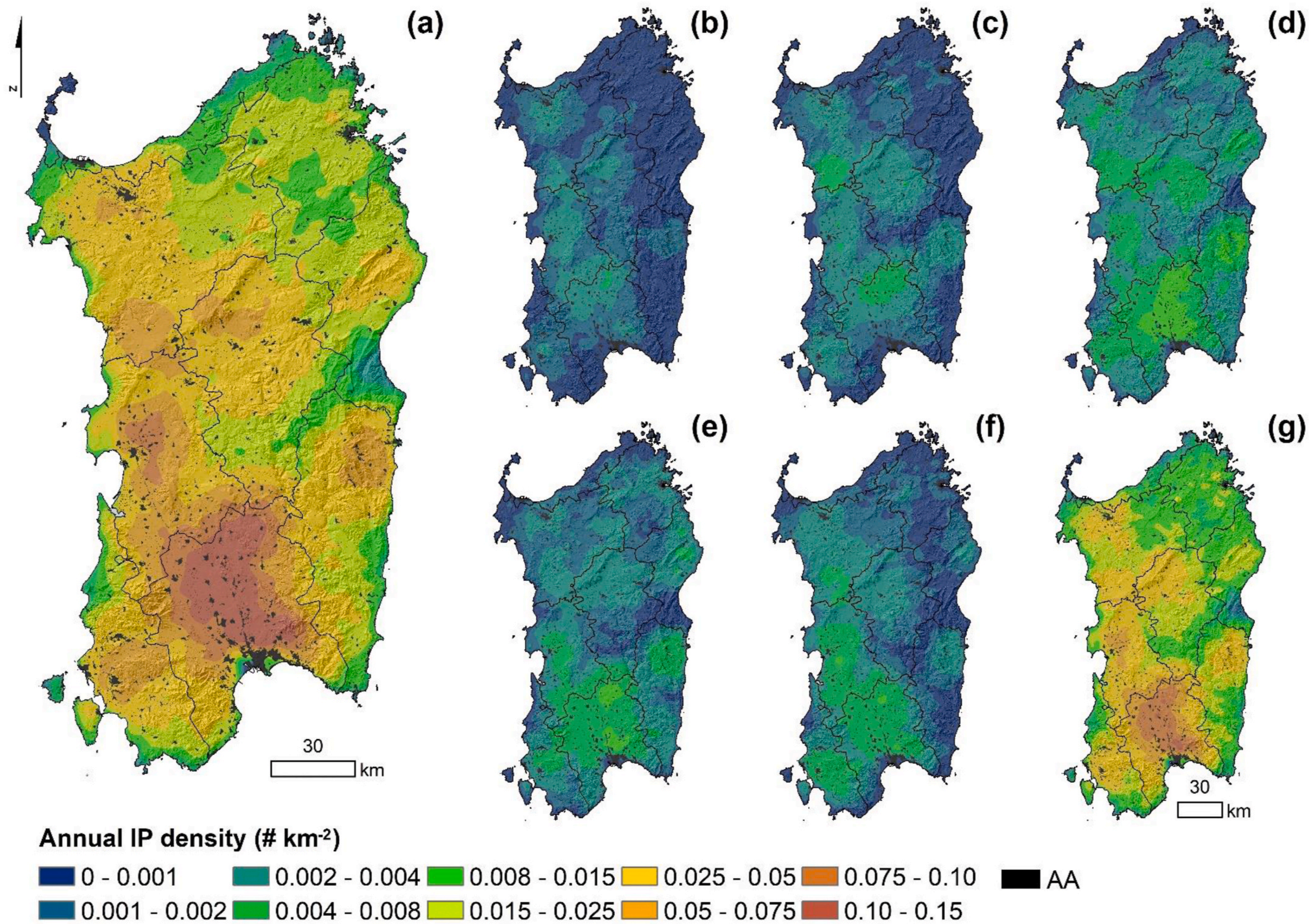

Fig. 5. (a) Maps of the annual wildfire ignition point density (IPd), at 100 m resolution, derived from the combination of wildfire simulations, as described in the Methods. (a) Overall IPd for days with at least a fire larger than 50 ha. (b–g) IPds under very large wildfire days (VLWD, with at least a fire larger than 200 ha) and large wildfire days (LWD, with at least a fire in the range 50–200 ha). Wind conditions: (b) = VLWD, 180°; (c) = VLWD, 225°; (d) = VLWD, 270°; (e) = VLWD, 315°; (f) = VLWD, other wind directions; (g) = LWD. AA = anthropic areas.

values (>15 exposed str. yr^{-1}) were mainly located in the municipalities of the NW WZ, where Sassari concentrated the bulk of exposure (about 100 exposed str. yr^{-1}) (Table 4). Other populated and vast municipalities in the NW, W and C WZs of the island (such as Alghero, Nuoro, Ozieri, and Oristano) also presented exposure results above the average (>15 exposed str. yr^{-1}). The coastal sites of northeastern Sardinia showed a high exposure cluster with values peaking in Olbia (about 32 exposed str. yr^{-1}). The overall exposure values were generally lower in southern Sardinia, except for some few communities located in dryland agricultural plains and close to the coast (e.g., Oristano, Guspini, Assemini and Sestu). The normalization of the annual amount of structures exposed, by dividing the annual exposure of structures and the number of structures per hexcell, allowed highlighting the high exposure of some communities in remote rural areas, mostly located in central and western Sardinia: in those zones (about 5% of the Sardinia area), the considerable likelihood of large wildfires was combined with the low number of structures, which resulted in a high annual probability (15–35%) of the structures to be affected by wildfires (Figs. 8*b* and 3*a*, SD-F2). Conversely, about 2/3 of the island presented normalized values of structures annually exposed below 5%. So, the relationships among wildfire ignition density, large wildfire propagation, and exposed structures are complex, follow complex spatial patterns, and a high wildfire frequency does not necessarily connote a high wildfire risk.

Fig. 8*c* shows the average amount of incoming wildfires in Sardinia from a low of <10% (colder colors) to a high of >70% (warmer colors), using hexcells with 1000 ha cell size. The zones with the highest percentage (>70%) of incoming wildfires are located in C, NW, and W WZs, which are the zones where the occurrence of very large wildfires was more frequent for both the historical wildfires during the study period 1998–2016 and the simulations (Figs. 2 and 6). Due to their size, the largest events can cross multiple land use boundaries and cause large amounts of incoming burned area. In more detail, C, NW and W WZs showed about 32.5%, 25.3% and 13.2% of their relative area with incoming fires >70%, respectively (Fig. 4*c*). Lands with colder colors, and therefore with lower amounts of incoming fires, are mostly located in southern Sardinia, and particularly in grasslands, where the percentage of incoming events is generally lower than 50% (Fig. 8*c*). As presented in Fig. 4*c*, about 88% of the relative area of S and SW WZs was characterized by a percentage of incoming events below the 50% threshold. These results can be linked with the fact that Southern Sardinia land uses overall present a large amount of non-transmitted wildfires, related to the high number of events that have very limited size and therefore cannot spread to other land uses.

Wildfire transmission analysis revealed that grasslands, shrublands and natural pastures received about 62% (23.5%, 22.7% and 15.6%, respectively) of all wildfires and transmitted about 66% (25.8%, 22.3% and 17.9%) of all outgoing wildfires (Fig. 9*a*), while they cover approximately 26.1%, 27.6% and 6.1% of Sardinia territory, respectively (Fig. 1). According to these values, the role played by natural pastures is quite interesting: a small land use (6.1% of Sardinia lands) is

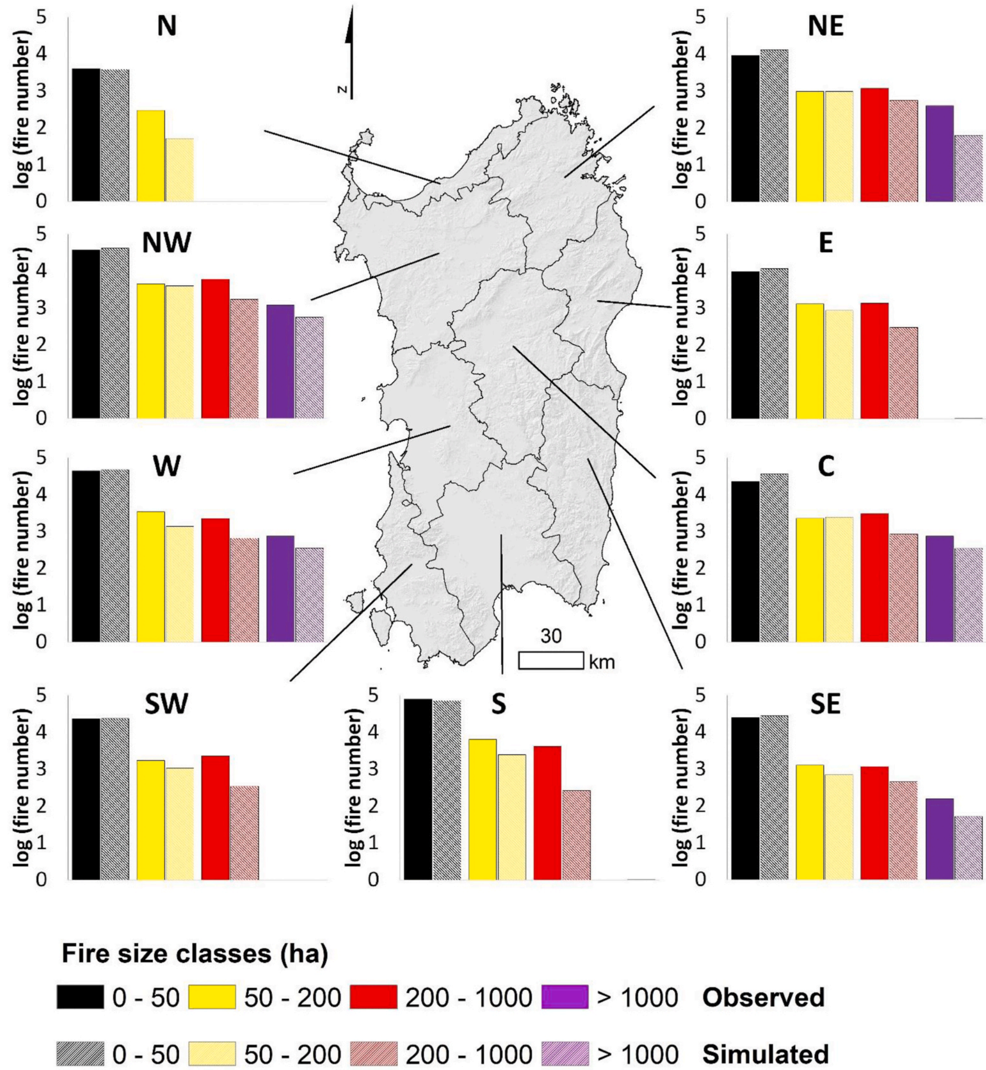

Fig. 6. Log plot of observed vs. simulated wildfire sizes and frequencies for the different Sardinia WZs, considering the whole set of simulations carried out (300,000 wildfires).

associated to the occurrence of large-scale wildfire events (17.9% of total outgoing events). By contrast, the role played by these land uses in terms of non-transmitted wildfires is much more different: about 45.4% and 31.3% of all self-burning is observed in grasslands and shrublands, while natural pastures only account for 9.7% of the total non-transmitted events (Fig. 9*a*). The high incidence of self-burning in grasslands and shrublands can be related to the large dimensions of grasslands and shrublands polygons (wildfires mostly burn inside them before escaping) and to the large amount of small wildfires ignited in the grasslands of S and W WZs.

Anthropic areas present the highest percentage of incoming wildfires (78%) (Fig. 9*b*). Incoming wildfires are the most common transmission type for wooded areas, which reveal percentages ranging from about 44% (broadleaf and *Quercus suber* L. forests) to 50% (conifer stands). On the other hand, the lowest share of incoming wildfires is observed in grasslands (27.3%). The lowest percentages of area burned related to self-burning conditions are observed in agroforestry areas and sparse vegetation, with 8.5% and 10.9%, respectively (Fig. 9*b*). Excluding anthropic areas, outgoing wildfires account from 46.5% (heterogeneous agricultural areas) to 30.1% (grasslands): overall, this transmission type was relevant in low fuel load vegetation types (e.g.: heterogeneous agricultural areas, sparse vegetation and permanent crops) (Fig. 9*b*). Wildfire transmission analysis for the diverse VLWD and LWD conditions is presented in SD-F3.

The wildfire transmission network (Fig. 10) shows that wildfires were transmitted among the main land use classes via 52 network edges (i.e. directed edges), considering transmission pathways greater than 40 ha yr^{-1}, i.e., transmitted fires <40 ha yr^{-1} between two land uses were not considered. The wildfire transmission network has 11 nodes, 43 direct edges and a density of 0.39, i.e. 39% of all possible linkages (Fig. 10). Each node has a variable size based on the amount of burned area received from that node, with shrublands, grasslands and natural pastures having the largest size. Compared to Fig. 9, the network shows not only how much incoming and outgoing fire, but also who is sending or receiving and to whom, indicated by the variable arrow size. Grasslands and shrublands are the greatest source of transmitted wildfires within the study area and account for about 2300 ha yr^{-1} and 2000 ha yr^{-1} of transmitted events, respectively. In addition, they present the highest amount of fire exchange between land uses, followed by grasslands and natural pastures, and by shrublands and natural pastures (Fig. 10). Shrublands are the main source of transmitted wildfires for broadleaf, natural pastures, sparse vegetation, and conifer and mixed forests. Grasslands account for about 50% of wildfires affecting anthropic areas, for which they represent the most relevant transmitter of wildfires.

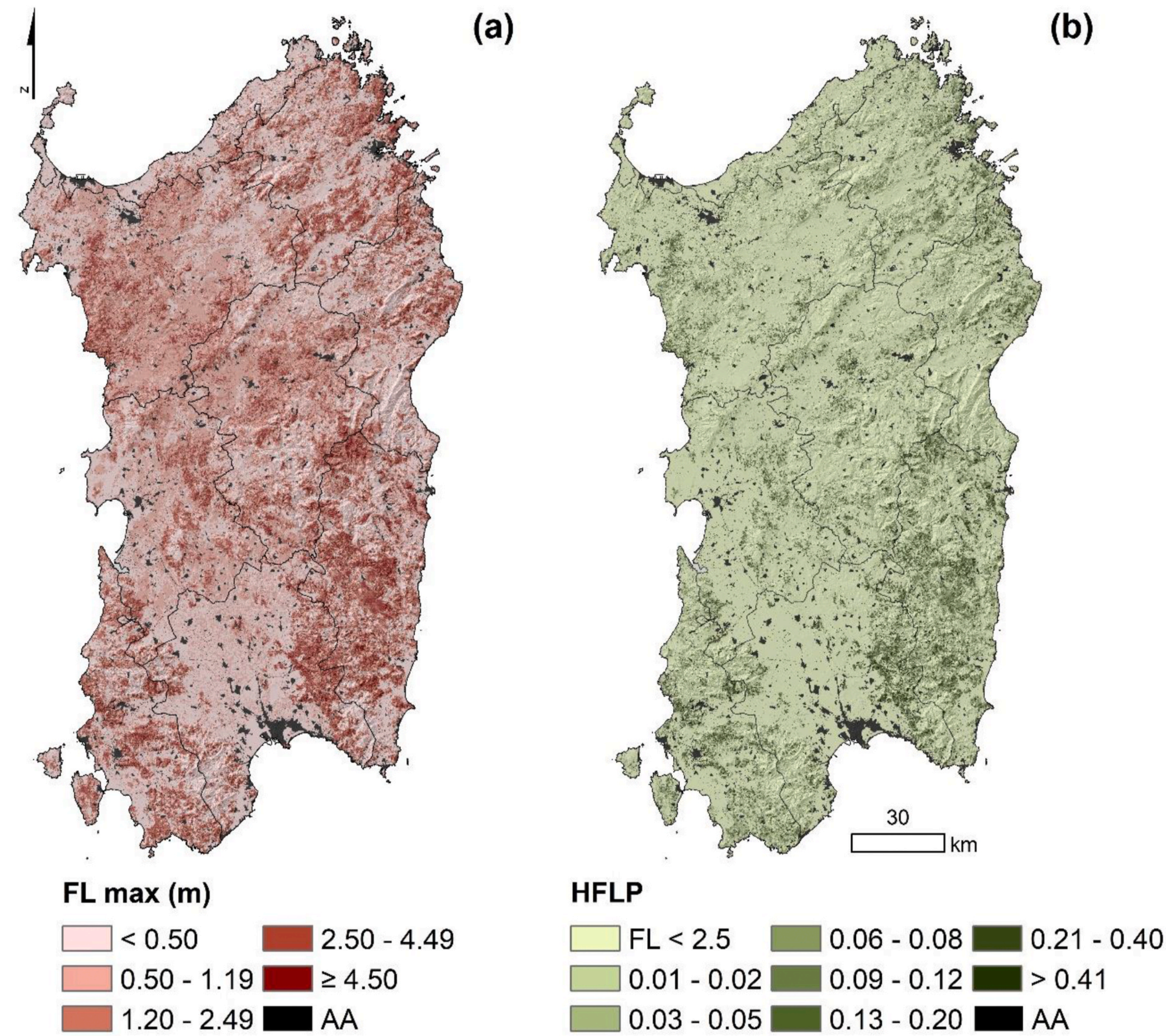

Fig. 7. (a) Map of the maximum flame length (FL) under VLWD and LWD conditions. (b) Map of the high flame length probability (HFLP), which represents the probability (from 0 to 1) to have high flame length (FL > 2.5 m) in a given pixel considering the whole set of wildfire simulations. AA = anthropic areas.

4. Discussion

In this study, we employed and advanced simulation modeling approaches to examine wildfire exposure and transmission across the island of Sardinia, Italy. The simulation approaches presented in this manuscript allowed us to characterize fine-scale (100-m resolution) wildfire exposure and risk factors that were informed by data on historical fire regimes, weather patterns, and fuel moisture focusing on the days that were associated to the occurrence of large (>50 ha) and very large (>200 ha) wildfires.

Overall, the simulated outputs were consistent with the historical fire frequency and patterns of Sardinia, and realistically agreed with the local knowledge about wildfire conditions within the different areas of the island. The agreement between simulated and observed wildfire size classes by considering a large number of variables in the simulations (in terms of fuels, weather and ignition locations) is the result of an accurate preliminary calibration phase before carrying out wildfire spread simulations [91]. In this light, the calibration phase of the fire spread model used in the present work was based on several previous papers, research projects and investigations on wildfires of different sizes that occurred in Sardinia, which were studied and analyzed with the support of the Sardinia Forest Service and other Regional Institutions (e.g., [29,50,80,81,88,92]). The subdivision of Sardinia into homogeneous areas (based on weather and bio-climatic classifications) in terms of wildfire regime, fuels and weather-climatic conditions allowed us to further refine the assessment and mapping of wildfire exposure and risk transmission profiles compared to previous research (e.g., [50,57]). In fact, we were able to tune all inputs related to winds and fuels according to the scenarios historically associated with the major events on the island. Moreover, by selecting only the days with wildfires >50 ha, we better discriminated and captured the disturbance factor related to the numerous but overall small events in the southern area of the island. From a spatial point of view, the Sardinia BP maps obtained by [50,57] considering the study period 1995–2009 were affected by this limitation. The concentration of small-size wildfire ignitions in the southern and western plains, and the consequent effect on wildfire transmission, can be mostly due to the fact that these zones, generally covered by herbaceous fuels and with high human pressure levels, present the lowest productivity and greenness values of the island and tend to burn more easily and with longer fire seasons compared to the rest of Sardinia [93,94]. Consequently, high ignition likelihood does not necessarily correspond to significant risk of large wildfire occurrence, because the spread of large events in Sardinia is basically driven by the combination of strong winds, relatively complex topography and the presence of unmanaged fuels, as for instance natural pastures or shrublands. These findings agree with previous studies that reported large contrasts

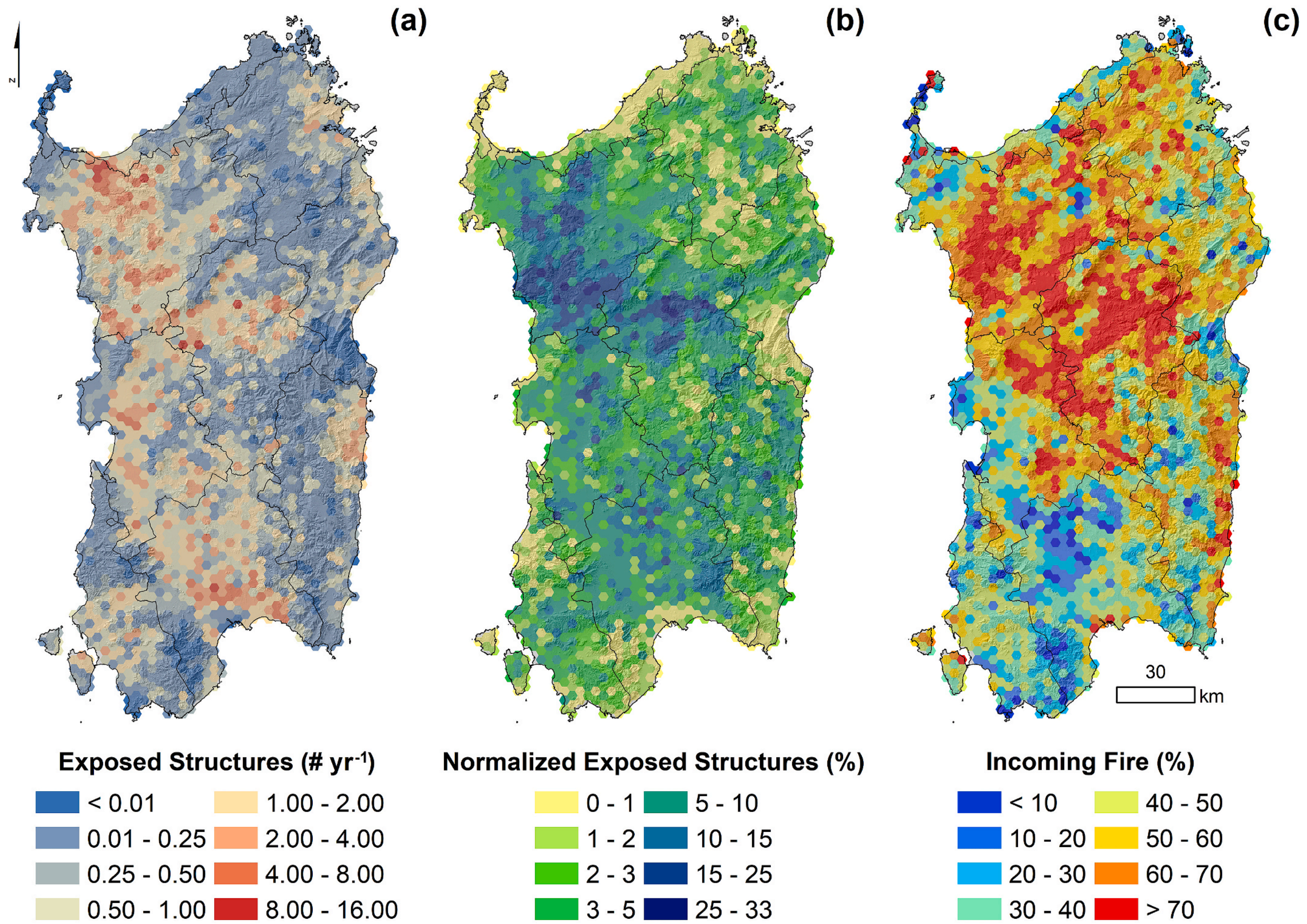

Fig. 8. (a) Annual number of exposed structures across Sardinia. (b) Annual number of structures exposed as percentage contribution to each hexcell in Sardinia. (c) Average percentage of incoming fires. The study area is divided in 1000-ha hexcells (n= 2364).

Table 4
Number of structures exposed to wildfires per year for the 20 most exposed municipalities in Sardinia. The total exposure in the study area is about 1816 exposed structures yr^{-1} (about 4.82 exposed structures yr^{-1} per municipality). We used municipality polygons (n = 377) to delineate the community extent (sardegnageoportale.it). The top 64 municipalities (17% of Sardinia municipalities) account for the 50% of annual exposure in Sardinia.

Municipality	WZ	Municipal Area (ha)	Number of structures	Average aBP	Exposed str. yr^{-1} (number)	Exposed str. yr^{-1} (%, regional level)	Exposed str. yr^{-1} (%, municipal level)
Sassari	NW	54,734	24,899	0.0058	99.5	5.48	0.40
Olbia	NE	38,246	19,781	0.0042	32.6	1.79	0.16
Alghero	NW	22,524	9977	0.0045	26.3	1.45	0.26
Nuoro	C	19,217	5730	0.0078	25.7	1.42	0.45
Oristano	W	8568	6316	0.0078	25.1	1.38	0.40
Osilo	NW	9791	1728	0.0152	24.7	1.36	1.43
Bonorva	NW	14,973	1768	0.0150	24.0	1.32	1.36
Orotelli	C	6108	1136	0.0243	20.8	1.14	1.83
Assemini	S	11,834	5137	0.0040	18.7	1.03	0.36
Sedilo	C	6857	3363	0.0110	18.4	1.01	0.55
Ozieri	NW	24,595	5154	0.0047	17.2	0.95	0.33
Villanova Monteleone	NW	20,227	1566	0.0119	17.1	0.94	1.09
Guspini	W	17,470	3681	0.0072	16.8	0.92	0.46
Quartu Sant'Elena	S	9662	10,589	0.0036	16.8	0.92	0.16
Ittiri	NW	11,150	2015	0.0155	16.7	0.92	0.83
Sestu	S	4822	3205	0.0085	16.6	0.92	0.52
Pozzomaggiore	NW	7969	1298	0.0186	16.4	0.90	1.26
Macomer	NW	12,259	2346	0.0148	15.9	0.88	0.68
Villacidro	S	18,336	5122	0.0052	15.4	0.85	0.30
Uta	S	13,477	2913	0.0049	14.2	0.78	0.49
Iglesias	SW	20,728	5502	0.0047	13.3	0.73	0.24
Sinnai	S	22,337	5188	0.0069	13.1	0.72	0.25
Decimoputzu	S	4452	2221	0.0090	12.9	0.71	0.58
Scano di Montiferro	NW	6053	1217	0.0121	12.8	0.71	1.05

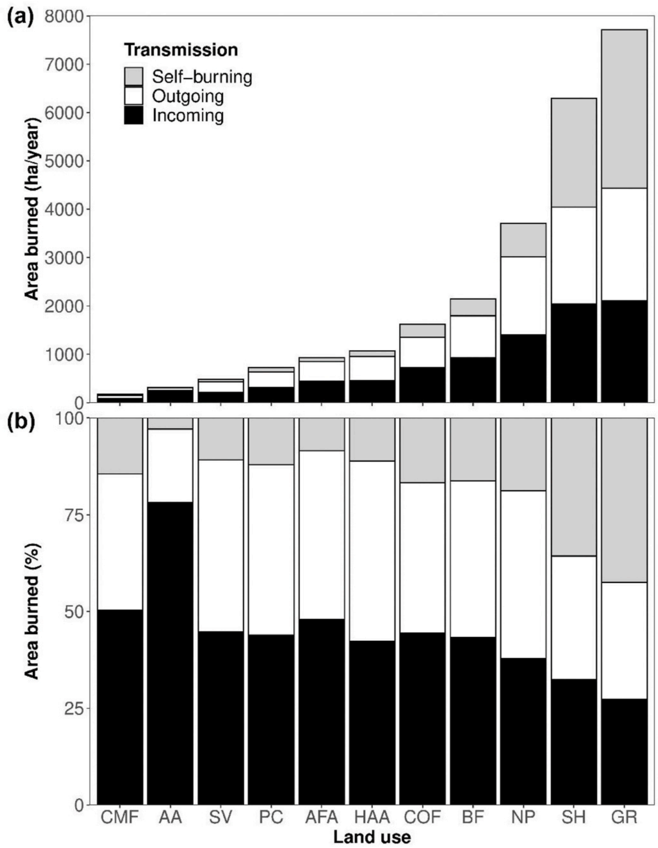

Fig. 9. Simulated wildfire area burned by land use classes as a function of the transmission types in Sardinia. The data report the sum of the annual wildfire received and transmitted (a), and the percentages of wildfire transmission types of each land use class (b). CMF: conifer and mixed forests; AA: anthropic areas; SV: sparse vegetation; PC: permanent crops; AFA: agro-forestry areas; HAA: heterogeneous agricultural areas; COF: cork oak forests; BF: broadleaf forests; NP: natural pastures; SH: shrublands; GR: grasslands.

between probability of ignition and large wildfire probability [95–98]. Our study highlighted a great wildfire transmission from herbaceous fuel types and shrublands to denser forest areas, and this is consistent with previous studies carried out in southern Europe that pointed out the role of shrubs and grasses in wildfire occurrence [99–101,135]. Moreover, with respect to the above studies, we went a step further in quantifying wildfire transmission between fuel types: in fact, we quantified the relevance of incoming and outgoing fires at WZs and fuels level, as well as which fuel type is sending or receiving fires and to whom.

We highlighted the existence of a relationship between large and very large wildfire occurrence and prevailing winds. In more detail, we observed that downwind WZs were often more exposed to large size events than upwind areas, and this in turn affected burn probability and wildfire transmission. For instance, we showed how northern and western Sardinia WZs presented the worst wildfire risk conditions in days with southern and southwestern winds: the advection of hot and dry air masses from the south through the inner parts and the north of the island results in an evident wildfire risk gradient from south to north. On the other hand, strong winds from the west and north-west promoted an increase in wildfire risk in eastern and southern WZs. Similarly to Sardinia, and particularly to the northern and western areas of the island, hot and dry conditions due to southerly advections (SW and S winds) triggered the majority of wildfires and area burned in Catalonia (Spain) [102] and northern Tunisia [103]; likewise, Rodrigues et al. [104] reported that southerly winds boosted wildfire size for mainland Spain. The significant role played by air advection on wildfire regime and risk, as well as on large wildfire occurrence, in Mediterranean climate contexts, was also confirmed by a number of other studies (e.g., [105–113]).

Few prior studies applied wildfire spread simulation modeling to explore wildfire transmission and exposure at large scales and fine resolutions in southern Europe [23,55,79,114]. From this point of view, this work provides a novel modeling approach and represents a relevant contribution to wildfire risk assessment in Mediterranean areas. At broader scales, characterizing wildfire exposure and risk profiles with objective variables such as burn probability, wildfire intensity, or wildfire transmission can help reduce fragmentation and differences in existing risk evaluation methods and systems at the regional and national levels in the Mediterranean areas. Even if wildfire risk management is affected by several intrinsic uncertainties, particularly in areas where ignitions are largely determined by human factors such as in southern Europe or in other Mediterranean climate areas, this work can provide a sound basis to characterize topological properties of wildfire risk and to incorporate potential wildfire spread and behavior into the current regional, provincial or municipality plans for improving wildfire prevention and risk mitigation. From this perspective, our results underline the importance of collaborative planning and strategies among municipalities or landscapes which present similar wildfire exposure profiles or are interconnected by cross-boundary wildfire transmission networks [23,115–118]. Overall, the development of comprehensive fire management strategies is of prominent concern in Southern European areas, due to the expanding scale of wildfire risk and associated extreme events [119,120]. With our work, we offer quantitative methods to assess wildfire exposure and risk on Mediterranean fire-prone ecosystems: this is a preliminary fundamental step towards the definition of the most effective means to build fire resilient landscapes and fire adapted communities, and to reduce potential wildfire exposure and losses by adequate strategies [121–123]. Moreover, our work has the potential to support wildfire and landscape management strategies, as well as to inform ongoing investments and efforts devoted to increase landscape fire-resilience and human community protection in Mediterranean areas. For instance, the areas characterized by the highest wildfire transmission values ideally represent priority zones for landscape fuel treatments devoted to reducing wildfire intensity and fuel connectivity, and therefore at enhancing wildfire suppression potential and limiting escaped events. Another relevant aspect is the identification of the municipalities and structures with the highest exposure values: promoting strategic fuel management activities to given targets nearby the home ignition zone can be critical to lower the potential losses related to extreme wildfires and to protect human life, values and assets. In this light, the high-risk interface areas of northeastern coastal Sardinia, where we have been observing a progressive increase of dispersed housing units close to wilderness, touristic fluxes in the summer season and wildfires burning nearby these areas, represent a key zone to pay attention to [124,125]. In addition, our findings can be used to detect the natural or anthropic values most vulnerable to wildfires, and to characterize them in terms of expected wildfire behavior or transmission potential. This information can be crucial to inform and optimize current and future fuel management, urban planning, and agro-forestry policies according to local fine-scale wildfire exposure profiles. Likewise, wildfire exposure and transmission outputs can be used to inform fire managers about the specific sites where potential wildfire spread and behavior largely overwhelm fire suppression capacity, so that interventions of terrestrial and aerial forces in those zones can be limited or even excluded for safety reasons. Analyses of potential effects of wildfires on environmental factors such as soil erosion [126–128], water supply protection and carbon cycling [129,130], as well as on economic losses and suppression costs [54,131,132], can be also informed and quantified with probabilistic frameworks based on similar wildfire spread modeling approaches, in order to account for the uncertainty in wildfire occurrence, spread and intensity.

Although MTT wildfire models can provide relevant elements for the

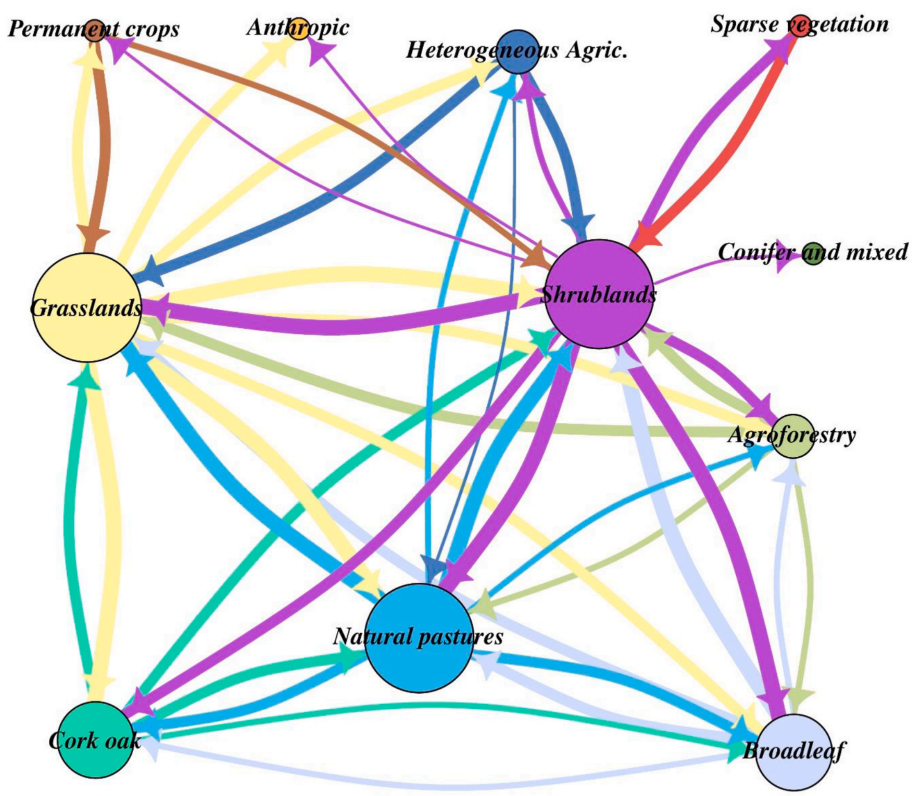

Fig. 10. Wildfire transmission network for the main land uses of Sardinia. Network edges represent wildfires transmitted from one land use to another, as shown by the arrow and colored by its source. The size of each node is related to the amount of wildfires received from that node. Arrows are colored by the source ignition and width represents the area burned at four scales (<50, 50–100, >100–250 and > 250 ha yr^{-1}). Node size represents the sum of incoming fire at four scales (<250, 250–500, >500–1000 and > 1000 ha yr^{-1}). Self-burning and edges less than 40 ha yr^{-1} are not shown.

estimation of wildfire spread and behavior and the optimization of management strategies, the inherent limitations and assumptions of the modelling equations and variables involved should be taken into consideration [133,134], as well as the need of careful calibration and validation before their application [29,88,91]. In addition, the network analysis performed in this work quantified the transmission from the initial land use source to the final sink, but did not consider the sequence of transmission through multiple land uses and the effects of land uses in between. Future work will focus on this aspect, and in more detail in the identification of land types and landscape situations where wildfires are accelerated.

Work is also in progress to replicate the methodological approach proposed in this study and assess wildfire exposure and transmission in neighboring Italian and French regions (Corsica, Tuscany, Liguria and PACA Region). At present, the above regions use different methods to characterize and map wildfire hazard and risk, even if wildfire behavior and dynamics in high-danger days are relatively comparable and risk is often exacerbated by the great incidence of touristic fluxes and facilities in areas highly exposed to wildfires during the whole summer season.

5. Conclusions

European and National programs on wildfire prevention and management underline the need to implement more holistic fire management approaches with the primary goals of reducing the incidence and extent of wildfires and promoting the definition and application of standardized methodologies, thus overcoming the differences imposed by national and regional boundaries. This study offers a novel comprehensive and quantitative method to assess wildfire exposure and transmission across Mediterranean fire-prone ecosystems. The method is based on the application of a wildfire spread and behavior modeling approach that allows us to derive objective measures of risk variables such as burn probability, flame length or wildfire transmission. With the present work, we intend to improve the promotion of common wildfire management and prevention strategies and to strengthen the potential to protect natural and cultural values and communities from extreme events in the Mediterranean Basin, as well as to cope with the challenges posed by future climate changes in terms of increased wildfire risk in this area.

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.ijdrr.2021.102189.

References

[1] FAO, Plan Bleu, State of Mediterranean Forests 2018, Food and Agriculture Organization of the United Nations, Rome and Plan Bleu, Marseille, 2018, ISBN 978-92-5-131047-2.

[2] J. San-Miguel-Ayanz, T. Durrant, R. Boca, G. Libertà, A. Branco, D. de Rigo, D. Ferrari, P. Maianti, T. Artés Vivancos, D. Oom, H. Pfeiffer, Forest fires in Europe, Middle East and north africa 2018, 978-92-76-11234-1, EUR 29856 EN (2020), https://doi.org/10.2760/1128.

[3] N. Andela, D.C. Morton, L. Giglio, Y. Chen, G.R. van der Werf, P.S. Kasibhatla, R. S. DeFries, G.J. Collatz, S. Hantson, S. Kloster, D. Bachelet, M. Forrest, G. Lasslop, F. Li, S. Mangeon, J.R. Melton, C. Yue, J.T. Randerson, A human-driven decline in global burned area, Science 356 (2017) 1356–1362.

[4] A. Jiménez-Ruano, M. Rodrigues Mimbrero, J. de la Riva Fernández, Exploring spatial–temporal dynamics of fire regime features in mainland Spain, Nat. Hazards Earth Syst. Sci. 17 (2017) 1697–1711, https://doi.org/10.5194/nhess-17-1697-2017.

[5] M. Turco, J. Bedia, F. Di Liberto, P. Fiorucci, J. von Hardenberg, N. Koutsias, M.-C. Llasat, F. Xystrakis, A. Provenzale, Decreasing fires in mediterranean Europe, PloS One 11 (3) (2016), e0150663, https://doi.org/10.1371/journal.pone.0150663.

[6] M.A. Adams, Mega-fires, tipping points and ecosystem services: managing forests and woodlands in an uncertain future, For. Ecol. Manag. 294 (2013) 250–261, https://doi.org/10.1016/j.foreco.2012.11.039.

[7] M. Castellnou, N. Prat-Guitart, E. Arilla, A. Larrañaga, E. Nebot, X. Castellarnau, J. Vendrell, J. Pallàs, J. Herrera, M. Monturiol, J. Cespedes, J. Pagès, C. Gallardo, M. Miralles, Empowering strategic decision-making for wildfire management: avoiding the fear trap and creating a resilient landscape, Fire Ecology 15 (2019) 31, https://doi.org/10.1186/s42408-019-0048-6.

[8] J. Ruffault, T. Curt, V. Moron, R.M. Trigo, F. Mouillot, N. Koutsias, F. Pimont, N. Martin-StPaul, R. Barbero, J.-L. Dupuy, A. Russo, C. Belhadj-Khedher, Increased likelihood of heat-induced large wildfires in the Mediterranean Basin, Sci. Rep. 10 (2020) 13790, https://doi.org/10.1038/s41598-020-70069-z.

[9] P.M. Fernandes, A.M.G. Barros, A. Pinto, J.A. Santos, Characteristics and controls of extremely large wildfires in the western Mediterranean Basin, J. Geophys. Res.: Biogeosciences 121 (2016) 2141–2157, https://doi.org/10.1002/2016JG003389.

[10] F. Tedim, V. Leone, M. Amraoui, C. Bouillon, M. Coughlan, G. Delogu, P. M. Fernandes, C. Ferreira, S. McCaffrey, T. McGee, J. Parente, D. Paton, M. G. Pereira, L. Ribeiro, D. Viegas, G. Xanthopoulos, Defining extreme wildfire events: difficulties, challenges, and impacts, Fire 1 (9) (2018), https://doi.org/10.3390/fire1010009.

[11] P.A. Werth, B.E. Potter, C.B. Clements, M.A. Finney, S.L. Goodrick, M. E. Alexander, M.G. Cruz, J.A. Forthofer, S.S. McAllister, Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. Gen. Tech. Rep. PNW-GTR-854, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 2011, p. 144.

[12] L. Brotons, N. Aquilué, M. De Caceres, M.J. Fortin, A. Fall, How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes, PloS One 8 (2013), https://doi.org/10.1371/journal.pone.0062392.

[13] B. Chergui, S. Fahd, X. Santos, J.G. Pausas, Socioeconomic factors drive fire-regime variability in the Mediterranean Basin, Ecosystems (2017), https://doi.org/10.1007/s10021-017-0172-6.

[14] P. Corona, D. Ascoli, A. Barbati, G. Bovio, G. Colangelo, M. Elia, V. Garfì, F. Iovino, R. Lafortezza, V. Leone, R. Lovreglio, M. Marchetti, E. Marchi, G. Menguzzato, S. Nocentini, R. Picchio, L. Portoghesi, N. Puletti, G. Sanesi, F. Chianucci, Integrated forest management to prevent wildfires under Mediterranean environments, Annals of Silvicultural Research 39 (2015) 1–22.

[15] F. Moreira, O. Viedma, M. Arianoutsou, T. Curt, N. Koutsias, E. Rigolot, A. Barbati, P. Corona, P. Vaz, G. Xanthopoulos, F. Mouillot, E. Bilgili, Landscape-wildfire interactions in southern Europe: implications for landscape management, J. Environ. Manag. 92 (2011) 2389–2402.

[16] P.M. Fernandes, Fire-smart management of forest landscapes in the Mediterranean basin under global change, Landsc. Urban Plann. 110 (2013) 175–182.

[17] S. Oliveira, L. Zezere, Assessing the biophysical and social drivers of burned area distribution at the local scale, J. Environ. Manag. 264 (2020) 1–15, https://doi.org/10.1016/j.jenvman.2020.110449.

[18] J.G. Pausas, S. Fernandez-Munoz, Fire regime changes in the Western Mediterranean Basin: from fuel limited to drought-driven fire regime, Climatic Change 110 (2012) 215–226.

[19] M.G. Pereira, J. Parente, M. Amraoui, A. Oliveira, P.M. Fernandes, 3 - the Role of Weather and Climate Conditions on Extreme Wildfires. Extreme Wildfire Events and Disasters - Root Causes and New Management Strategies, 2020, pp. 55–72, https://doi.org/10.1016/B978-0-12-815721-3.00003-5.

[20] M. Salis, B. Arca, F. Alcasena-Urdiroz, A. Massaiu, V. Bacciu, F. Bosseur, P. Caramelle, S. Dettori, A.S. Fernandes De Oliveira, D. Molina-Terren, G. Pellizzaro, P.-A. Santoni, D. Spano, C. Vega-Garcia, P. Duce, Analyzing the recent dynamics of wildland fires in Quercus suber L. woodlands in Sardinia (Italy), Corsica (France) and Catalonia (Spain), Eur. J. For. Res. 138 (2019) 415–431, https://doi.org/10.1007/s10342-019-01179-1.

[21] M. Turco, S. Jerez, S. Augusto, P. Tarín-Carrasco, N. Ratola, P. Jiménez-Guerrero, R.M. Trigo, Climate drivers of the 2017 devastating fires in Portugal, Sci. Rep. 9 (2019), https://doi.org/10.1038/s41598-019-50281-2.

[22] A.A. Ager, A.M.G. Barros, H.K. Preisler, M.A. Day, T.A. Spies, J.D. Bailey, J. P. Bolte, Effects of accelerated wildfire on future fire regimes and implications for the United States federal fire policy, Ecol. Soc. 22 (2017) 12, https://doi.org/10.5751/ES-09680-220412.

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

[24] D.E. Calkin, J.D. Cohen, M.A. Finney, M.P. Thompson, How risk management can prevent future wildfire disasters in the wildland-urban interface, Proc. Natl. Acad. Sci. Unit. States Am. 111 (2014) 746–751, https://doi.org/10.1073/pnas.1315088111.

[25] M.A. Finney, The wildland fire system and challenges for engineering, Fire Saf. J. (2020), https://doi.org/10.1016/j.firesaf.2020.103085.

[26] A.A. Ager, N.M. Vaillant, M.A. Finney, A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure, For. Ecol. Manag. 259 (2010) 1556–1570.

[27] P. Palaiologou, K. Kalabokidis, A.A. Ager, M.A. Day, Development of comprehensive fuel management strategies for reducing wildfire risk in Greece, Forests 11 (2020) 789.

[28] E.D. Reinhardt, R.E. Keane, D.E. Caulkin, J.D. Cohen, Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States, For. Ecol. Manag. 256 (2008) 1997–2006.

[29] M. Salis, B. Arca, F. Alcasena, M. Arianoutsou, V. Bacciu, P. Duce, B. Duguy, N. Koutsias, G. Mallinis, I. Mitsopoulos, J.M. Moreno, J.R. Perez, I. Rodriguez, F. Xystrakis, G. Zavala, D. Spano, Predicting wildfire spread and behavior in Mediterranean landscapes, Int. J. Wildland Fire 25 (2016) 1015–1032.

[30] G. Bovio, M. Marchetti, L. Tonarelli, M. Salis, G. Vacchiano, R. Lovreglio, M. Elia, P. Fiorucci, D. Ascoli, Gli incendi boschivi stanno cambiando: cambiamo le strategie per governarli, Forest@ - Rivista di Selvicoltura ed Ecologia Forestale 14 (2017) 202–205.

[31] T. Curt, T. Frejaville, Wildfire policy in Mediterranean France: how far is it efficient and sustainable? Risk Anal. 38 (2017) 472–488.

[32] M.-A. Parisien, Q.E. Barber, K.G. Hirsch, C.A. Stockdale, S. Erni, X. Wang, D. Arseneault, S.A. Parks, Fire deficit increases wildfire risk for many communities in the Canadian boreal forest, Nat. Commun. 11 (2020) 1–9.

[33] M.P. Thompson, D.G. MacGregor, C.J. Dunn, D.E. Calkin, J. Phipps, Rethinking the wildland fire management system, J. For. 116 (2018) 382–390, https://doi.org/10.1093/jofore/fvy020.

[34] T.D. Penman, C. Eriksen, R. Blanchi, M. Chladil, A.M. Gill, K. Haynes, J. Leonard, J. McLennan, R.A. Bradstock, Defining adequate means of residents to prepare property for protection from wildfire, International Journal of Disaster Risk Reduction 6 (2013) 67–77, https://doi.org/10.1016/j.ijdrr.2013.09.001.

[35] A.M.S. Smith, C.A. Kolden, T.B. Paveglio, M.A. Cochrane, D.M.J.S. Bowman, M. A. Moritz, A.D. Kliskey, L. Alessa, A.T. Hudak, C.M. Hoffman, J.A. Lutz, L. P. Queen, S.J. Goetz, P.E. Higuera, L. Boschetti, M. Flannigan, K.M. Yedinak, A. C. Watts, E.K. Strand, J.W. van Wagtendonk, J.W. Anderson, B.J. Stocks, J. T. Abatzoglou, The science of firescapes: achieving fire-resilient communities, Bioscience 66 (2016) 130–146.

[36] V. Leone, F. Tedim, G. Xanthopoulos, 11 - Fire Smart Territory as an Innovative Approach to Wildfire Risk Reduction. Extreme Wildfire Events and Disasters - Root Causes and New Management Strategies, 2020, pp. 201–215, https://doi.org/10.1016/B978-0-12-815721-3.00011-4.

[37] C.S. Olsen, J.D. Kline, A.A. Ager, K.A. Olsen, K.C. Short, Examining the influence of biophysical conditions on wildland–urban interface homeowners' wildfire risk mitigation activities in fire-prone landscapes, Ecol. Soc. 22 (2017) 21, https://doi.org/10.5751/ES-09054-220121.

[38] T.B. Paveglio, C.M. Edgeley, M. Carroll, M. Billings, A.M. Stasiewicz, Exploring the influence of local social context on strategies for achieving fire adapted communities, Fire 2 (2019) 26, https://doi.org/10.3390/fire2020026.

[39] J.P. Prestemon, D.T. Butry, K.L. Abt, R. Sutphen, Net benefits of wildfire prevention education efforts, For. Sci. 56 (2010) 181–192.

[40] D.E. Calkin, A.A. Ager, M.P. Thompson, A Comparative Risk Assessment Framework for Wildland Fire Management: the 2010 Cohesive Strategy Science Report. Gen. Tech. Rep. RMRS-GTR-262, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 2011, p. 63.

[41] C. Miller, A.A. Ager, A review of recent advances in risk analysis for wildfire management, Int. J. Wildland Fire 22 (2012) 1–14, https://doi.org/10.1071/WF11114.

[42] J.H. Scott, M.P. Thompson, D.E. Calkin, A Wildfire Risk Assessment Framework for Land and Resource Management. Gen. Tech. Rep. RMRS-GTR-315, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2013, p. 83.

[43] A.A. Ager, M.A. Day, K.C. Short, C.R. Evers, Assessing the impacts of federal forest planning on wildfire risk mitigation in the Pacific Northwest, USA, Landsc. Urban Plann. 147 (2016) 1–17, https://doi.org/10.1016/J.LANDURBPLAN.2015.11.007.

[44] F. Allaire, J.-B. Filippi, V. Mallet, Generation and evaluation of an ensemble of wildland fire simulations, Int. J. Wildland Fire 29 (2020) 160–173, https://doi.org/10.1071/WF19073.

[45] B. Arca, T. Ghisu, M. Casula, M. Salis, P. Duce, A web-based wildfire simulator for operational applications, Int. J. Wildland Fire 28 (2019) 99–112, https://doi.org/10.1071/WF18078.

[46] K. Kalabokidis, A. Ager, M. Finney, N. Athanasis, P. Palaiologou, C. Vasilakos, AEGIS: a wildfire prevention and management information system, Nat. Hazards Earth Syst. Sci. 16 (2016) 643–661.

[47] S. Monedero, J. Ramirez, A. Cardil, Predicting fire spread and behaviour on the fireline. Wildfire analyst pocket: a mobile app for wildland fire prediction, Ecological Modeling 392 (2019) 103–107.
[48] M.-A. Parisien, D.A. Dawe, C. Miller, C.A. Stockdale, O. Bradley Armitage, Applications of simulation-based burn probability modelling: a review, Int. J. Wildland Fire 28 (2019) 913–926, https://doi.org/10.1071/WF19069.
[49] F. Rodríguez y Silva, J.R. Molina Martínez, M.A. Herrera Machuca, J. M. Rodríguez Leal, VISUAL-SEVEIF, a tool for integrating fire behavior simulation and economic evaluation of the impact of wildfires, in: González-Cabán A (Tech. Coord), Proceedings of the Fourth International Symposium on Fire Economics, Planning, and Policy: Climate Change and Wildfires. Gen. Tech. Rep. PSW-GTR-245, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 2013, pp. 163–178.
[50] M. Salis, A.A. Ager, B. Arca, M.A. Finney, V. Bacciu, P. Duce, D. Spano, Assessing exposure of human and ecological values to wildfire in Sardinia, Italy, Int. J. Wildland Fire 22 (2013) 549–565, https://doi.org/10.1071/WF11060.
[51] F.J. Alcasena, M. Salis, C. Vega-Garcia, A fire modeling approach to assess wildfire exposure in central Navarra, Spain, Eur. J. For. Res. 135 (2016) 87–107.
[52] F.J. Alcasena, A.A. Ager, M. Salis, M.A. Day, C. Vega-García, Optimizing prescribed fire allocation for managing wildfire risk in central Catalonia, Sci. Total Environ. 621 (2018) 872–885, https://doi.org/10.1016/j.scitotenv.2017.11.297.
[53] B. Botequim, P.M. Fernandes, J.G. Borges, E. González-Ferreiro, J. Guerra-Hernández, Improving silvicultural practices for Mediterranean forests through fire behaviour modelling using LiDAR-derived canopy fuel characteristics, Int. J. Wildland Fire 28 (2019) 823–839.
[54] I. Mitsopolous, G. Mallinis, M. Arianoutsou, Wildfire risk assessment in a typical Mediterranean wild-land urban interface of Greece, Environ. Manag. 55 (2015) 900–915.
[55] T.M. Oliveira, A.M.G. Barros, A.A. Ager, P.M. Fernandes, Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission, Int. J. Wildland Fire 25 (2016) 619–632.
[56] P. Palaiologou, A.A. Ager, M. Nielsen-Pincus, C.R. Evers, K. Kalabokidis, Using transboundary wildfire exposure assessments to improve fire management programs: a case study in Greece, Int. J. Wildland Fire 27 (2018) 501–513, https://doi.org/10.1071/WF17119.
[57] M. Salis, A.A. Ager, M.A. Finney, B. Arca, D. Spano, Analyzing spatiotemporal changes in wildfire regime and exposure across a Mediterranean fire-prone area, Nat. Hazards 71 (2014) 1389–1418, https://doi.org/10.1007/s11069-013-0951-0.
[58] M. Salis, L. Del Giudice, B. Arca, A.A. Ager, F. Alcasena-Urdiroz, O. Lozano, V. Bacciu, D. Spano, P. Duce, Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area, J. Environ. Manag. 212 (2018) 490–505, https://doi.org/10.1016/j.jenvman.2018.02.020.
[59] L.F. Galizia, F. Alcasena, G. Prata, M. Rodrigues, Assessing expected economic losses from wildfires in eucalypt plantations of western Brazil, For. Pol. Econ. 125 (2021), https://doi.org/10.1016/j.forpol.2021.102405.
[60] C. Gomez, M. Mangeas, T. Curt, T. Ibanez, J. Munzinger, P. Dumas, A. Jérémy, M. Despinoy, C. Hély, Wildfire risk for main vegetation units in a biodiversity hotspot: modeling approach in New Caledonia, South Pacific, Ecology and Evolution 5 (2015) 377–390, https://doi.org/10.1002/ece3.1317.
[61] A.A. Ager, R. Lasko, V. Myroniuk, S. Zibtsev, M.A. Day, U. Usenia, V. Bogomolov, I. Kovalets, C.R. Evers, The wildfire problem in areas contaminated by the Chernobyl disaster, Sci. Total Environ. 696 (2019) 133954, https://doi.org/10.1016/j.scitotenv.2019.133954.
[62] R. Jahdi, M. Salis, F. Alcasena, M. Arabi, B. Arca, P. Duce, Evaluating wildfire exposure in northwestern Iran, Nat. Hazards 101 (2020) 911–932, https://doi.org/10.1007/s11069-020-03901-4.
[63] U. Oliveira, B. Soares-Filho, W.L. de Souza Costa, L. Gomes, M. Bustamante, H. Miranda, Modeling fuel loads dynamics and fire spread probability in the Brazilian Cerrado, For. Ecol. Manag. 482 (2021) 118889, https://doi.org/10.1016/j.foreco.2020.118889.
[64] S. Canu, L. Rosati, M. Fiori, A. Motroni, R. Filigheddu, E. Farris, Bioclimate map of sardinia (Italy), J. Maps 11 (2015) 711–718, https://doi.org/10.1080/17445647.2014.988187.
[65] Ramm, OpenStreetMap Data in Layered GIS Format (Data available at, 2019, https://www.geofabrik.de/data/. (Accessed 30 January 2021).
[66] P.A. Chessa, A. Delitala, Il clima della Sardegna, in: Collana Note Tecniche Di Agrometeorologia per la Sardegna, vols. 17–38, Chiarella, Sassari, 1997.
[67] S.E. Fick, R.J. Hijmans, WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas, Int. J. Climatol. 37 (2017) 4302–4315. http://www.worldclim.com/version2. (Accessed 30 January 2021).
[68] Assessorato della Difesa dell'Ambiente, Decreto dell'Assessore della Difesa dell'Ambiente della Regione Sardegna del 27 marzo 2006, n. 11/VI, 2006. http://www.regione.sardegna.it/j/v/2644?s=1&v=9&c=390&c1=1260&id=2821. (Accessed 30 January 2021).
[69] N.M. Vaillant, A.A. Ager, J. Anderson, ArcFuels10 System Overview. General Technical Report PNW-GTR-875. Portland, OR, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 2013, p. 65.
[70] M.A. Finney, An overview of FlamMap fire modeling capabilities, in: P. L. Andrews, B.W. Butler (Eds.), Fuels Management-How to Measure Success, vol. 41, US Department of Agriculture, Forest Service, Proceedings RMRS-P-, 2006, pp. 213–220.
[71] H.E. Anderson, Aids to Determining Fuel Models for Estimating Fire Behavior, US Department of Agriculture, Forest Service, 1982. General Technical Report INT-122.
[72] J.H. Scott, R. Burgan, Standard Fire Behavior Fuel Models: a Comprehensive Set for Use with Rothermel's Surface Fire Spread Model, US Department of Agriculture, Forest Service, 2005. General Technical Report RMRS-GTR-153.
[73] B. Arca, V. Bacciu, G. Pellizzaro, M. Salis, A. Ventura, P. Duce, D. Spano, G. Brundu, Fuel model mapping by IKONOS imagery to support spatially explicit fire simulators, in: 7th International Workshop on Advances in Remote Sensing and Gis Applications in Forest Fire Management towards an Operational Use of Remote Sensing in Forest Fire Management, 2009. Matera, Italy.
[74] P. Duce, G. Pellizzaro, B. Arca, V. Bacciu, M. Salis, D. Spano, P.A. Santoni, T. Barboni, V. Leroy, D. Cancellieri, E. Leoni, L. Ferrat, Y. Perez, Fuel types and potential fire behaviour in Sardinia and Corsica islands: a pilot study, in: D. Spano, V. Bacciu, M. Salis, C. Sirca (Eds.), 2012. Modelling Fire Behaviour and Risk, 2012, ISBN 978-88-904409-7-7, pp. 2–8.
[75] INFC, Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. Ministero delle Politiche Agricole Alimentari e Forestali, Ispettorato Generale Corpo Forestale dello Stato. CRA Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, 2005. http://www.sian.it/inventarioforestale/.
[76] M. Salis, M. Laconi, A.A. Ager, F.J. Alcasena, B. Arca, O. Lozano, A.F. de Oliveira, D. Spano, Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area, For. Ecol. Manag. 368 (2016) 207–221.
[77] G. Pellizzaro, A. Ventura, P. Zara, Influence of seasonal weather variations on fuel status for some shrubs typical of Mediterranean Basin, in: Proceedings of the 6th Fire and Forest Meteorology Symposium and 19th Interior West Fire Council Meeting, Canmore, AB, Canada, 2005, pp. 24–27.
[78] G. Pellizzaro, P. Duce, A. Ventura, P. Zara, Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin, Int. J. Wildland Fire 16 (2007) 633–641.
[79] M. Salis, A.A. Ager, F. Alcasena, B. Arca, M.A. Finney, G. Pellizzaro, D. Spano, Analyzing seasonal patterns of wildfire likelihood and intensity in Sardinia, Italy, Environ. Monit. Assess. 187 (2015) 4175, https://doi.org/10.1007/s10661-014-4175-x.
[80] G. Nudda, P. Botti, F. Tola, M. Chessa, G. Diana, S. Cocco, C. Masnata, F. Congiu, G. Delogu, M.P. Giannasi, S. Mavuli, G. Muntoni, A.M. Pirisi, A. Sattanino, G. Pulina, A. Casula, G. Patteri, G. Bianco, M. Fiori, P. Capece, M. Salis, C. Sirca, L. Del Giudice, C. Scarpa, O. Lozano, P. Duce, B. Arca, G. Pellizzaro, V. Bacciu, Rapporto sugli incendi boschivi e rurali in Sardegna - anno 2015, in: Regione Autonoma Della Sardegna – Assessorato Alla Difesa dell'Ambiente, 2016, ISBN 978-888-881-706-4, p. 80.
[81] G. Nudda, P. Botti, F. Tola, M. Chessa, G. Diana, S. Cocco, C. Masnata, F. Congiu, G. Delogu, M.P. Giannasi, S. Mavuli, G. Muntoni, A.M. Pirisi, A. Sattanino, G. Pulina, A. Casula, G. Patteri, G. Bianco, M. Fiori, P. Capece, C. Sirca, L. Del Giudice, C. Scarpa, O. Lozano, P. Duce, B. Arca, G. Pellizzaro, M. Salis, V. Bacciu, Rapporto sugli incendi boschivi e rurali in Sardegna - Anno 2016, in: Regione Autonoma Della Sardegna – Assessorato Alla Difesa dell'Ambiente, 2017, p. 88. http://www.regione.sardegna.it/documenti/1_274_20170525122956.pdf.
[82] G. Pellizzaro, A. Ventura, B. Arca, A. Arca, P. Duce, Weather Seasonality and Temporal Pattern of Live and Dead Fuel Moisture Content in Mediterranean Shrublands, General Assembly 2009, European Geosciences Union (EGU), Vienna (Austria), 2009, p. 12100, http://meetings.copernicus.org/egu2009.
[83] E. Chuvieco, M. Yebra, S. Jurdao, I. Aguado, F.J. Salas, M. García, H. Nieto, A. De Santis, D. Cocero, D. Riaño, S. Martínez, E. Zapico, C. Recondo, J. Martínez-Vega, M.P. Martín, J. Riva, F. Pérez, F. Rodríguez-Silva, Field Fuel Moisture Measurements on Spanish Study Sites, Department of Geography, University of Alcalá, Spain, 2011. Version 1. Available online at: http://www.geogra.uah.es/emilio/FMC_UAH.html.
[84] M.A. Finney, Fire growth using minimum travel time methods, Can. J. For. Res. 32 (2002) 1420–1424, https://doi.org/10.1139/x02-068.
[85] R.C. Rothermel, A Mathematical Model for Predicting Fire Spread in Wildland Fuels, US Department of Agriculture, Forest Service, 1972. INT-115.
[86] C.E. Van Wagner, Conditions for the start and spread of crown fire, Can. J. For. Res. 7 (1977) 23–34.
[87] J.H. Scott, E.D. Reinhardt, Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 2001, p. 59.
[88] B. Arca, P. Duce, M. Laconi, G. Pellizzaro, M. Salis, D. Spano, Evaluation of FARSITE simulator in Mediterranean maquis, Int. J. Wildland Fire 16 (2007) 563–572, https://doi.org/10.1071/WF06070.
[89] O. Lozano, M. Salis, A.A. Ager, B. Arca, F.J. Alcasena, A. Monteiro, M.A. Finney, L. Del Giudice, E. Scoccimarro, D. Spano, Assessing climate change impacts on wildfire exposure in Mediterranean areas, Risk Anal. 37 (2017) 1898–1916.
[90] P.L. Andrews, F.A. Heinsch, L. Schelvan, How to Generate and Interpret Fire Characteristics Charts for Surface and Crown Fire Behavior, USDA Forest Service, 2011, p. 40.
[91] R.D. Stratton, Guidance on Spatial Wildland Fire Analysis: Models, Tools, and Techniques. Technical Report RMRS-GTR-183, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colo, USA, 2006, 2006.
[92] G. Nudda, P. Botti, F. Tola, M. Chessa, G. Diana, S. Cocco, G. Delogu, M. P. Giannasi, S. Mavuli, F. Congiu, G. Muntoni, A. Pirisi, A. Sattanino, G. Pulina, A. Casula, G. Patteri, G. Bianco, M. Fiori, P. Capece, V. Bacciu, M. Salis, C. Sirca, P. Duce, B. Arca, Rapporto sugli incendi boschivi e rurali in Sardegna - anno 2014, in: Regione Autonoma Della Sardegna – Assessorato Alla Difesa

dell'Ambiente & Centro Euro-Mediterraneo Sui Cambiamenti Climatici, vol. 74, 2015, ISBN 978-889-766-606-6.
[93] S. Bajocco, C. Ricotta, Evidence of selective burning in Sardinia (Italy): which land-cover classes do wildfires prefer? Landsc. Ecol. 23 (2008) 241–248, https://doi.org/10.1007/s10980-007-9176-5.
[94] A. De Angelis, S. Bajocco, C. Ricotta, Phenological variability drives the distribution of wildfires in Sardinia, Landsc. Ecol. 27 (2012) 1535–1545, https://doi.org/10.1007/s10980-012-9808-2.
[95] H.K. Preisler, D.R. Brillinger, R.E. Burgan, J.W. Benoit, Probability based models for estimation of wildfire risk, Int. J. Wildland Fire 13 (2004) 133–142, https://doi.org/10.1071/WF02061.
[96] A.D. Syphard, V.C. Radeloff, N.S. Keuler, R.S. Taylor, T.J. Hawbaker, S.I. Stewart, M.K. Clayton, Predicting spatial patterns of fire on a southern California landscape, Int. J. Wildland Fire 17 (2008) 602–613, https://doi.org/10.1071/WF07087.
[97] M.-A. Parisien, S. Snetsinger, J.A. Greenberg, C.R. Nelson, T. Schoennagel, S. Z. Dobrowski, M.A. Moritz, Spatial variability in wildfire probability across the western United States, Int. J. Wildland Fire 21 (2012) 313–327, https://doi.org/10.1071/WF11044.
[98] T. Ye, Y. Wang, Z. Guo, Y. Li, Factor contribution to fire occurrence, size, and burn probability in a subtropical coniferous forest in East China (last access January 30, 2021), PloS One 12 (2017), e0172110, https://doi.org/10.1371/journal.pone.0172110 (last access January 30, 2021), www.sardegnageoportale.it, https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps, http://interreg-maritime.eu/.
[99] M.C.S. Nunes, M.J. Vasconcelos, J.M.C. Pereira, N. Dasgupta, R.J. Alldredge, F. C. Rego, Land cover type and fire in Portugal: do fires burn land cover selectively? Landsc. Ecol. 20 (2005) 661–673, https://doi.org/10.1007/s10980-005-0070-8.
[100] S. Oliveira, F. Moreira, R. Boca, J. San-Miguel-Ayanz, J.M.C. Pereira, Assessment of fire selectivity in relation to land cover and topography. A comparison between Southern European countries, Int. J. Wildland Fire 23 (2013) 620–630, https://doi.org/10.1071/WF12053.
[101] M. D'Este, A. Ganga, M. Elia, R. Lovreglio, V. Giannico, G. Spano, G. Colangelo, R. Lafortezza, G. Sanesi, Modeling fire ignition probability and frequency using Hurdle models: a cross-regional study in Southern Europe, Ecological Processes 9 (2020), https://doi.org/10.1186/s13717-020-00263-4.
[102] A. Duane, L. Brotons, Synoptic weather conditions and changing fire regimes in a Mediterranean environment, Agriculture and Forest Meteorology 253–254 (2018) 190–202.
[103] C. Belhadj-Khedher, T. El-Melki, F. Mouillot, Saharan hot and dry sirocco winds drive extreme fire events in mediterranean Tunisia (north africa), Atmosphere 11 (2020) 590, https://doi.org/10.3390/atmos11060590.
[104] M. Rodrigues, J.C. González-Hidalgo, D. Peña-Angulo, A. Jiménez-Ruano, Identifying wildfire-prone atmospheric circulation weather types on mainland Spain, Agric. For. Meteorol. 264 (2019) 92–103, https://doi.org/10.1016/j.agrformet.2018.10.005.
[105] M. Billmire, N.H.F. French, T. Loboda, R.C. Owen, M. Tyner, Santa Ana winds and predictors of wildfire progression in southern California, Int. J. Wildland Fire 23 (2014) 1119–1129, https://doi.org/10.1071/WF13046.
[106] A. Cardil, C.S. Eastaugh, D.M. Molina, Extreme temperature conditions and wildland fires in Spain, Theor. Appl. Climatol. 122 (2011) 219–228.
[107] A. Cardil, M. Salis, D. Spano, G. Delogu, D.M. Terren, Large wildland fires and extreme temperatures in Sardinia (Italy), IForest 7 (2014) 162–169.
[108] N.J. Nauslar, J.T. Abatzoglou, P.T. Marsh, The 2017 north bay and southern California fires: a case study, Fire 1 (2018) 18, https://doi.org/10.3390/fire1010018.
[109] M.G. Pereira, R.M. Trigo, C.C. da Camara, J.M.C. Pereira, S.M. Leite, Synoptic patterns associated with large summer forest fires in Portugal, Agriculture and Forest Meteorology 129 (2005) 11–25.
[110] J. Ruffault, V. Moron, R.M. Trigo, T. Curt, Objective identification of multiple large fire climatologies: an application to a Mediterranean ecosystem, Environ. Res. Lett. 11 (2016) 7.
[111] J. Ruffault, V. Moron, R.M. Trigo, T. Curt, Daily synoptic conditions associated with large fire occurrence in Mediterranean France: evidence for a wind-driven fire regime, Int. J. Climatol. 37 (2017) 524–533, https://doi.org/10.1002/joc.4680.
[112] R.M. Trigo, P.M. Sousa, M.G. Pereira, D. Rasilla, C.M. Gouveia, Modelling wildfire activity in iberia with different atmospheric circulation weather types, Int. J. Climatol. 36 (2016) 2761–2778.
[113] M. Rodrigues, R.M. Trigo, C. Vega-García, A. Cardil, Identifying large fire weather typologies in the Iberian Peninsula, Agric. For. Meteorol. 280 (2020) 107789, https://doi.org/10.1016/j.agrformet.2019.107789.
[114] P. Palaiologou, A.A. Ager, C.R. Evers, M. Nielsen-Pincus, M.A. Day, H.K. Preisler, Fine-scale assessment of cross-boundary wildfire events in the western United States, Nat. Hazards Earth Syst. Sci. 19 (2019) 1755–1777.
[115] A.A. Ager, M.A. Day, K. Vance-Borland, N.M. Vaillant, Analyzing the transmission of wildfire exposure on a fire-prone landscape in Oregon, USA, For. Ecol. Manag. 334 (2014) 377–390, https://doi.org/10.1016/j.foreco.2014.09.017.
[116] A.A. Ager, P. Palaiologou, C.R. Evers, M.A. Day, A.M.G. Barros, Assessing transboundary wildfire exposure in the southwestern United States, Risk Anal. 38 (2018) 2105–2127, https://doi.org/10.1111/risa.12999.
[117] F. Alcasena, M. Salis, A.A. Ager, R. Castell, C. Vega-García, Assessing wildland fire risk transmission to communities in northern Spain, Forests 8 (2) (2017) 30, https://doi.org/10.3390/f8020030.
[118] J.H. Scott, M.P. Thompson, J.W. Gilbertson-Day, Examining alternative fuel management strategies and the relative contribution of National Forest System land to wildfire risk to adjacent homes - a pilot assessment on the Sierra National Forest, California, USA, For. Ecol. Manag. 362 (2016) 29–37.
[119] D.X. Viegas, M.F. Almeida, L.M. Ribeiro, J. Raposo, M.T. Viegas, R. Oliveira, D. Alves, C. Pinto, H. Jorge, A. Rodrigues, D. Lucas, S. Lopes, L.F. Silva, O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017, Centro de Estudos sobre Incêndios Florestais da Faculdade de Ciências e Tecnologia da Universidade de Coimbra, 2017, p. 238.
[120] European Commission, Forest Fires - Sparking Firesmart Policies in the EU, 2018, ISBN 978-92-79-77493-5, https://doi.org/10.2777/181450. https://op.europa.eu/en/publication-detail/-/publication/0b74e77d-f389-11e8-9982-01aa75ed71a1/language-en.
[121] M.P. Thompson, J.R. Haas, J.W. Gilbertson-Day, J.H. Scott, P. Langowski, E. Bowne, D.E. Calkin, Development and application of a geospatial wildfire exposure and risk calculation tool, Environ. Model. Software 63 (2015) 61–72, https://doi.org/10.1016/j.envsoft.2014.09.018.
[122] A.A. Ager, C.R. Evers, M.A. Day, H.K. Preisler, A.M.G. Barros, M. Nielsen-Pincus, Network analysis of wildfire transmission and implications for risk governance, PloS One 12 (2017), e0172867, https://doi.org/10.1371/journal.pone.0172867.
[123] S. Oliveira, A. Gonçalves, A. Benali, A. Sá, J.L. Zêzere, J.M. Pereira, Assessing risk and prioritizing safety interventions in human settlements affected by large wildfires, Forests 11 (2020) 859, https://doi.org/10.3390/f11080859.
[124] G. Pellizzaro, B. Arca, G. Pintus, R. Ferrara, P. Duce, Wildland urban interface dynamics during the last 50 years in North East Sardinia, in: D. Spano, V. Bacciu, M. Salis, C. Sirca (Eds.), Modelling Fire Behavior and Risk, Nuova Stampa Color Publishers: Muros), 2012, ISBN 978-88-904409-7-7, pp. 249–254.
[125] C. Sirca, F. Casula, C. Bouillon, B.F. García, M.M. Fernández Ramiro, B.V. Molina, D. Spano, A wildfire risk oriented GIS tool for mapping Rural-Urban Interfaces, Environ. Model. Software 94 (2017) 36–47.
[126] W.J. Elliot, M.E. Miller, N. Enstice, Targeting forest management through fire and erosion modelling, Int. J. Wildland Fire 25 (2016) 876–887, https://doi.org/10.1071/WF15007.
[127] J. Haas, M. Thompson, A. Tillery, J.H. Scott, Capturing spatiotemporal variation in wildfires for improving post-wildfire debris-flow hazard assessments, in: first ed., in: K. Riley, P. Webley, M. Thompson (Eds.), 'Natural Hazard Uncertainty Assessment: Modeling and Decision Support. Geophysical Monograph 223, vol. 20, American Geophysical Union, Washington, DC, USA), 2017, pp. 301–317.
[128] M. Salis, L. Del Giudice, P.R. Robichaud, A.A. Ager, A. Canu, P. Duce, G. Pellizzaro, A. Ventura, F. Alcasena-Urdiroz, D. Spano, B. Arca, Coupling burn probability and erosion models to quantify post-fire erosion before and after fuel treatments: a case study from Northern Sardinia, Italy, Int. J. Wildland Fire 28 (2019) 687–703, https://doi.org/10.1071/WF19034.
[129] A.A. Ager, M.A. Finney, A. McMahan, J. Cathcart, Measuring the effect of fuel treatments on forest carbon using landscape risk analysis, Nat. Hazards Earth Syst. Sci. 10 (2010) 2515–2526.
[130] B.M. Gannon, Y. Wei, L.H. MacDonald, S.K. Kampf, K.W. Jones, J.B. Cannon, B. H. Wolk, A.S. Cheng, R.N. Addington, M.P. Thompson, Prioritising fuels reduction for water supply protection, Int. J. Wildland Fire 28 (2016) 785–803, https://doi.org/10.1071/WF18182.
[131] M.S. Hand, K.M. Gebert, J. Liang, D.E. Calkin, M.P. Thompson, M. Zhou, 'Economics of Wildfire Management: the Development and Application of Suppression Expenditure Models', Springer Briefs in Fire, Springer, New York, 2014.
[132] M.P. Thompson, J.R. Haas, M.A. Finney, D.E. Calkin, M.S. Hand, M.J. Browne, HalekM, K.C. Short, I.C. Grenfell, Development and application of a probabilistic method for wildfire suppression cost modeling, For. Pol. Econ. 50 (2015) 249–258.
[133] F.A. Albini, Estimating Wildfire Behavior and Effects. USDA Forest Service, vol. 30, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR, Ogden, UT), 1976.
[134] M.G. Cruz, M.E. Alexander, Uncertainty associated with model predictions of surface and crown fire rates of spread, Environ. Model. Software 47 (2013) 16–28.
[135] A. Sebastián-López, R. Salvador-Civil, J. Gonzalo-Jiménez, J. San Miguel-Ayanz, Integration of socio-economic and environmental variables for modelling long-term fire danger in Southern Europe, Eur. J. For. Res. 127 (2008) 149–163, https://doi.org/10.1007/s10342-007-0191-5.
[136] A. Benali, A.C. Sá, J. Pinho, P. Fernandes, J.M. Pereira, Understanding the impact of different landscape-level fuel management strategies on wildfire hazard, Forests (2021). In press, https://www.preprints.org/manuscript/202103.0040/v1.