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Research article

Evaluating priority locations and potential benefits for building a nation-wide fuel break network in Portugal

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ABSTRACT

Despite growing interest in developing extensive fuel treatment programs to prevent catastrophic wildfires in the Mediterranean region, there is little information on the projected effectiveness of fuel treatments in terms of avoided exposure and risk. In Portugal, a fuel management plan aiming to prevent loss of lives, reduce large fires (>500 ha), and reduce annual burned area is under implementation, with particular emphasis on the nation-wide fuel break network (FBN). In this study, we evaluated the effectiveness of the planned FBN in terms of meeting fire management objectives, costs, and benefits. We first estimated the overall effectiveness of the FBN at intersecting modeled large fires (>500 ha) and at reducing exposure to protected areas and residential buildings using wildfire simulation modeling. Then, the fuel break burn-over percentage, i.e. the percentage of fires that are not contained at the FBN, was modeled as a function of pre-defined flame length thresholds for individual FBN segments. For the planned FBN, the results suggested a potential reduction of up to 13% in the annual burned area due to large fires (ca. 13,000 ha), of up to 8% in the annual number of residential buildings exposed (ca. 100 residential buildings), and up to 14% in the annual burned area in protected areas (ca. 2400 ha). The expected burn-over percentage was highly variable among the segments in response to estimated fire intensity, and an average decrease of 40% of the total benefits was estimated. The most important fuel breaks typically showed a higher percentage of fire burn-over, and hence reduction in effectiveness. We also showed that the current implementation of FBN follows a random sequence, suboptimal for all objectives. Our results suggest that additional landscape-scale fuel reduction strategies are required to meet short-term national wildfire management targets.

1. Introduction

Extreme wildfires are a well-known source of relevant environmental and socio-economic disturbances (Butry et al., 2001). In recent years, extreme fire seasons have led to historically high extents of burned area and economic losses across countries and regions (e.g. Portugal 2017; California 2018; Australia 2020; Greece, Italy, and Turkey 2021). In several Mediterranean countries, both the total burned area and fire impacts have increased in the last decades as a result of climate and land-use changes, despite an increasing investment in fire suppression resources (Beighley and Hyde, 2018; Bowman et al., 2017; San-Miguel-Ayanz et al., 2019; Tedim et al., 2018). The main drivers include more frequent extreme weather conditions (i.e., severe droughts and heatwaves) during summer seasons, and increases in wildland fuel load and continuity in rural landscapes (Calheiros et al., 2020; Moreira et al., 2020; Williams et al., 2019). The rapid fuel encroachment is largely explained by rural exodus and small community depopulation in remote areas, where traditional management activities such as farming on small properties, extensive grazing, and forest thinning for firewood are used to prevent dead biomass accumulation and shrubland expansion in open lands (Fernandes et al., 2014; Pausas and Fernández-Muñoz, 2012; Viedma et al., 2015).

Given the increase in extreme fire behavior and important environmental and socio-economic losses, the scientific community and landscape wildfire managers advocate for an urgent paradigm shift towards creating more fire-resilient landscapes (Moreira et al., 2020; Wunder

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et al., 2021). One of the most proposed initiatives is the implementation of new (or expansions of existing) fuel break networks (FBN). Fuel breaks are "strategically located wide blocks or strips, on which a cover of dense, heavy, or flammable vegetation has been permanently changed to one of lower fuel volume or reduced flammability" (Green, 1977). These are typically implemented alongside ridges, road networks, and main rivers, facilitating access to suppression vehicles (Agee et al., 2000; Varela et al., 2014a; Zong et al., 2021). In addition, the implementation of a FBN along mountain ridges is expected to decrease the upslope fire spread rate and intensity ahead of reaching the ridgeline, which will, in turn, decrease the probability of spotting over the fuel break and the potential for dangerous and erratic fire behavior caused by reverse wind flows on the lee slope of the ridge (Sharples, 2009). Hence, implementing a nation-wide FBN along ridgelines is likely to increase the effectiveness and safety of wildfire containment operations, promoting adequate fire suppression capacity and safe conditions to engage in firefighting, which ultimately leads to fire containment and significantly decrease in burned areas (Oliveira et al., 2016; Syphard et al., 2011a, 2011b).

The implementation of FBN and firebreaks (i.e., strips of bare soil) have been employed as fire control strategies worldwide (Ager et al., 2019b; Morgan et al., 2020; Pilliod et al., 2021; Syphard et al., 2011b; Zong et al., 2021), and are a regular practice in the Mediterranean region (Ascoli et al., 2018; Xanthopoulos et al., 2006). In southern Europe, fuel breaks of 6–40 m wide were implemented in coastal pine forests in the late 19th century and later expanded to hinder fire growth (Oliveira et al., 2016), and currently, wildfire spread is mainly reduced through the forest compartmentalization by FBN (Varela et al., 2014b).

In Portugal, the 2017 fire season was particularly harsh, causing a record-breaking area burned of 557 thousand ha, 119 fatalities, thousands of structures destroyed, and over 1456 million euros in economic losses (Guerreiro et al., 2018; Ribeiro et al., 2020). This motivated the Portuguese authorities to develop a new 10-year fuel management plan to reduce national wildfire risk (AGIF, 2020; RCM, 2021), where a nation-wide FBN is expected to play an important role. Nevertheless, the contribution of the FBN under construction to short-term national targets is largely unknown.

In this study, we used modeled fire perimeters and intensity (Alcasena et al., 2021) to assess the benefits of the Portuguese nation-wide FBN. Despite being widely suggested and implemented across fire-prone countries, studies on FBN benefits in the Mediterranean region are rare (but see Oliveira et al., 2016). Specifically, we conducted the intersections between the FBN and modeled fire footprints to assess the burned area decline and exposure reduction in residential buildings and protected natural sites. Next, we used simulated flame lengths in the adjacent areas to account for exceeding fire intensity conditions at which active suppression efforts in the FBN are inefficient, thereby failing to aid fire containment. Exposure reduction results were then used to estimate the FBN cost-efficiency by transect. Finally, we compared ongoing treatments with a 5-year implementation sequence prioritized by segment based on the effectiveness of FBN segments. We discuss how the modeling framework and its results can be used to

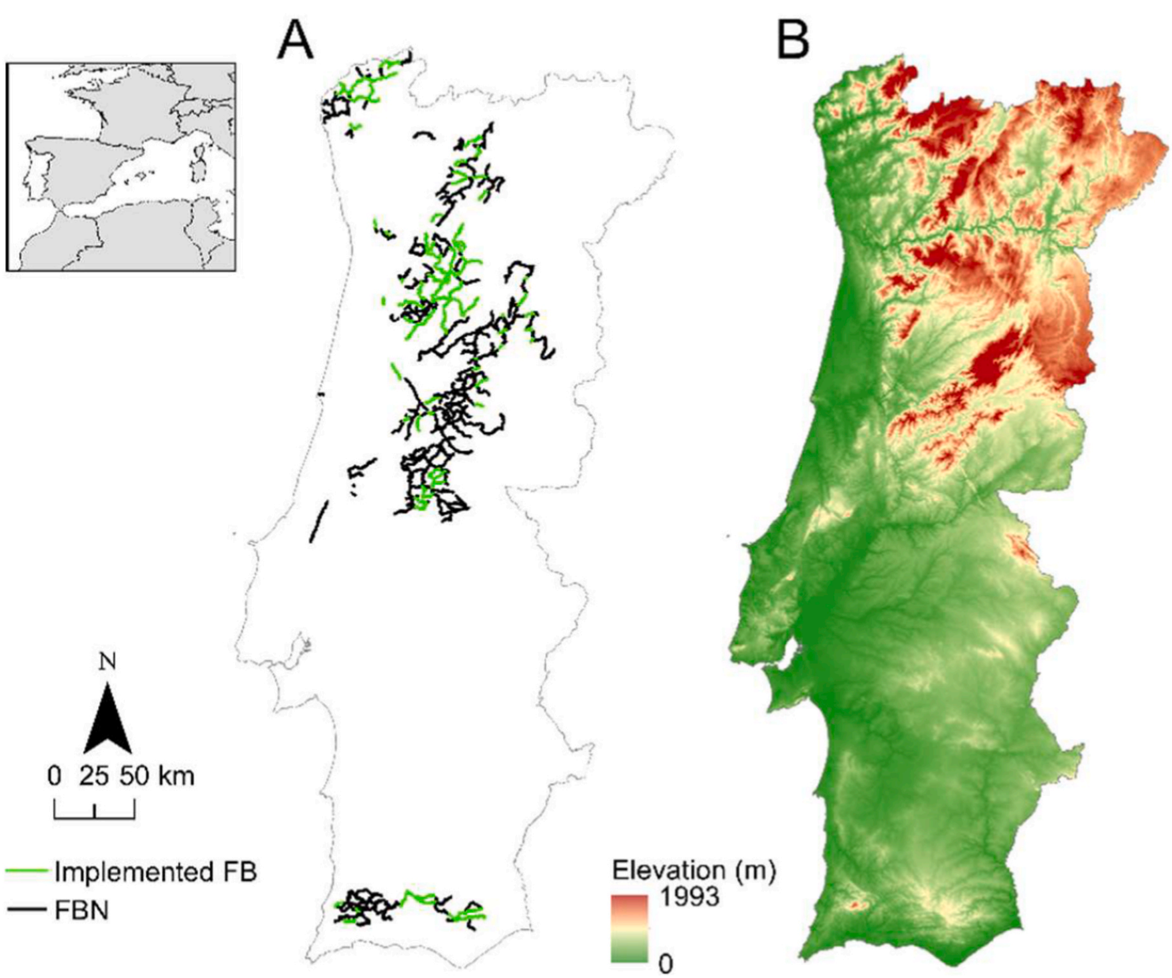

Fig. 1. Location of mainland Portugal and mapping of the planned fuel break network (FBN; black) and of the implemented FBN segments (green) during the period 2018–2020 (A) and elevation (B; Farr et al., 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

support the implementation of the nationwide FBN as a relevant fire management strategy, and existing synergies with landscape-scale fuel treatment projects. The methods presented in this work may result valuable for evaluating the fuel break systems in any fire-prone areas elsewhere.

2. Material and methods

2.1. Study area

The study was conducted for mainland Portugal (Fig. 1), with an area of 88,889 km^2. The population is unevenly distributed across the country, with more than half (over 5 million) living in Lisbon, Coimbra, Braga, and Porto main metropolitan areas. The climate is classified under Köppen's system as Mediterranean hot summer (Csa – mostly located in south of Tagus river) and Mediterranean warm summer (Csb – mostly located in the north of Tagus river). The dominant land cover types in Portugal are forests (39%), croplands (26%) and shrublands (12%) (DGT, 2018a). The northern and central regions of Portugal have ca. 65% and ca. 75% of the country's total forest and shrubland areas, respectively. Conifer forests (*Pinus pinaster* Aiton. and *Pinus pinea* L.) and *Eucalyptus globulus* Labill. plantations are the main forest types in coastal sites and northern areas, while interior mountainous areas have a mosaic of grasslands and shrublands with scattered patches of deciduous forests of *Quercus pyrenaica* Willd. and *Castanea sativa* Mill.

In Portugal, between 1980 and 2019 more than 4.6 million ha burned, with particular incidence in the years 2003, 2005, and 2017 (San-Miguel-Ayanz et al., 2020). On average, about 137 thousand ha burned each year in Portugal for the period 2001–2019. The majority of the burned area is due to ca. 10% of the fires (Royé et al., 2020). Moreover, fire occurrence is unevenly distributed, with the central and northern regions having higher fire frequency and susceptibility (Oliveira et al., 2021).

2.2. Portuguese fire management objectives and fuel break network

The Portuguese 2020–2030 fuel management plan proposes three strategic objectives (AGIF, 2020; RCM, 2021): 1) reduction of the cumulative burned area to less than 660,000 ha; 2) reduction of the percentage of fires larger than 500 ha to less than 0.3% of the total number of fires; and 3) reduction of loss of lives in rural fires to a rare event. To achieve these and related objectives, the plan proposes the expansion of fuel management programs targeting rural areas and the implementation of a fuel break network (FBN).

Initially, a total of 10,761 km, primarily along mountain ridges, were mapped as candidates for the FBN. Then, a set of priority segments were selected to be implemented based on various criteria, such as historical fire regime, local expert knowledge, predominant wind direction, fuel type, proximity to communities, ecological and economic value, and costs (Oliveira et al., 2016; Pereira and LePage, 2019). As a result, the network was reduced to 3538 km, corresponding to ca. 44,500 ha (0.5% of the total extent of Portugal) (Fig. 1). Currently, the FBN is still under implementation. The existing implementation status of the FBN was assessed from remote sensing data, as described in Aubard et al. (2020). Between 2018 and 2020 an average of ca. 9500 ha yr^{-1} (a total of ca. 28, 000 ha) was implemented in mountain ridges (but only ca. 8000 ha/944 km implemented in the planned FBN, corresponding to ca. 25% of the total). In this work, we evaluated the full extent of the network.

Technical specifications for the FBN prescribed a minimum width of 125 m (MAMAOT, 2014), with tree cover density gradually decreasing from the outer edge of the FBN segments to the middle, ensuring horizontal discontinuity of the tree stratum (Aubard et al., 2020). The innermost 10 m on each side of the central road should have vegetation totally removed (herbaceous, shrubs, and trees). In the remaining FBN segments, vertical fuel discontinuity must be guaranteed by pruning the lower branches of trees and by periodical reduction of understory fuels (Aubard et al., 2020).

2.3. Residential building and protected areas data

Data on residential buildings were obtained as spatial points from the Instituto Nacional de Estatistica (INE, 2011). The total number of residential building locations across mainland Portugal was about 3.3 million structures. We excluded for the analysis the buildings located in non-burnable urban and industrial developed areas (i.e., artificial land-covers; DGT, 2018b). We used the 2021 version of nationally designated protected areas in Portugal to identify sites of particular environmental interest (EEA, 2021). The different designation classes in protected sites included national parks, nature reserves, protected landscapes, natural monuments, and private protected areas. Mainland Portugal has 109 protected sites, covering 12,197 km^2, or about 14% of the country area.

2.4. Wildfire simulation data

We used the wildfire simulation modeling library published in a previous study (Alcasena et al., 2021). This study used the minimum travel time algorithm (MTT; Finney, 2002) as implemented in the FconstMTT command-line program to replicate observed fire size distribution and annually burned areas in mainland Portugal. The MTT algorithm is a mechanistic wildfire spread modeling system that calculates two-dimensional fire growth by searching for the set of pathways with minimum fire spread times from the cell corners. The algorithm models fire spread using Rothermel's equation (1972), and fire intensity is then converted to flame length (Byram, 1959). The MTT has been widely used in previous works to model fire spread and behavior in Mediterranean areas (Alcasena et al., 2019; Palaiologou et al., 2020; Sá et al., 2022; Salis et al., 2021).

The library contains an extensive set of simulated fire perimeters (n = 1,654,448) plus a 100 m spatial grid with fire intensity records corresponding to 10,000 years or modeled iterations. The fire ignitions were located within the modeling domain assuming historically based ignition densities. Each fire is modeled individually, keeping the weather conditions constant during the entire burn period. Only extreme fires escape the initial attack, and therefore, fire modeling was conducted assuming 99th percentile fire-weather conditions (i.e., winds and fuel moisture content) by 14 predefined pyroregion. Such weather conditions are similar to those observed during Portugal's 2017 catastrophic wildfire season (Guerreiro et al., 2018). The modeled set of fires showed a fairly good agreement with observed historical fire perimeters, which burned 97% of the pixels at least once, and more than 150 times on average. See further details in supplementary material A.

2.5. Estimating the fuelbreak burn-over percentage

The burn-over is the fuelbreak segment length or area failing to contain the wildfire spread, either active or passively. In this work, we used fire intensity and annual burn probability data to estimate the burn-over percentage in each FBN segment. We first calculated the annual burn probability using simulated fire perimeters as:

$$aBP = \frac{N_{xy}}{Y} \tag{1}$$

where the *aBP* is the pixel-level annual burn probability, N_{xy} is the number of times the *xy*-th pixel is burned from surface fires, and *Y* is the number of modeled years (n = 10,000) (Finney et al., 2011). Then, we estimated the burn-over as:

$$BO = \frac{\sum FLP_{>2.5\ m} \times aBP}{\sum FLP_i \times aBP} \times 100 \tag{2}$$

where the *BO* is the burn-over area in each fuelbreak segment as a percentage, FLP_i is the flame length probability of a fire at the *i*-th flame length category (Ager et al., 2014), and *aBP* is the annual burn probability. The library provides pixel-level fire intensity estimates as FLPs for 0.5-m flame length 20-bin categories. Flame length is calculated in each fire spread simulation using the rate of spread and the fireline intensity, following Wilson's modification (Wilson, 1980) of Byram's equation (Byram, 1959) for SI units, as detailed in Ager et al. (2011). We calculated the burn-over within a 200 m buffer area for each segment, assuming a 2.5-m flame length fire containment threshold. Fire intensity is widely used as a proxy for fire suppression difficulty (Alexander and Cruz, 2018). Flame lengths over a 2.5 m threshold will likely enable crown fires to launch embers over the 125-m wide linear treatments, hence decreasing the effectiveness of the fuelbreaks (see supplementary material B; Alexander and Lanoville, 1989,; Tedim et al., 2018).

The burn-over percentage was later used to estimate the containment success by segment (i.e., calculate the worst-case scenario considering a partial or total failure) for the different management objectives and national targets. We estimated the 95% confidence interval for each FBN segment using Monte Carlo sampling from the probability distribution of the flame lengths at each pixel. This adjustment allows providing a lower bound for the benefits of the fuelbreaks and better characterize the network.

2.6. Estimating FBN effectiveness

For the planned FBN we used the simulated fire perimeters intersected with the FBN segments to perform a series of the following analyses. First we estimated the potential effectiveness by estimating the reduction in: 1) burned area from large fires (>500 ha); 2) number of residential buildings exposed to fires; and 3) burned area inside protected areas. The effectiveness was calculated under two different scenarios: a full containment scenario that assumes that no possible burn-over and suppression at the fuelbreak is successful (a fire will always stop when intersecting a fuelbreak); and a burn-over scenario that assumes the possibility for partial or total burn-over of the fuelbreak (as explained above). The analysis was performed at the scale of individual fuel breaks, where the segments intersected by each fire perimeter were first identified, and then ranked by their benefit per unit length of the fuel break, namely in terms of the estimation of avoided burned area due to large fires (>500 ha); avoided exposure of residential buildings to fire; and avoided burned area in protected areas. Each fire perimeter was intersected with the FBN, resulting in several split fire footprints. The fire footprint containing the ignition point is kept for the analysis, while the other fire footprints are deleted, representing the fire stop at the FBN. When two or more fuel break segments are required to separate the fire perimeter, the benefit (avoided burned area, avoided exposure of residential buildings to wildfires and avoided burned area in protected areas) is proportional to the length of intersection between the fire perimeter and the fuel break segment. We assumed that fire spread is not affected by the FBN whenever a fire perimeter is not completely intersected by the FBN.

Lastly, we estimated how well the planned FBN would meet the national fuel management objectives for 2020–2030 (AGIF, 2020; RCM, 2021), namely that: 1) the percentage of fires extending across more than 500 ha stays below 0.3% of the total number of fires; and 2) the cumulative burned area extent over a decade is less than 660,000 ha (66, 000 ha yr^{-1}). Objective 2 was quantified by identifying the area burned by each individual large fire until its intersection with a FBN segment. The annual burned area avoided was then calculated as the difference between the burned area without and with the planned FBN. We then estimated the cost-efficiency of implementing the fuel breaks and the avoided suppression cost.

2.7. Fuel treatment and fire suppression cost

We estimated the fuel treatment cost in the planned FBN based on available cost rates (CAOF, 2016; Junta de Extremadura, 2022). The cost was essentially determined based on fuel types (herbaceous, shrubland, conifer and broadleaved forests), slope intervals (<5, 5 to 25, and >25%), and canopy cover classes (<50, 50 to 65, 65 to 80, and >80%). We assumed that surface fuels would be reduced with prescribed burning, except for broadleaved forests, where we considered mechanical mastication. The tree canopy cover was thinned to 50% as described in the fuelbreak treatment technical specifications (MAMAOT, 2014). The cost ranged from about 100 € ha^{-1} in open grasslands to over 2500 € ha^{-1} in dense broadleaved forests, located in steep slopes and requiring thinning operations (see details in supplementary material C).

We used data for the total suppression cost and total burned area for the period of 2013–2016 (the latest period available; data for individual years are not available) (CTI, 2017) to assess the avoided cost of suppression. We calculated the annual suppression cost per hectare burned by dividing the suppression cost for the period considered by the burned area (in hectares) for the same period. The annual suppression cost was then updated to 2020 values using the annual inflation rate for Portugal (Inflation, 2022). Between 2016 and 2020 the inflation rate for Portugal was 2.7%, with 2020 as the only year with a negative inflation value. The suppression costs avoided were calculated using the difference between the estimated annual burned area with and without the FBN.

2.8. Treatment prioritization and tradeoff analysis

To understand how strategic prioritization of the planned FBN according to fire simulation outputs might increase the effectiveness during implementation, we simulated a five-year implementation scenario. In this scenario, the planned FBN was implemented by treating ca. 9500 ha annually, which matched the implementation rate over the 2018–2020 period. A scheduling scenario of implementation was created for each objective (i.e. avoided burned area by large fires, avoided exposure of residential buildings to fire and avoided burned area in protected areas) based on the ratio between the effectiveness of each FBN segment and its length. These prioritization scenarios were compared against a null scenario where FBN segments were implemented randomly over the five years. This way, the potential benefits of prioritizing the implementation according to fire simulation outputs could be assessed.

We also evaluate tradeoffs between prioritizing implementation of the planned FBN based on avoided burned area, avoided exposure of residential buildings to fire, and avoided burned area in protected areas measured as a total per-unit cost. We simulated 11 scenarios using a weighting scheme for each of the three objective metrics. Here, each objective was weighted pairwise (weights ranging from 0 to 1 with increments of 0.1; if objective A = 0.4, objective B = 0.6, etc.) and used to prioritize the implementation sequence of FBN segments. The tradeoffs were calculated per year of implementation, excluding the last year, when the tradeoff would be null. This method of assessing tradeoffs was adapted from Ager et al. (2019a).

3. Results

3.1. Wildfire behavior adjacent to fuelbreaks

About 27% of the area adjacent to the FBN had flame lengths between 2.5 and 3.5 m, and about 3% of the area had flame lengths between 3.5 and 10 m (representing an average of 30% of burn-over percentage). Flame length >2.5 m was assumed to exceed the containment threshold as established by Tedim et al. (2018) and were considered to burn-over the fuel break (Table B1). This analysis shows that ca. 70% of the total number of FBN segments (representing ca. 75% of the FBN length) have at least 25% of the adjacent area capable to generate flame lengths >2.5 m (i.e. 25% of burn-over). Most of these FBN segments are located in Portugal's central and northern regions. FBN segments with at least 50% of the neighbouring area capable of generating flame lengths >2.5 m are mostly located in central Portugal (Fig. 2).

3.2. Estimating FBN effectiveness

Under the full containment scenario, the annual burned area due to large fires was reduced by 13% (ca. 13,000 ha), the annual number of residential buildings exposed was reduced by 8% (ca. 104), and the annual burned area inside protected areas was reduced by 14% (ca. 2400 ha). Considering the burn-over scenario translated into an annual increase of 4800 ha area burned by large fires, 38 additional residential buildings exposed, and additional 900 ha area burned inside protected areas than estimated under the full containment scenario. This represents a FBN effectiveness reduction of 40% in terms of area burned by large fires, as 35% of these fires were not expected to be contained.

Regarding the area burned due to large fires that is avoided, the effect of expected burn-over percentage on the effectiveness of the planned fuel breaks was concentrated in the central-northern region (Figure D2 A). Overall, the high burn-over percentage in ca. 4% of the FBN segments (ca. 7% of the total length of FBN) is responsible for ca. 30% of the total decrease in FBN benefits for this objective.

For the objective of avoiding exposure of residential buildings to wildfires, the FBN segments with the highest exposure reductions are spatially distributed across the country, with important FBN segments located in the north, center and south regions (Figure D2 B). For this objective, the burn-over percentage in ca. 3% of the FBN segments (ca. 5% of the length FBN) is responsible for ca. 40% of the total decrease in the FBN benefits.

Finally, for the objective of avoiding burned area inside protected areas, the FBN segments with the highest reductions are mostly located in the northern region of Portugal (Figure D2 C). The burn-over percentage in ca. 5% of the FBN segments (ca. 9% of the total length of FBN) is responsible for ca. 70% of the total decrease in the FBN benefits for this objective.

In terms of national targets, the contribution of the FBN implementation for the reduction in the proportion of large fires (>500 ha) was 0.04% under the full containment scenario and 0.026% when considering the burn-over scenario. For the objective of reducing the total burned area to an average of 66,000 ha yr^{-1}, implementing the FBN was estimated to reduce the annual burned area by 13,000 ha for the full containment scenario, and 8100 ha when considering the burn-over scenario (Table 1).

Figure D1 (supplementary material D) shows the fire size up to the moment of intersection between large fires and the planned FBN. As illustrated, only ca. 25% of the large fires are intersected before burning less than 500 ha. In fact, most fires are intersected after burning between 500 and 2500 ha. Consequently, despite the planned FBN being able to avoid a considerable extent of area from burning each year, the full implementation of the planned FBN has a limited effect in reducing the proportion of fires larger than 500 ha (Table 1).

3.3. Prioritization and tradeoff analysis

The cumulative response to implementing FBN segments according to their contribution to fire management objectives showed a declining marginal value, with a sharp increase in the early years of implementation, until reaching a plateau (Fig. 3). The point where the curve converges differs considerably among objectives, with the reduction in large fires reaching the plateau in the last year of implementation compared to the 4th year and the beginning of the 5th year for residential buildings. The reduction in burn area inside protected areas plateaus after two years of implementation. Comparing scenarios where fuel break segments are prioritized according to their contribution to management objectives considering the full containment scenario *versus* random prioritization shows that the latter generates linear benefits with increasing treatments and that the current state of FBN implementation is within the random scheduling scenario. The differences in the effectiveness of implementing the FBN listed above can also be observed in Fig. 3 (solid line representing the effectiveness under the full containment scenario and the dashed line representing fire burn-over scenario). The large variability of these estimates derived from Monte Carlo sampling using the probability distribution of the burn-over percentage suggests that these effects could be considerably higher or lower, with ca. 20% variability. Additionally, the current FBN implementation is not following the scheduling suggested by the experts at the moment of its design (Supplementary Material Figure D3).

Fig. 4 shows the spatial allocation of the FBN segments per year of implementation and per objective. As expected, the location of the priority FBN segments is dependent on the defined objective: when aiming to reduce burned area due to large fires, the most important FBN segments are located in central-northern Portugal; when aiming to avoid annual exposure of residential buildings, the most priority FBN segments are not only identified in the central-northern region, but also in the Algarve region, in southern Portugal; under the objective of avoiding the annual burned area inside protected areas, the FBN segments that should be implemented first are located in northern Portugal, with some relevant clusters in central and southern Portugal.

The potential reduction in effectiveness due to extreme fire behavior was also quantified for the FBN segments, grouped by year of implementation. For all objectives, the FBN segments with the highest burn-over percentage are scheduled for implementation in the earlier years (Figure D4). For example, for avoiding burned areas due to large fires, the burn-over percentage represents almost 50% of the area outside the FBN segments scheduled for implementation in the first year. For the objective of avoiding burned area inside protected areas, only the first two years of implementation show a similar pattern to that described previously. This is because, by the second year of scheduling, the maximum benefit for that objective would already have been fulfilled, and the remaining FBN segments are irrelevant for the overall effectiveness (see Fig. 3).

Fig. 5 shows the tradeoffs per year of implementation between different levels of prioritization given each one of the objectives. All groups show that even when a given objective has full priority over the others, there still are benefits for the non-priority objective. The tradeoffs between the objectives of avoiding burned area due to large fires and avoiding exposure of residential buildings were found to be the smallest. In contrast, the greatest tradeoffs were obtained when coupling the objectives of reducing burned area inside protected areas and reducing exposure of residential buildings.

3.4. Cost-efficiency of fuel break segments and avoided suppression costs

The cost per km of implementing the FBN varied substantially among FBN segments, from a minimum of about 550 € km^{-1} (excluding FBN segments surrounded by unburnable areas) to a maximum of ca. 21,000 € km^{-1}, with a mean cost of ca. 5000 € km^{-1} (Fig. 6). The lowest values were found for FBN segments in low-slope, open areas, or forested land edges, where thinning was not required and prescribed fire can be directly used to reduce surface fuels. The most expensive fuel break segments were located in dense broadleaved forests on steep slopes, which were assumed to require expensive manual thinning followed by mechanical mastication to meet the standards in the fuel treatment prescriptions. The segments estimated to generate the most significant benefits for all the objectives mostly had costs near the average value (ca. 5000 € km^{-1}). The lack of correlation between cost and the estimated benefits for the implemented portion of the FBN (Fig. 6) shows that the current implementation is not being conducted as would be expected based on the fire simulation outputs.

The analysis of avoided costs from suppression revealed possible annual savings of 4–6 million € (depending on priority of objectives – Fig. 5) after the first year of implementation. After the full implementation of the FBN, the annual savings from avoided suppression costs due to large fires can reach 11 million €.

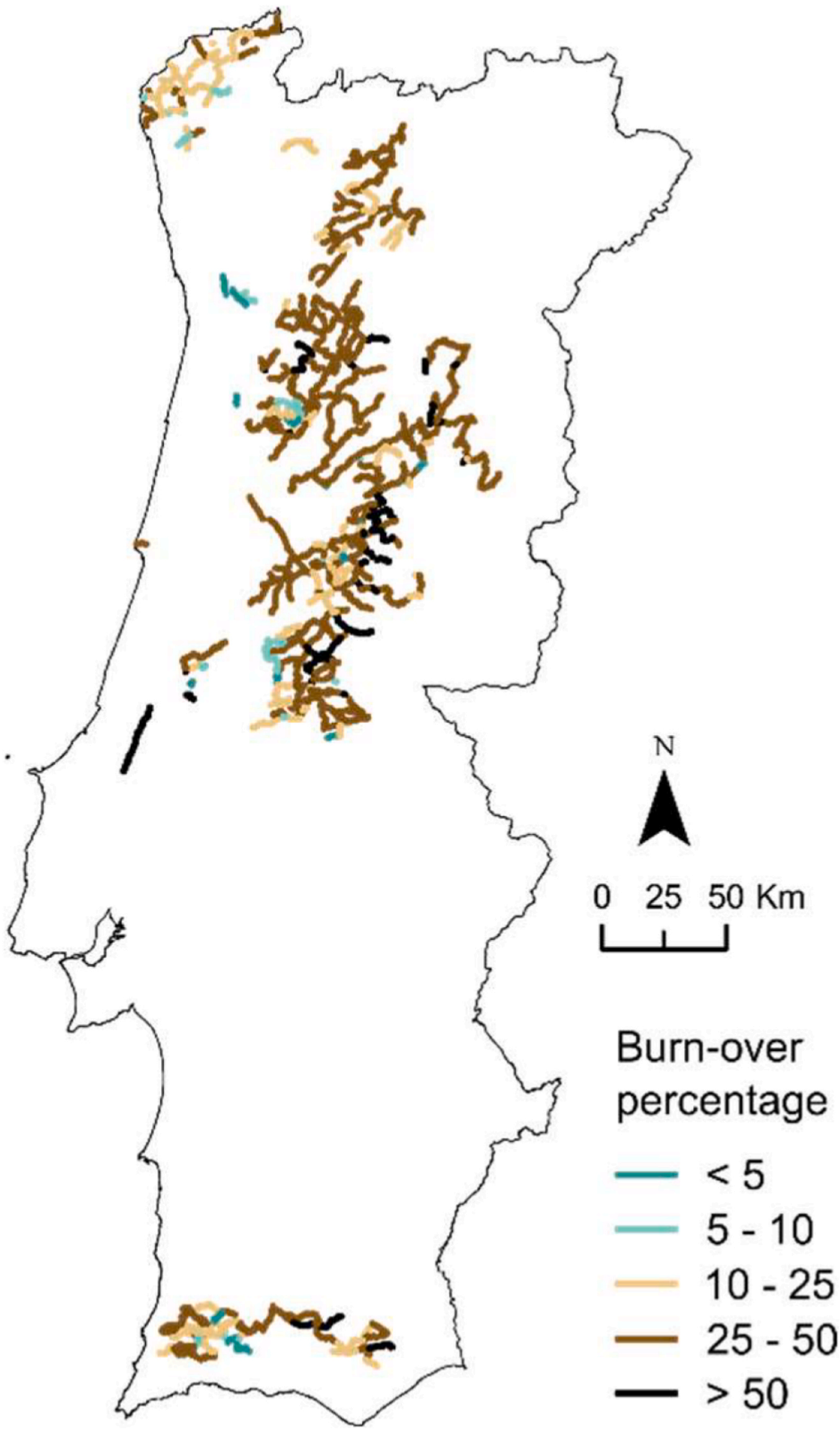

Fig. 2. Map of the planned FBN in Portugal with segments displaying the burn-over percentage.

Table 1
Estimated effectiveness of the planned FBN relatively to national fire management objectives described in the Portuguese fuel management plan for 2020–2030 (AGIF, 2020; RCM, 2021). Current conditions were characterized using dated fire perimeters in Benali et al. (2016). This database was updated to 2019 and complemented with additional satellite imagery analysis and field data analysis. *indicates that the value is only due to large fires (>500 ha).

	Current conditions (2001–2019)	Δ After FBN	
		Full containment scenario	Burn-over scenario
The percentage of wildfires that burn-over 500 ha is less than 0.3% of the total wildfires	0.66%	−0.04%	−0.026%
The total burned area (in 2020–2030) is lower than 660,000 ha (average 66,000 ha yr^{-1})	137,000 ha y^{-1}	−13,000* ha yr^{-1}	−8100* ha yr^{-1}

4. Discussion

Linear fuel breaks and firebreaks (i.e., strips of bare soil) are a common practice in the Mediterranean fire-prone areas (Xanthopoulos et al., 2006). This landscape compartmentalization is currently the main strategy to reduce wildfire spread (Varela et al., 2014b). Despite their wide applications, FBN are often criticized, and studies about their potential effectiveness are rare in the scientific community. In this study, we examined the potential benefits of implementing a nation-wide FBN in a fire-prone Mediterranean country. We evaluated the benefits of Portuguese FBN, which is a key part of the national fuel management plan, and estimated its effectiveness using fire spread modeling. The costs and benefits of implementing the FBN were quantified using multiple analytical methods and effectiveness metrics.

Our results showed that the full implementation of the Portuguese FBN could provide significant contributions to the proposed fire management objectives of the country, i.e., a 13% reduction in annual burned area due to large fires, a 8% reduction in the annual number of residential building exposure, and a reduction of 14% in annual burned area in the protected areas at the assumed maximum effectiveness of the FBN (i.e., fire containment). However, our analysis revealed that the effectiveness of the FBN in decreasing large fires (>500 ha) was marginal. This indicates that the planned FBN is not dense enough to intercept fires at the early stages before they become large fires.

The results of prioritized implementation showed a declining marginal value for all objectives with a sharp increase in the early years of implementation. Compared to the objective of avoiding burned areas in protected areas, meeting the objectives of avoiding burned area due to large fires and avoiding exposure of residential buildings was more dependent on the amount of FBN segments implemented, reflecting the widespread risk of large fires and fire exposure of residential buildings across the country (Alcasena et al., 2021; Ferreira-Leite et al., 2013; Oliveira et al., 2020, 2021). The objectives of avoiding burned area due to large fires and reducing the exposure of residential buildings were found to be most dependent on the full implementation of the FBN. Such results reflect both the potential of large fires to occur in all regions of Portugal (Ferreira-Leite et al., 2013; Oliveira et al., 2021) and the great number of exposed residential buildings across the country (Alcasena et al., 2021; Oliveira et al., 2020). Our study allowed to identify clusters of highly effective FBN segments across objectives in central and north of Portugal, which is the region known for a high fire incidence and susceptibility (Oliveira et al., 2021; Tonini et al., 2017). Our analysis also revealed that the effect of the current implementation sequencing of FBN segments is not significantly different from that of a random scenario, suggesting that better cumulative effects can be achieved if the effectiveness is considered in the implementation sequencing and

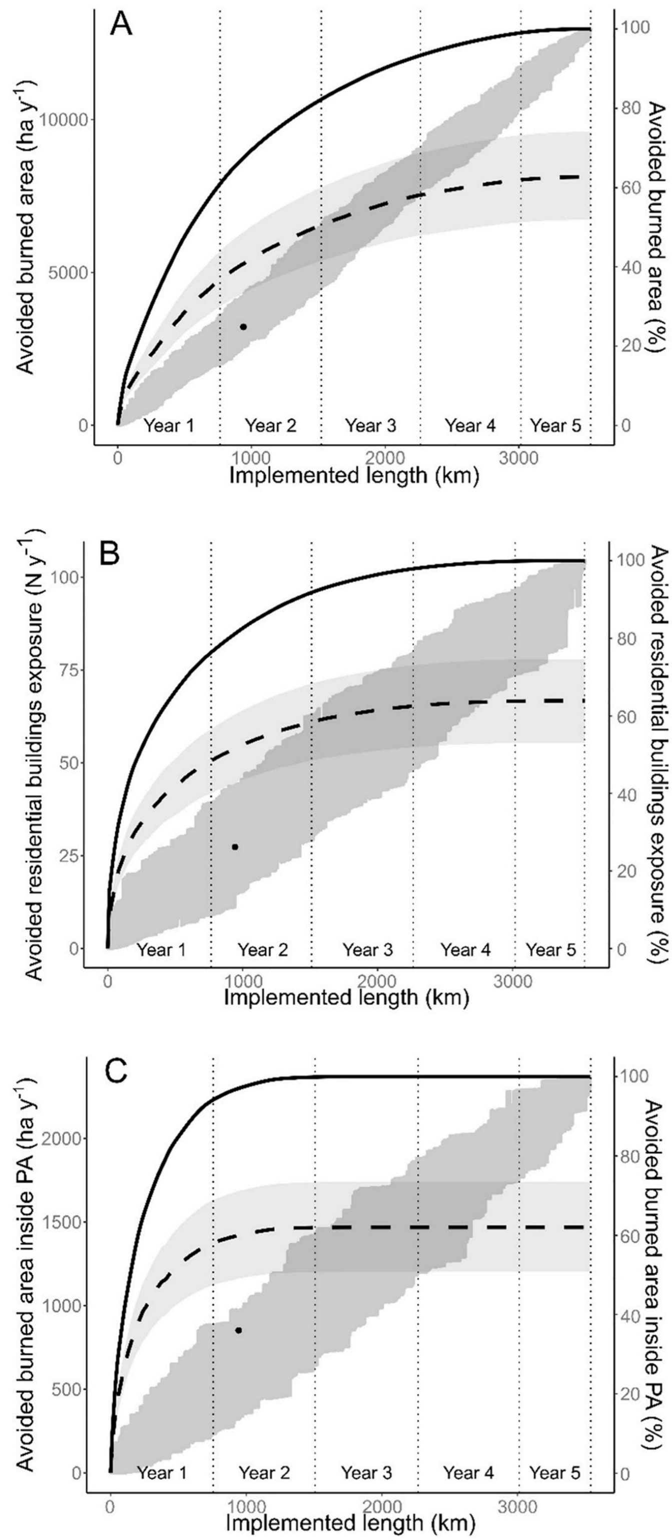

Fig. 3. Cumulative annual effect of FBN implementation for avoided burned area due to large fires (A), avoided exposure of residential buildings (B), and avoided burned area inside protected areas (PA) (C). The solid line represents the optimal implementation scenario for each criterion; the dark grey area represents 100 random scenarios of implementation; and the solid dot represents the current stage of FBN implementation (identified in Fig. 1). All these elements consider that the FBN is always effective at stopping the fire spread. The dashed line represents the optimal implementation scenario after adjusting each FBN segment's effectiveness given the fire behavior and spotting distance in its surroundings (i.e. burn-over percentage); the light grey area following the dashed line represents the 95% confidence envelope.

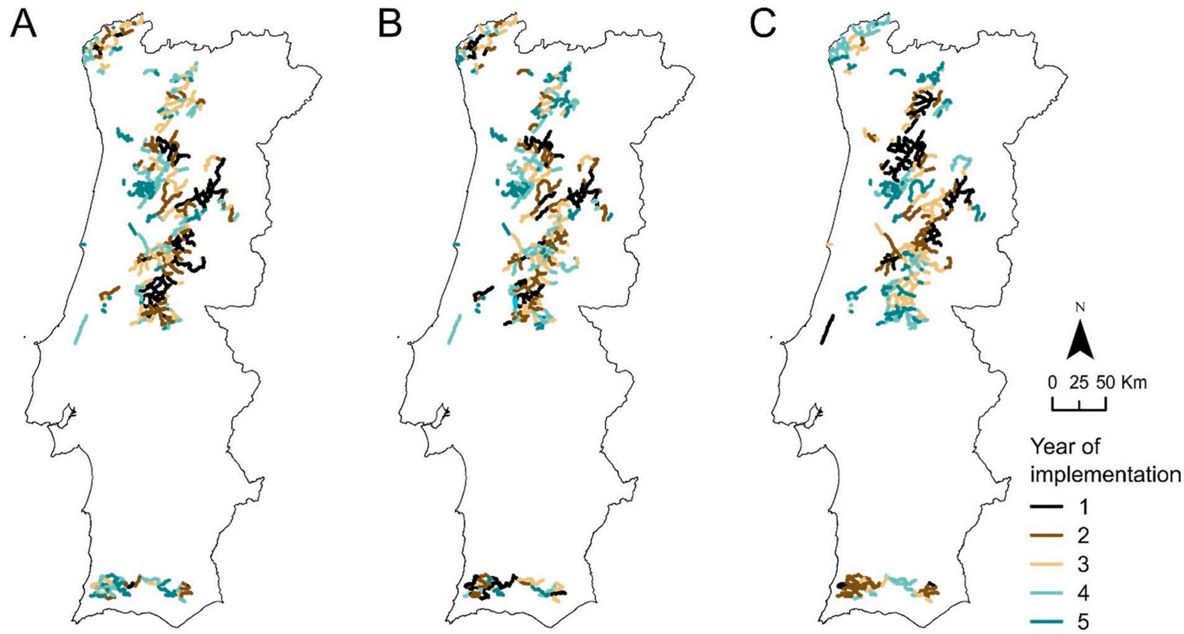

Fig. 4. Prioritization of the implementation of FBN segments per year, under the criteria of avoiding the annual burned area due to large fires (A), avoiding the annual exposure of residential buildings (B), and avoiding the annual burned area inside protected areas (C).

prioritization process of FBN segments.

This study identified the FBN segments with high burn-over percentage caused by extreme fire behavior under severe weather conditions. Extreme fire behavior (as indicated by the burn-over percentage) can jeopardize the safety of firefighters and ignite new fires over the FBN through intense crowning and long-distance spotting (Alexander and Cruz, 2018; Alexander and Lanoville, 1989,; Tedim et al., 2018). When assessing the effectiveness while allowing burn-over percentage, the benefits of the FBN were dropped by almost 40% on average for the three objectives studied, and 35% of the large fires may not be stopped by the FBN, even assuming full readiness of fire suppression operations. This estimate is at the lower end of the range reported for the past fires that did not stop or change their behavior when intersecting with FBN (Syphard et al., 2011b). This approximation to the minimum empirical value is possibly due to the assumptions of permanent FBN maintenance and the readiness of fire suppression operations, which were shown to be crucial factors to stop fire spread (Syphard et al., 2011b).

The tradeoff analysis among the three objectives revealed that compromises may occur between the objectives. Tradeoffs involving fire management and ecological objectives are long known to practitioners (e.g. Ager et al., 2019a; Hartsough et al., 2008). Our analysis shows that the objectives of avoiding burned area inside protected areas and avoiding the exposure of residential buildings yielded the greatest tradeoffs. This may be due to the low residential density near or within the protected areas. On the other hand, the objectives of avoiding burned area due to large fires and avoiding exposure of residential buildings to fire appeared to yield relatively small tradeoffs between the two objectives, indicating that many FBN segments can contribute to both objectives simultaneously.

Prior studies of fuel treatment effectiveness in the Mediterranean region are rare. A prior study in Portugal (Oliveira et al., 2016) examined the effectiveness of fuel break segments in the country's southern region. This study found that a regional FBN could reduce the overall fire size by up to 17%, conditional burn probability by up to 31%, and burned area by up to 17%. However, the authors did not consider wildfire burn-over in high intensity areas in their study. In contrast, a more recent study in Portugal showed that prescribed fire treatments, despite having a high rate of intersection with fires, are insufficient to reduce wildfire growth due to small areas treated and small size of treatment units (Davim et al., 2021). The prescribed burning treatments in Portugal described in this study are mainly located in the northern and central Portugal mountains, characterized by rough terrain, and high occupancy by flammable forest types and shrublands, which have been leading to frequently large fires (Fernandes, 2019; Fernandes et al., 2012; Oliveira et al., 2012).

The cost-efficiency analysis of FBN segments showed that implementation costs vary greatly among individual segments and they are not necessarily proportional to the effectiveness. Our methodology introduced in this study can be used to identify and prioritize FBN segments for maximum cost-efficiency, providing a guide and needed data for informed decision-making regarding FBN implementation.

4.1. Management implications

Our study highlights two most highly relevant findings for FBN and fire management. First, the results showed that a relatively small portion of the FBN can largely contribute to the objectives, which highlights the importance of strategic location of the FBN segments in realizing the maximum benefits. Once the implementation of the FBN is finished, these highlighted FBN segments should be monitored and regularly maintained to avoid fuel build-up. Because the maintenance of FBN is often the most likely element to fail in the fuel reduction plans (Agee et al., 2000; Schimke and Green, 1970), identifying these FBN segments can help prioritize the maintenance actions, ultimately preventing the FBN failure.

Second, widespread high burn-over percentages indicate that the FBN itself may not be sufficient to substantially reduce the spread of large fires and thus needs to be integrated with ecological restoration treatments outside the FBN to reduce the intensity and size of wildfires in key sites (Castro Rego et al., 2021). We suggest that prescribed burning and preventive silviculture designed to decrease fire spread and intensity should be implemented outside (but synchronized with) the FBN to improve the effectiveness and enhance the safety of fire suppression operations (Alcasena et al., 2018; Rouet-Leduc et al., 2021). The easy access to the surrounding areas of the FBN can also decrease the cost of prescribed burns, increasing the potential for synergies. Additionally, the afforestation of the areas nearby the FBN with fire-prone tree species that potentially project embers and that are easily

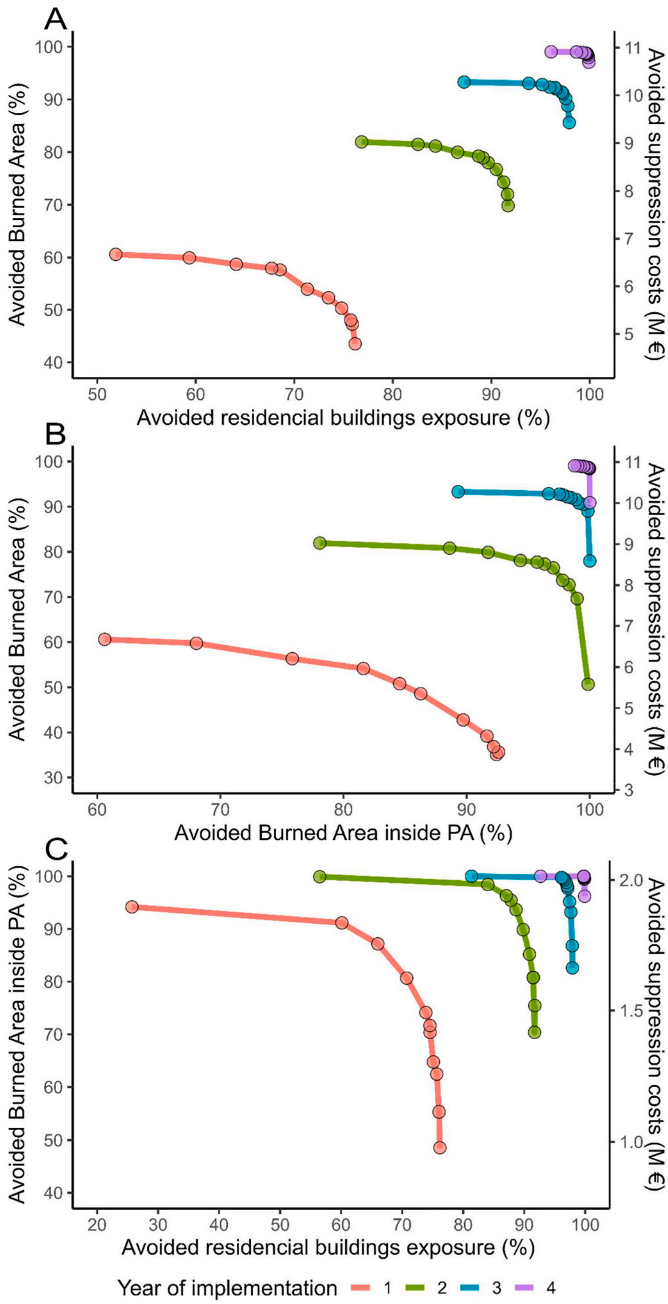

Fig. 5. Tradeoffs between the different objective considered: avoided burned area due to large fires and avoided exposure of residential buildings (A), avoided burned area due to large fires and avoided burned area inside protected areas (B), and avoided burned area inside protected areas and avoided exposure of residential buildings (C). The secondary y-axis represents the avoided suppression costs (€) under each scenario, following the avoided burned area and the avoided burned area in protected areas. Each point has corresponding value in the three axis. Each line corresponds to sequent years of implementation (1st to 4th). The implementation is cumulative, i.e., for example the tradeoffs in the second year contain the FBN segments implemented during the first year and those implemented in the second year.

ignited by them must be avoided (Della Rocca et al., 2018; Viegas et al., 2014). The areas with high burn-over percentages or important high-benefit yielding fuel break segments can be identified and prioritized to ensure early and maximum realization of the benefits.

4.2. Limitations and assumptions

We acknowledge important limitations in our fire spread simulation modeling and assumptions about fuel break burn-over percentage. First, fire simulations represented a snapshot of the existing landscape when the model was built. This means that the predictions of fire models may only be useful for a narrow time window due to vegetation growth and fuel accumulation in recently burned areas, the occurrence of new fires, and land use changes. A clear example is the western Algarve region, south Portugal, where FBN segments were highlighted as effective in reducing annual exposure to residential buildings from wildfires and annual burned area inside protected sites, but not for the overall burned area from large fires. This result may seem counter-intuitive, as the western Algarve region is known for generating mega-fires in the past (Oliveira et al., 2016; Tedim et al., 2013, 2015). However, the occurrence of a mega-fire in 2018 that burned more than 27,000 ha, mainly affecting eucalypt plantations, cork oak woodlands, and shrublands in the region (OTI et al., 2019), significantly reduced the amount of fuel load and, consequently, lowered the probability of the occurrence of large fires in our fire simulations conducted based on post 2018 fire conditions.

Several assumptions were also made regarding the effectiveness of the FBN for stopping fires. First, we created the full containment scenario under the assumption that all fires would be stopped when the fire perimeter is intersected and dissected by FBN segments. This represents the most optimistic scenario, since it assumes the readiness of firefighters in the FBN segments to suppress the fire, which may not be always possible due to the high number of simultaneous occurrences or high number of complex events during critical periods of fire seasons (CTI, 2017). We also assumed FBN segments would be continually maintained and easily accessible as needed. All these factors were proven to be essential for controlling large fires (Syphard et al., 2011a, 2011b). Second, we assumed a threshold value of flame length >2.5 m to define the burn-over percentage. Although one can argue that the threshold used may underpredict the effectiveness of the FBN, we argue that this represents a conservative approach to quantify the benefits of FBN that contrasts with the values obtained when considering the full containment scenario (optimistic scenario). We advocate that the values from both analyses must be interpreted together, as they are able to provide an expected interval of the contribute of FBN in meeting the national objectives for the decade. We further argue that providing an interval of benefits for the FBN is more informative than a simple value assuming a full containment, even acknowledging the uncertainty in assigning fuel models, fuelbed loads, and a fixed threshold to define burn-over.

Despite the limitations above, we believe our results still provide valuable information for planning and implementing the FBN. The fire simulation model was carefully calibrated to reproduce the fire regime in different areas of Portugal (Alcasena et al., 2021). Many FBN segments in Portugal were purposely placed on the mountain ridges for their recognized effects on decreasing upslope fire-spread rate and intensity, and decreasing the probability of spotting over the fuel break and the potential for dangerous and erratic fire behavior (Sharples, 2009). Moreover, the FBN was projected with a road in the innermost portion, which allows the access to the FBN segment by the firefighters, and hence increasing their probability of successfully controlling a fire (Agee et al., 2000), and ultimately stopping the fire spread (Oliveira et al., 2016; Syphard et al., 2011a). Given the legal commitment (Portuguese fuel management plan for 2020–2030) in implementing and maintaining the FBN and in improving the effectiveness and efficiency of fire suppression (AGIF, 2020), the assumptions employed in this study are considered reasonable and supportable.

5. Conclusions

Extensive fuel treatment programs such as FBN have been

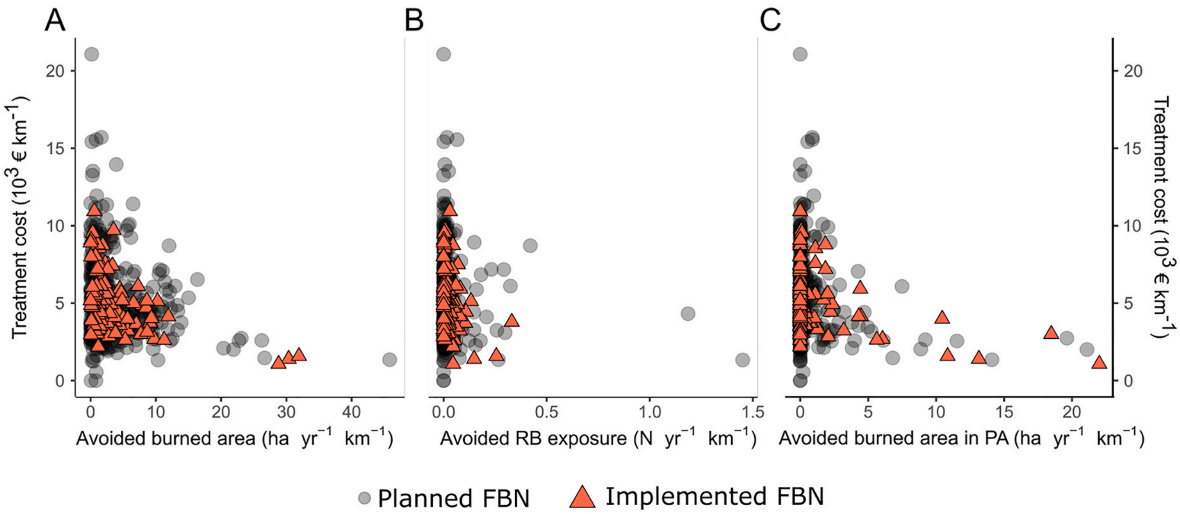

Fig. 6. Treatment cost (€) and extent of annually burned area reduction due to large fires (A), exposure of residential buildings (B), and burned area reduction in protected areas (C) per FBN segment length (in km). Grey circles represent all the planned FBN segments and the orange triangle represent the FBN segments already implemented. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

implemented widely in Mediterranean countries for decades, despite the lack of information on the projected effectiveness of fuel treatments in decreasing exposure and risk. We presented a framework that quantifies FBN effectiveness and identifies the FBN segments with the highest burn-over percentages. Given the wide geographical application of FBN, we advocate that this study is of particular relevance to all fire-prone regions where FBN are (or are planned to become) a relevant part of fire mitigation strategy.

Altogether, we show that the FBN has the potential to play an important role in meeting the fuel management objectives for 2020–2030 in Portugal, especially if integrated with an ecological restoration plan. However, to date a large majority of the FBN has not been built (Aubard et al., 2020), and doubts still remain about the benefits of implementing a nation-wide FBN. Although we share these concerns, the fact that in Portugal (and in most southern European countries), forest land is mostly privately owned (Pulla et al., 2013), are mostly fragmented into small parcels, and often abandoned or lacking management (Beires et al., 2013), might support the implementation of FBN as the most feasible fuel reduction strategies in the short-term.

Credit author statement

Bruno A Aparício: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Fermín Alcasena**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Alan Ager**: Conceptualization, Methodology, Software, Resources, Supervision, Writing – review & editing. **Woodam Chung**: Conceptualization, Resources, Supervision, Writing – review & editing. **José M C Pereira**: Validation, Data curation, Supervision, writing—review and editing. **Ana C L Sá**: Validation, Data curation, Supervision, writing—review and editing.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

8. Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115920.

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