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Synergistic effects on fire hazard from combined linear fuel breaks and mosaic fuel treatments

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Abstract

Background Designing large-scale fuel reduction programs has increasingly become a complex planning process owing to multifaceted fire management objectives that vary in space and time. In many fire-prone systems, fuel management strategies rely on fuel break networks (FBN) and fuel treatment mosaics (FTM) to mitigate wildfire impacts. While both archetypes are being widely implemented as part of newer fire management initiative, managers must decide how to allocate investments to best achieve desired long-term outcomes. This problem creates a new spatial prioritization paradigm that has long-term implications on fire management but has yet to be explored in sufficient detail to make management recommendations. In this study, we simulated treatment scenarios in four diverse regions in Portugal where the two archetypes were simultaneously implemented under different spatial arrangements to understand how they can be combined to reduce fire hazard.

Results The results indicated that co-implementation of FTM in the vicinity of FBN significantly improved multiple wildfire management metrics including containment probability, reduction in burned area and high-intensity fire occurrence. This synergistic effect was observed across the spectrum of land use types ranging from forest to agro-pastoral regions and associated fire regimes. The overall contribution of the FBN to reducing burned area was higher in forest-dominated areas whereas FTM had a consistent impact in terms of reducing high-intensity burned area.

Conclusions The results suggest that optimizing the co-implementation archetypes needs to consider local land use patterns and associated fire regimes to optimize investments in the alternative fuel management archetypes.

Keywords Fuel break networks, Fuel reduction treatments, Fuel treatment mosaics, Landscape restoration, Spatial optimization

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Resumen

Antecedentes El diseño de reducción de combustibles a gran escala está resultando en procesos de planeamiento complejos debido a los diferentes y multifacéticos objetivos de manejo del fuego que varían en tiempo y espacio. En muchos ecosistemas propensos al fuego, las estrategias de manejo de los combustibles se basan en redes de barreras de combustibles (FBN) y tratamientos de combustible en mosaicos (FTM) para mitigar los impactos de los incendios de vegetación. Aunque ambos arquetipos están siendo ampliamente implementados como parte de una nueva iniciativa para el manejo del fuego, los gestores de incendios deben decidir cómo y dónde ubicar esas aplicaciones para lograr alcanzar los resultados deseados en el largo plazo. Este problema crea un nuevo paradigma de priorización espacial que tiene implicancias a largo plazo en el manejo del fuego, aunque deben todavía explorarse con suficiente detalle como para hacer recomendaciones de manejo. En este estudio, simulamos escenarios de tratamientos en cuatro regiones diversas de Portugal donde estos dos arquetipos fueron simultáneamente implementados bajo diferentes arreglos espaciales, para entender cómo ambos pueden ser combinados para reducir el riesgo de incendios.

Resultados Los resultados indican que la co-implementación de FTM en la vecindad de FBN mejora significativamente las múltiples métricas en lo que hace al manejo del fuego, incluyendo la probabilidad de contención, la reducción del área quemada, y la disminución en la ocurrencia de fuegos de alta intensidad. Este efecto sinérgico fue observado a través de un espectro de tipos de uso de la tierra que variaba desde bosques a regiones agro-pastoriles y sus regímenes de fuego asociados. La contribución general del FBN a la reducción del área quemada fue mayor en las aéreas dominadas por bosques, mientras que el FTM tuvo un impacto consistente en términos de reducción de la alta intensidad del área quemada.

Conclusiones Los resultados sugieren que la optimización de la co-implementación de arquetipos necesita considerar patrones de uso local de la tierra y sus regímenes de fuego asociados para optimizar las aplicaciones en el manejo alternativo de ambos arquetipos.

Background

In recent years, an increase in the occurrence of large and severe wildfires has been observed around the globe, especially in the Mediterranean basin (Mitsopoulos et al. 2016; Ribeiro et al. 2020), California (Li and Banerjee 2021), Australia (Abram et al. 2021), and Canada (Parisien et al. 2023). The warming climate and more frequent and longer hot and dry summer conditions coupled with fuel accumulation has catalyzed increasingly severe fires seasons (Turco et al. 2017; Barbero et al. 2015). Extreme wildfires are having significant deleterious impacts on multiple ecosystem conditions including substantial loss of aboveground biomass (Price et al. 2022), changes in species composition, structure and dynamics of plant communities, and others that collectively threaten ecosystem resiliency and the ecosystem services (Batllori et al. 2019). A growing number of extreme wildfires have also resulted in loss of human lives and assets as fire spread into and throughout developed areas (Molina-Terrén et al. 2019).

Many countries are beginning to adopt aggressive fire management policies that implement a panoply of key actions including prevention programs to reduce ignitions and strategic fuel reduction to enhance suppression effectiveness and improve wildfire resilience (Pandey et al. 2023). Fuel reduction programs are targeting multiple treatment archetypes (Ager et al. 2013) with a focus on linear fuelbreak networks (FBN) and fuel treatment mosaics (FTM) (AGIF 2020; Ministry of Environment and Energy Greece 2022; Pandey et al. 2023; USDA Forest Service 2022). FBN are defined as "strategically located wide blocks or strips, on which a cover of dense, heavy, or flammable vegetation" (Green 1977) is changed to reduce fuel volume and flammability. The main objective of FBN is to allow for effective and safe fire suppression activities, ultimately aiming to reducing burned areas and mitigate fire risk (AscoLi et al. 2018; Oliveira et al. 2016; Xanthopoulos et al. 2006). Empirical and simulation studies have shown that FBN is not always a barrier to fire spread and require active suppression to provide robust protection (Young et al. 2024; Gannon et al. 2023; Syphard et al. 2011a; 2011b). Even with fire suppression resources in the FBN, burning embers can jump over fuel breaks, depending on their width and surrounding topography, or the fire may be too intense to allow for safe and effective suppression (Zong et al. 2021; Agee et al. 2000; Gannon et al. 2023; Ortega et al. 2024; Wollstein et al. 2022; Weise et al. 2023).

By contrast, FTM are designed to modify the spatial patterns of fuels over larger landscapes and thus have broader socioeconomic and ecological objectives than facilitating suppression (Gray and Dickson 2016). FTM are used to fragment patterns of hazardous fuels to reduce spread rates and fire intensity (Ott et al. 2023). Both archetypes can enhance resilience to wildfire.

Despite the fact that most national fire management initiatives are investing in both types of treatment archetypes (AGIF 2020; Pandey et al. 2023), there is a lack of guidelines and research on how they can be co-implemented to realize synergistic benefits. For instance, in Portugal both archetypes are being employed with their respective prioritization under the guidance of multiple agencies, leading ad hoc approach at best (AGIF 2020). Together with other preventive strategies (such as reduction in ignitions), it is expected that fuel reduction treatments will contribute considerably to the objectives of the Portuguese 2020–2030 fuel management plan (AGIF 2020), namely (1) reduction of the cumulative burned area by half; (2) reduction of the percentage of fires larger than 500 ha by half; and (3) reduction of loss of lives in rural fires to a rare event.

In this study, we examined alternative prioritization strategies for FBN and FTM archetypes in Portugal to understand the potential for their synergies as measured by the reduction in burned area and related fire management goals. Portugal is the country in the Mediterranean region with the highest recorded extent of burned areas over the last decades (Turco et al. 2017). Between 1980 and 2022, more than 4.8 million hectares burned in Portugal (an area that is more than half of area of mainland Portugal), with notable peaks in 2003, 2005, and 2017 (San-Miguel-Ayanz et al. 2020). On average, around 130,000 ha burned annually in Portugal between 2001 and 2022, with approximately 10% of the fires accounting for the great majority of area burned (Royé et al. 2020). We used a spatial optimization model to create alternative implementation scenarios where FBN were re-enforced by additional FTM dispersed in the surrounding landscape. The effects on fire behavior were examined in relation to fire frequency and intensity to identify interactions with local fire regimes. Our methods and results provide a decision support framework to improve the co-implementation of divergent treatment archetypes currently underway on highly diverse Mediterranean landscapes.

Methods

Study area

The research was conducted in four different study areas in Portugal (Fig. 1): Serra da Cabreira (North), Serra da Estrela (Center), Pinhal Interior Sul (Center), and the area containing Serra de Monchique (hereafter Serra de Monchique; South). The study areas were chosen to sample the diverse fire regimes and vegetation types in Portugal. Serra da Cabreira primarily experiences a fire regime characterized by pastoral burns, with small areas subjected to small fires in forests and peri-urban areas; and an average annual area burned of 1926 ha (annual maximum of 6700 ha) for the period 2000–2022. Pinhal Interior Sul and Serra de Monchique exhibit a fire regime mainly characterized by high-intensity forest wildfires, and fires in croplands to a lesser extent. In the period 2000–2022, the annual average of burned area in Pinhal Interior Sul was 10,459 ha (annual maximum of ca. 81,000 ha), and in Serra de Monchique was 5316 ha (annual maximum of 68,000 ha). Serra da Estrela site represents the most heterogeneous fire regime, dominated by forest wildfires, but with significant area where pastoral lands and cropland are regularly burned, and to a lesser extent, small peri-urban fires (Fig. 1 and Figure SM1 and SM2) (Pereira et al. 2022). For the same period, an annual average of 11,322 ha burned in Serra da Estrela (annual maximum of ca 57,000 ha). Pastoral burns represent a "pre-industrial" fire regime, where the main cause of fire are burns for pasture renewal. Peri-urban small fires represent fires in the wildland-urban interface, where conditions for large fires are limited, but small fires can cause substantial losses and damages. Forest wildfires represent an "industrial" fire regime, characterized by sporadic (intervals of ± 25–40 years – Oliveira et al. 2012) but large and intense fires that occur in continuous areas with high fuel loads. Cropland burns represent the fire regime where fire incidence is lower and, generally, less problematic, with its main cause related with clearing of agricultural lands.

According to DGT (2018), Serra da Cabreira and Serra da Estrela are dominated by shrublands, followed by forests (coniferous and broadleaved, mainly eucalyptus). The Pinhal Interior Sul and Serra de Monchique are dominated by forests (coniferous and broadleaved, respectively; Figure SM3).

Wildfire simulation model

We used the Minimum Travel Time algorithm (MTT) (Finney 2002) as implemented in the FConstMTT command line version to model fire growth in Portugal. The MTT algorithm is a 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. MTT uses Rothermel's Eq. (1972) to model fire spread. Flame length is calculated using Byram's equation (Byram 1959). Flame length is considered a proxy of suppression difficulty and spotting activity (Tedim et al. 2018). The MTT has been widely used in previous studies to model fire spread and behavior with multiple applications in Mediterranean areas (Alcasena et al. 2019; Palaiologou et al. 2020; Sá et al. 2022).

In a previous study, Alcasena et al. (2021) divided mainland Portugal into 14 pyro-regions to parameterize the simulation model based on homogeneity of weather conditions, particularly prevailing winds during the fire

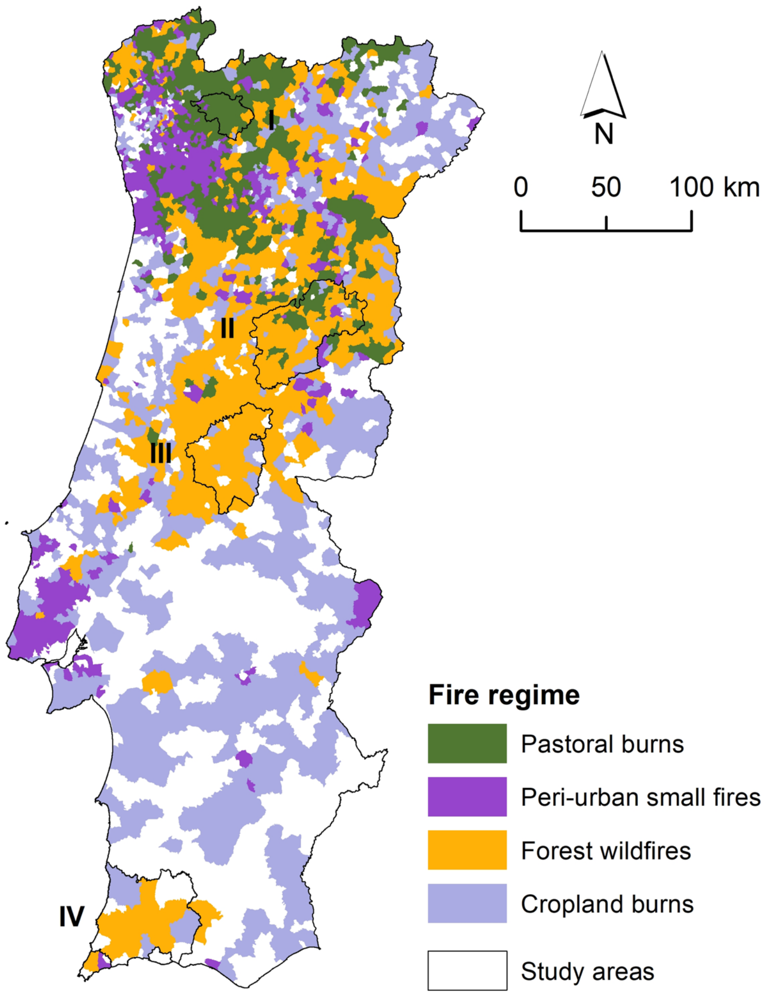

Fig. 1 Fire regimes in Portugal and the study areas. I—Serra da Cabreira; II—Serra da Estrela; III—Pinhal Interior Sul; IV—Serra de Monchique. White areas represent locations with a low fire occurrence and hence, without a classification. Fire regimes were adapted from Pereira et al. (2022) and include Pastoral burns, Peri-urban small fires, Forest wildfires and Cropland burns

season. We refined the pyro-region boundaries using newer fire regime maps (Pereira et al. 2022) and ancillary information. Wildfire simulations were run for each pyro-region that enclosed each of the 4 study areas ($n = 15$ pyro-regions; Figure SM4).

Fire simulation inputs

The Fconstmtt model requires inputs on fire weather, topography, fuel models and canopy cover, and ignitions (Ager et al. 2011). We derived fire weather conditions from prior large fires (≥ 100 ha) that burned between 2001 and 2022 (ICNF 2023). Fire perimeters were dated from satellite imagery following Benali et al. (2016a, b). For each fire, we extracted hourly weather variables from ERA5-Land climatology (Muñoz-Sabater et al. 2021). Weather data for simulating fires included wind speed, direction, temperature, and relative humidity. Topography (elevation, slope, and aspect) was derived from the European Digital Elevation Model (EEA 2017). Surface fuel models (Fernandes et al. 2009) were mapped following the methodology proposed by Sá et al. (2023); this approach uses data from multiple sources, including land use/land cover data from COS2018 (DGT 2018) and Corine 2018 (EEA 2018a). The fuel model classification corresponded to the typology developed by Fernandes et al. (2009) for Portugal, with two additional model types from Anderson (1982), representing dense pine regeneration stands and light logging slash. The initial fuel model assignments were adjusted based on recent disturbances (e.g., time elapsed since the last fire), and based

Table 1 Fuel treatment scenarios analyzed to quantify interactions between fuel treatment mosaics (FTM) and linear networks (FBN). In the "FBN + FTM Compact," 75% of the FTM are implemented within 1000 m from the fuel break and 25% of the FTM are implemented outside the 1000-m buffer; in the "FBN + FTM intermediate," 50% of the FTM are implemented within 1000 m from the fuel break and 50% of the FTM area implemented outside the 1000-m buffer; in the "FBN + FTM dispersed," 25% of the FTM are implemented within 1000 m from the fuel break and 75% of the FTM are implemented outside the 1000-m buffer; in the "Only FBN," only the 2/3 of the FBN segments are implemented; and in the "Only FTM," only the FTM are implemented. Note that in the "Only FTM" scenario, fuel treatments can be placed anywhere in the landscape as the FBN is not considered. In all scenarios, 20% of the treatable area in each study area was treated as FTM

Scenario name	Percentage of FTM implemented outside the 1000-m buffer (away from FBN)	Percentage of FTM implemented inside the 1000-m buffer (in the vicinity of FBN)	Spatial representation
FBN + FTM Compact	25	75	
FBN + FTM intermediate	50	50	
FBN + FTM dispersed	75	25	
Only FBN	-	-	
Only FTM	-	-	
Control	-	-	No treatments

on bioclimate and lithology information (Sá et al. 2023). Tree cover density was characterized using the European Environment Agency 2018 data (EEA 2018b). All fuels inputs and fire simulations were conducted at a spatial resolution of 100 m.

An ignition probability grid (100 m) was generated using historical ignitions obtained from the Forest Fire Information Management System (ICNF 2023) and augmented with data from MAPA (2016) and Mahood et al. (2022). The data were filtered to include fires ≥ 100 ha and covered the period 2001–2021. The data were smoothed using kernel density tool (ArcMap version 10.7.1) by setting a search radius defined by the peak distance identified by using the Incremental Spatial Autocorrelation tool. The search distance varied between pyro-regions based on Moran's *I* test (Alcasena et al. 2021). Details on the calibration of MTT fire spread model are shown in Sect."Study area"of Supplementary Material.

Scenarios

We simulated two distinct spatial fuel management archetypes, namely linear fuel breaks (FBN) and fuel treatment mosaics (FTM) and measured the performance in terms of reduction in area burned, area burned at high intensity (flame length ≥ 2.5 m), and number of fires contained at the FBN (detailed in section "Response variables"; see Figure SM5 for full list of landscape fuel management archetypes). Specifically, we created three scenarios to evaluate the synergies between FTM and FBN, differing from the proximity of FTM to the FBN: "FBN + FTM compact", where the majority of percentage FTM are placed close to the FBN rather than dispersed in the landscape; "FBN + FTM dispersed," where the majority of the FTM are dispersed across the landscape rather than close to the FBN; and "FBN + FTM intermediate", representing a balanced distribution of FTM (see Table 1 for more details).

The location of FTM within a buffer of 1000 m from the FBN is related to the calculation of the burn-over probability (described below). The spatial location of FTM is shown in Figure SM6. After locating the projects in the landscape the map of fuel models was modified to reflect management, following the rules detailed in Table SM2.

To create the fuel management scenarios, we assumed that only 2/3 of the planned FBN extent in each study area would be implemented, in accordance with the directives from the ICNF. The segments were selected based on their importance in reducing the burned area, following the methodology detailed in Aparício et al. (2022). This included intersecting the simulated fire perimeters with the FBN and assigning a value of avoided burned area to each FBN segment. The success in stopping the fire at the intersection is then calculated based on fire intensity in areas close to the FBN, with the assumption that the larger the extent of high-intensity fire close to the FBN, the lower the probability of containing the fire at the intersection (see section "Response variables" for more details).

FTM projects were optimized with a modified version of ForSys (Day et al. 2023) that wraps the Forsys-DLL in a R package (Aparício et al. 2024a, b). ForSys locates parcels (or treatment units) that maximize one or more objectives subject to constraints and treatment thresholds. The ForSys algorithm utilizes a greedy search approach, evaluating each parcel as a seed to create fuel reduction projects across the surrounding landscape (ForSys 2024). This search process continues by incorporating adjacent parcels until the project area constraint is fulfilled. Hence, neighboring parcels are joined into a project of area defined by the user. The optimality of ForSys solutions was evaluated against mathematical programming formulations, revealing that ForSys results were within 5–10% of the absolute optimum for single-objective scenarios (Ager 2024). ForSys has been applied in multiple contexts and geographies (Palaiologou et al. 2021; Michele Salis et al. 2016; USDA Forest Service 2022). The objective set in ForSys was to reduce the Conditional flame length (CFL; the equation is shown below) in the landscape, estimated from the fire spread simulations. Project size was defined as 50 ha. The total treated area corresponds to 20% of the treatable area at each study site, as it was showed in the past that this is a good balance between treatment intensity and effects (Finney et al. 2007). The areas defined as treatable exclude urban areas, water bodies, agriculture, and the defined 2/3 of the FBN.

The map of fuel models was modified to represent the changes in the landscape following the hypothetical fuel reduction treatments. These modifications are detailed in Table SM2. The creation of the scenarios is consistent with the Portuguese 2020–2030 fuel management plan (AGIF 2020).

Response variables

We processed the fire simulation outputs to derive three response metrics, namely area burned, area burned at high intensity, and number of fires contained at the FBN. To calculate the area burned, the results were annualized as follows:

$$\mathrm{aAB} = \frac{\text{total area burned}}{\text{N fire seasons}}$$

where aAB is the annual area burned, the total area burned is the sum of the area burned by all simulations in the pyro-region, and the N fire seasons is the number of fire seasons simulated (minimum of 10,000). Single FConstMTT fire simulations are independent from each other. This means that we did not truly simulate a minimum of 10,000 fire seasons, but rather we simulated thousands of independent fires that together represent the area burned expected after a minimum of 10,000 fire seasons. The area burned at high intensity was calculated as:

$$\mathrm{aABHI} = \frac{\text{total area burned with FL>2.5m}}{\text{N fire seasons}}$$

where aABHI is the annual area burned at high intensity, the total area burned with FL > 2.5 m is the sum of the area burned at high intensity in the pyro-region. Both area burned and area burned at high intensity were chosen given their relevance for policy targets (burned area – e.g., AGIF 2020) and following previous recommendations of quantifying area burned by high-intensity fires as a measure of the effectiveness of FTM (Fernandes 2015; Moreira et al. 2020).

Conditional flame length (CFL) was also estimated from the fire simulation as:

$$\mathrm{CFL} = \sum_{i=1}^{20} (\mathrm{FLP_i})(\mathrm{FL_i})$$

where FLPi is the flame length probability of a fire at the ith flame length class (20 classes, from 0 to > 9.5 m with a 0.5-m increment) and FLi is the midpoint of each of the 20 ith classes. CFL has been used as a proxy for fire hazard as it represents the probability-weighted flame length given that a fire occurs (e.g., Salis et al. 2013). CFL was calculated using flame length grids generated for each fire footprint by FConstMTT.

The FBN success rate was calculated from the burn-over probability (Aparício et al. 2022), which reflects

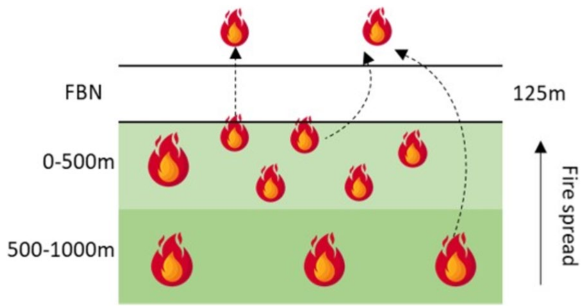

Fig. 2 Illustration of the burn-over in the FBN. The flame length thresholds used for burn-over probability was ≥ 2.5 m for the distance of 0–500 m, and ≥ 3.5 m for the distance of 500–1000 m (the size of the flames in the illustration represent the flame length threshold considered). A burn-over is set to possibly occur whenever the flame length is high enough to jeopardize fire suppression activities, resulting in the fire burning through the FBN (calculated for the 0–500 m; dashed straight line) and/or when the fire intensity is high enough to generate spotting across the FBN (calculated for 0–500 m and 500–1000 m; dashed curve line). The FBN success rate was calculated considering the fire spread direction, i.e., only considering the surrounding landscape where the fire is burning instead of the traditional buffer

the likelihood of FBN successfully contain the wildfire spread, based on fire intensity. Segments in FBN can fail in containing fires due to high fire intensity that preclude fire suppression activities in the FBN or due to ember projections originating new fires across the FBN (Fig. 2). In both cases, we consider that a fire burn-over occurred and fire spread was not contained at the FBN. Here we further develop this metric by calculating the burn-over probability for each individual fire, instead of calculating an average over all fires. The burn-over probability was then converted to the FBN success rate needed to stop the fire as:

$$\mathrm{SR_j} = \frac{\sum FL_{>x}}{\sum \mathrm{FL_i}} \times 100$$

where the SRj is the FBN success rate needed to stop fire *j* (hereafter simply FBN success rate), given as a percentage, FL > x represents the area close to the FBN with flame length high enough to potentially generate a burn-over, FLi represents all the flame length values of the pixels close to the FBN. The flame length considered for the occurrence of burn-over depends on the distance of the pixel to the FBN. Two levels of distance were considered based on the expected fire behavior described in Tedim et al. (2018): 0–500 m and 500–1000 m (Fig. 2). In the 0–500-m interval, we considered that a burn-over occurs for flame length values of at least 2.5 m, as such fires are considered very difficult to control and have a potential spotting distance of over 100 m. For the 500–1000 m burn-over was postulated to occur for flame length above 3.5 m, as the spotting distance can reach 1000 m. Similar values of flame length and distance were used in Benali et al. (2023).

Given that flame length was estimated for individual fire events, the burn-over probability was calculated individually for each fire perimeter. Hence, estimates of burned area, whether the fires were contained or not, and area burned at high intensity was calculated for individual fires. Note that, as illustrated in Fig. 2, the use of gridded flame lengths for individual fire footprints provided the spatial detail to consider localized fire behavior in the calculation of FBN success rate.

The benefits are also calculated continuously, from 0 to 100% FBN success rate. A value of 0% of FBN success rate means that all intersecting fires will not be contained, while a value of 100% of FBN success rate means that all fires that intersect the FBN will be contained, regardless of fire behavior. By providing this continuous scale of FBN success rate, we show the implications of co-implementing FBN and FTM for multiple levels of effectiveness and provide a probabilistic rather than deterministic approach.

Note that, when analyzing the benefits of co-implementing FBN and FTM, it is possible to have higher reduction in aABHI than in aAB, since a given site can still burn after fuel treatment mosaics (and maintain the aAB relatively unchanged), but it will burn at lower intensity in the treated area and its surrounding (Ott et al. 2023).

Estimating the expected benefits and synergies between landscape treatments

The independent effects of the two treatment archetypes were quantified by implementing only the FTM or only the FBN and measuring the response in terms of the reduction of area burned, reduction of area burned at high intensity, and increase in the number of fires contained. To estimate the benefits of implementing only the FTM, the fire spread simulations were carried out with the FTM treatments but without the FBN, i.e., by changing the fuel models where FTM treatments were located and without changing the fuel models where the FBN is planned to be implemented. Thus, since that in this scenario the FBN was not considered, the analysis of the intersections between the FBN and fire perimeters was not included. Then, we estimated the effect of implementing the FBN alone, i.e., without any FTM and considering the FBN success rate as explained in section "Response variables," on the same metrics. Summing the benefits of implementing the two archetypes isolated represents the cumulative benefits (sum of the parts). We estimated the synergistic effects of implementing FBN and FTM as the difference between the benefits attained

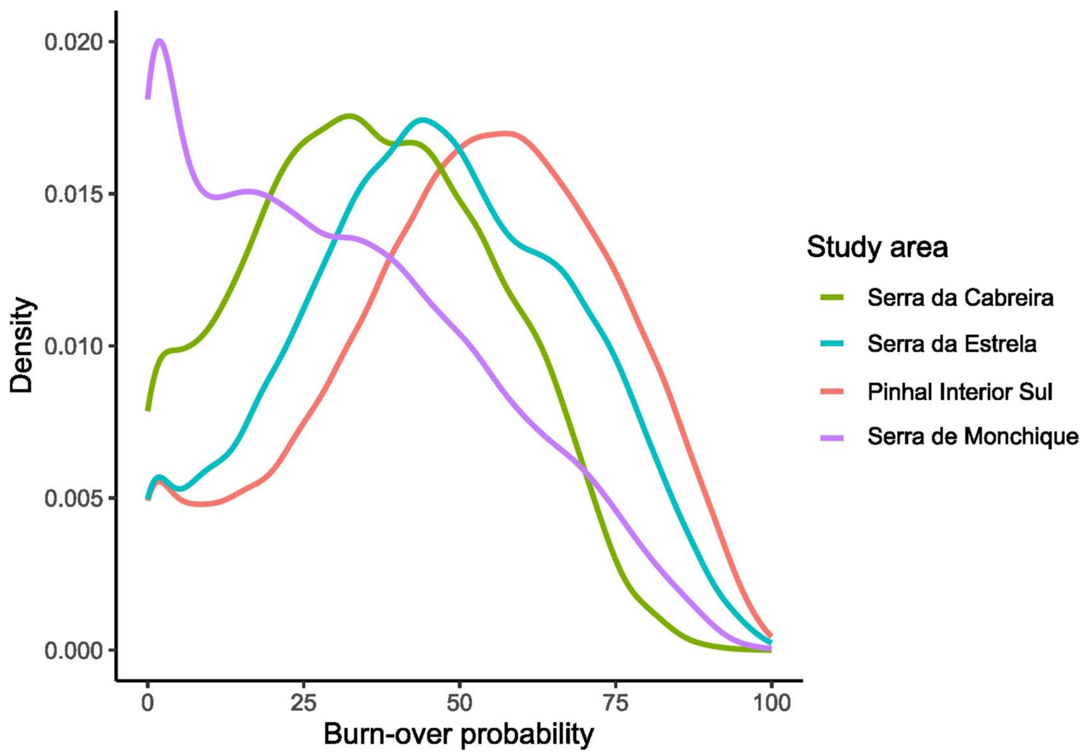

Fig. 3 Distribution of burn-over probability for all fires intersecting the FBN and for each study area. A burn-over probability of 0 means that fires are potentially easily contained, while a burn-over probability of 100 means fires potentially escape

when both are implemented simultaneously in their spatiotemporal extent and the sum of benefits when both are implemented individually (see Figure SM7 for details):

$$\text{Synergistic effect} = \text{Benefits simultaneous scenario-Benefits cumulative scenario}$$

When calculating the expected benefits when the two archetypes implemented alone (i.e., sum of parts, without accounting for possible synergistic effects), the same fires were simulated with both archetypes. Hence, to avoid accounting the same fire twice (i.e., fires originated in the same ignition point and under the same weather conditions that spread in the landscape with FBN or the landscape with FTM), only the smallest fire perimeter with the corresponding cell-specific flame length values was kept in the database. The resulting sum of the parts was then compared to the avoided area burned and avoided area burned at high intensity, estimated from the fire simulations with both the FBN and treatment mosaics. Hence, a higher difference when subtracting the sum of the parts (i.e., the two archetypes implemented alone) from the value obtained when jointly implementing both approaches represents a higher synergy between the archetypes, while a negative value represents an antagonistic interaction.

Results

Estimated burn-over probability

Figure 3 shows the estimated density distribution of burn-over probability distribution of all intersecting fires. Pinhal Interior Sul is the study area where the distribution of burn-over probability is shifted towards higher values of burn-over probability ($\bar{x} = 51\%$). This means that the majority of intersecting fires have high fire intensity and that more fires are expected to not be contained. Serra de Monchique is the study area where most fires have the smallest burn-over probability ($\bar{x} = 31\%$), despite some fires showing high intensity, illustrated by the long tail in the distribution. Serra da Cabreira also shows a relatively small burn-probability average ($\bar{x} = 36\%$), with the distribution showing that fires with a burn-over higher than 75% are extremely rare. Serra da Estrela shows a burn-over probability distribution and average between Serra da Cabreira and Pinhal Interior Sul ($\bar{x} = 46\%$).

Expected benefit of treatments

Figure 4 shows the predicted avoided area burned after implementing the FBN and the FTM simultaneously, following different success rate values, and considering the three location scenarios of FTM. A single value of benefits is shown per value of success rate, as it results from the sum of the effect of treatments for each individual fire.

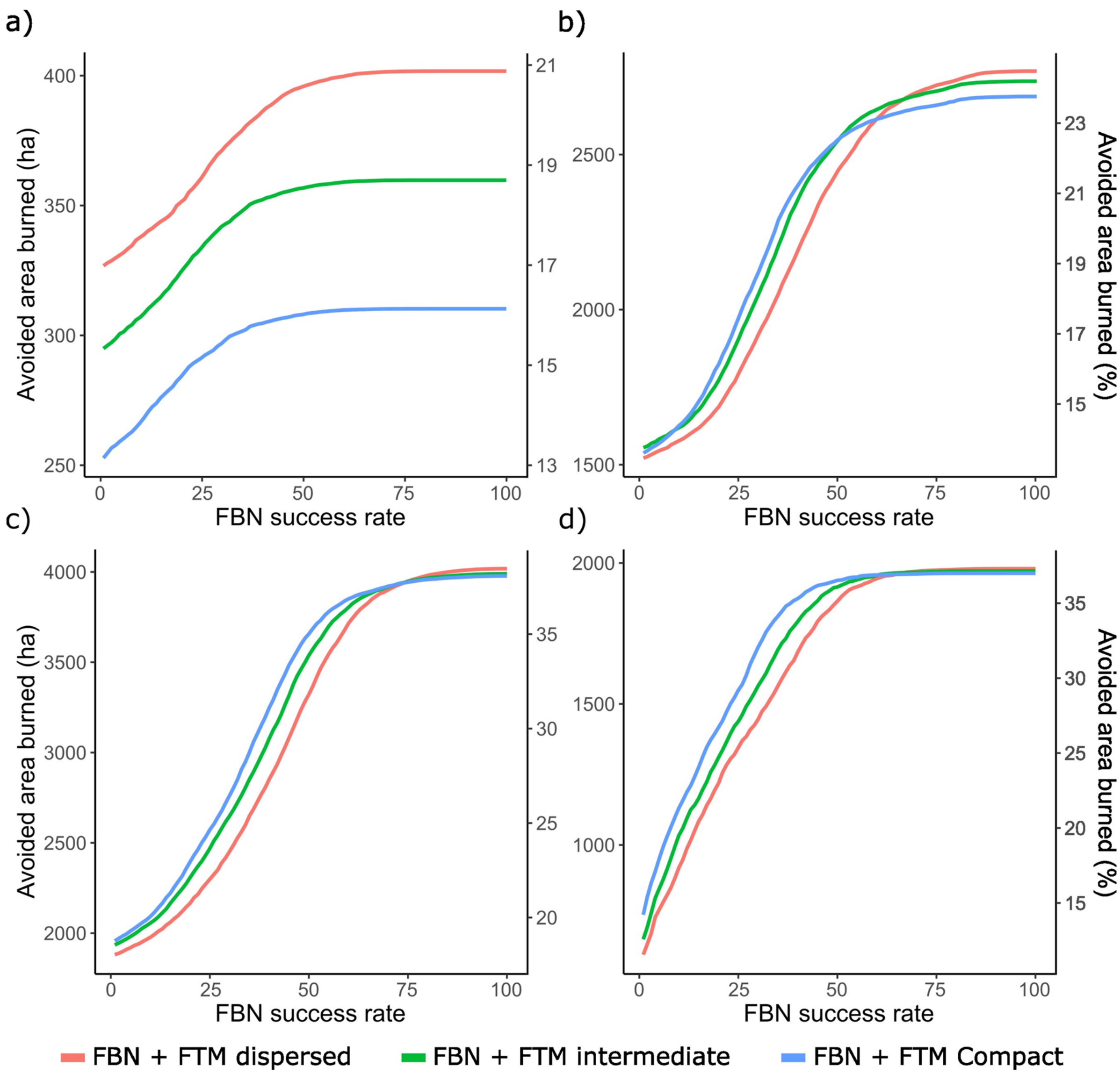

Fig. 4 Avoided area burned (ha on the leftmost *y*-axis and corresponding percentage of annual burned area in the absence of landscape fuel treatments on the rightmost *y*-axis) as a function of the FBN success rate, considering the three scenarios of FBN + FTM, for **a** Serra da Cabreira, **b** Serra da Estrela, **c** Pinhal Interior Sul, and **d** Serra de Monchique

From all the study areas, the Serra da Cabreira is the one with the smallest reduction in area burned (maximum of ca. 400 ha, which corresponds to a reduction of ca. 21% in the annual burned area of 1926 ha), and Pinhal do Interior Sul is the one with the largest reduction in area burned (maximum of ca. 4000 ha, which corresponds to a reduction of ca. 38% in the annual burned area of 10,459 ha; Table SM3). In Serra da Cabreira, the scenario that resulted in the highest reduction in area burned is "FBN + FTM dispersed," and the smallest reduction is with "FBN + FTM compact" (maximum difference of 91 ha corresponding to ca. 5% of the total burned area of 1926 ha). In this study area, all scenarios show a linear increase in the avoided area burned as the FBN success rate increases, up to a plateau of around 50%. In the remaining study areas, the scenario "FBN + FTM compact" shows the largest reduction in area burned when the FBN success rate is relatively small, followed by the "FBN + FTM intermediate" and "FBN + FTM dispersed", respectively. Placing more treatments close to the FBN ("FBN + FTM compact") instead of dispersing them across the landscape ("FBN + FTM dispersed") resulted in further reducing the annual burned area in up to 2% (238 ha), 4% (411 ha) and 5% (264 ha) of the total

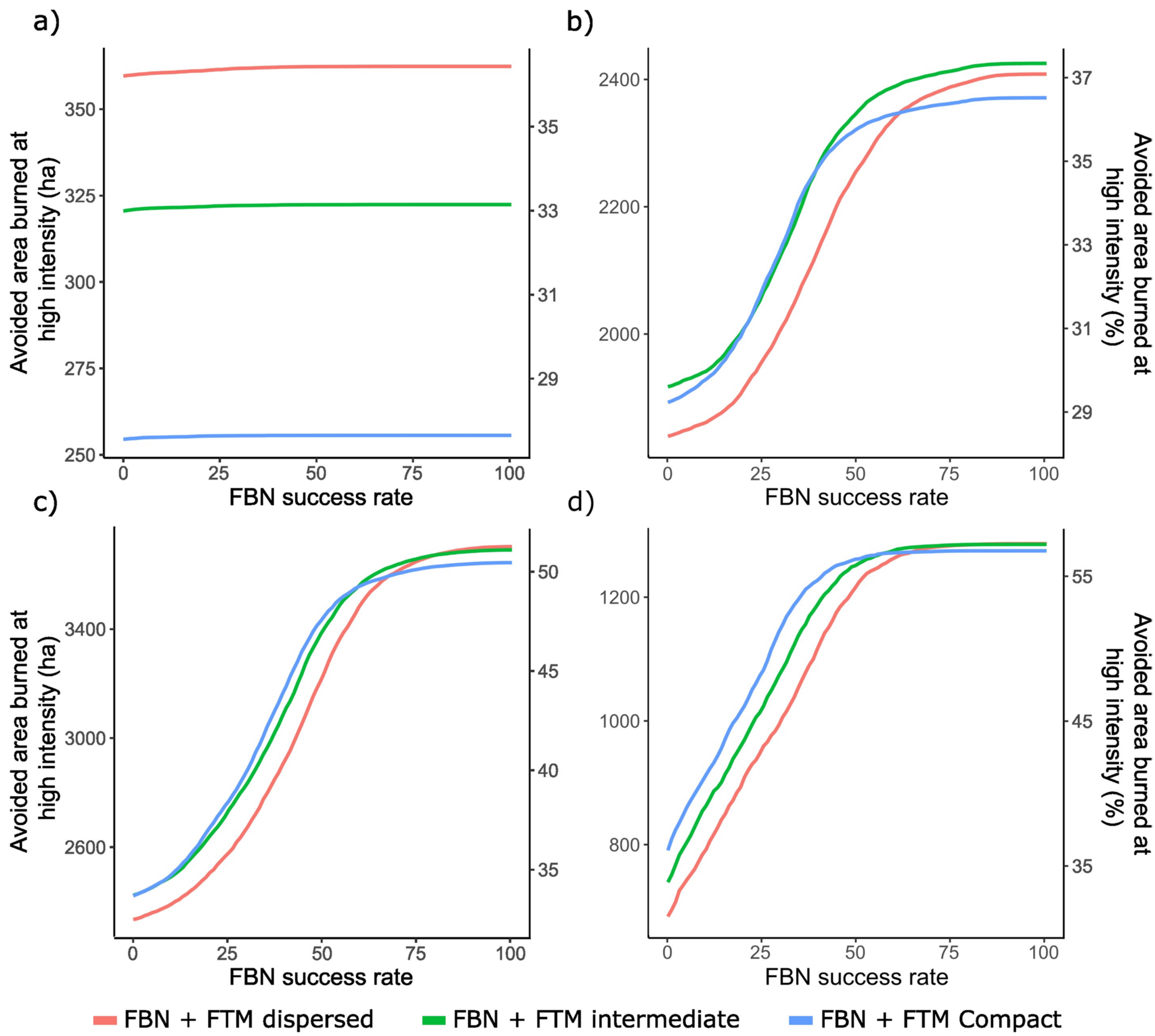

Fig. 5 Avoided area burned at high intensity (ha on the leftmost *y*-axis and corresponding percentage of annual burned area at high intensity in the absence of landscape fuel treatments on the rightmost *y*-axis) as a function of the FBN success rate considering the three scenarios of FBN + FTM, for **a** Serra da Cabreira, **b** Serra da Estrela, **c** Pinhal Interior Sul, and **d** Serra de Monchique

burned area, for Serra da Estrela, Pinhal Interior Sul and Serra de Monchique, respectively.

As the FBN success rate increases (i.e., as the FBN contains more high intensity fires), the difference between the scenarios decreases, until a crossover point is reached (except for Serra da Cabreira). The location of this crossover point depends on the study area and is due to the fact that as the FBN success rate increases, more fires are contained (even without the help of nearby mosaic treatments). Consequently, for high values of FBN success rate, almost all fires that intersect the FBN are stopped, reducing the relevance of placing treatment mosaics close to the FBN. Assuming that all fires stop when reaching the FBN, the scenario that reduces the most area burned is the "FBN + FTM dispersed," followed by the "FBN + FTM intermediate."

Figure 5 shows the predicted avoided area burned at high intensity after implementing the FBN and the FTM simultaneously. Again, the Serra da Cabreira is the one with the smallest reduction in area burned at high intensity (maximum of ca. 360 ha, which corresponds to a reduction of ca. 37% in the annual burned area), and Pinhal do Interior Sul is the one with the largest absolute reduction in area burned (maximum of ca. 3600 ha,

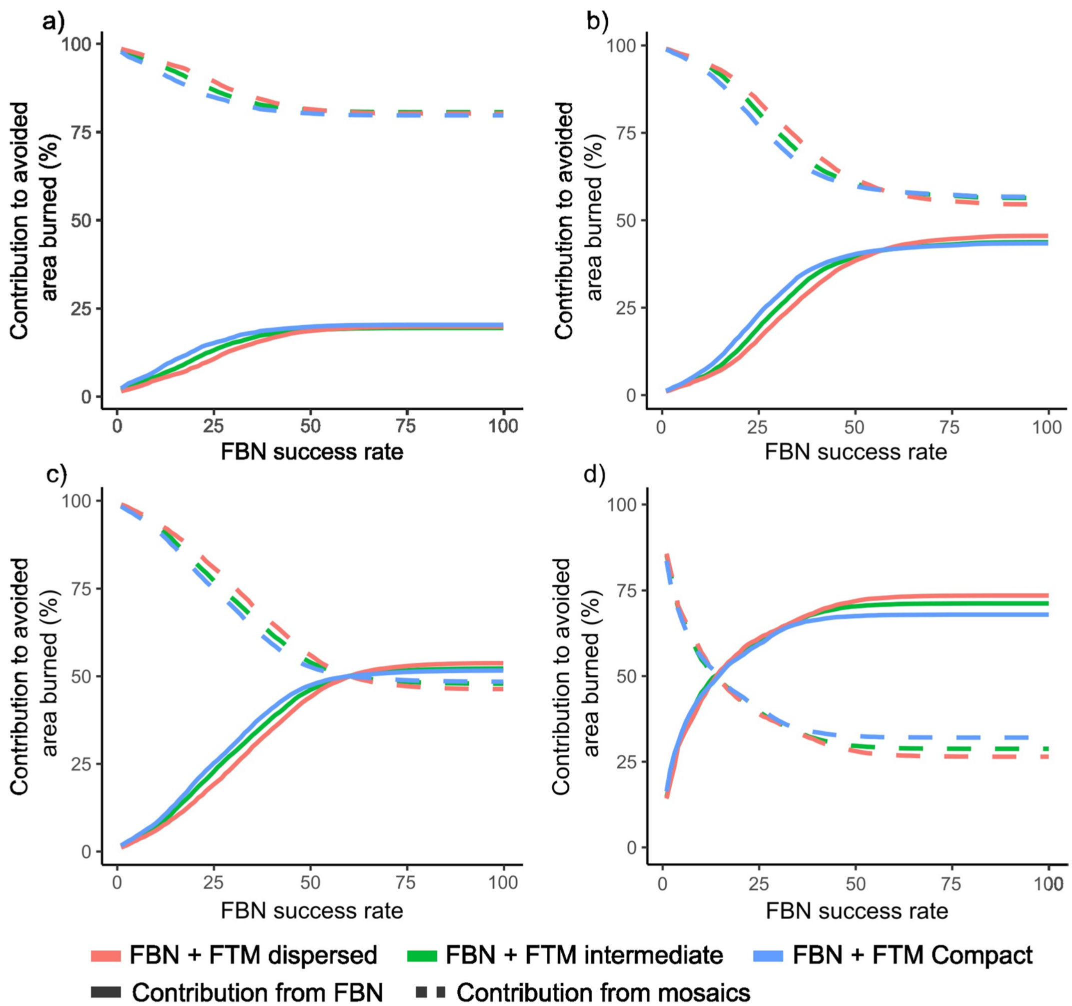

Fig. 6 Relative contribution of FTM and FBN to the overall reduction in burned area as function of FBN success rate for **a** Serra da Cabreira, **b** Serra da Estrela, **c** Pinhal Interior Sul, and **d** Serra de Monchique

which corresponds to a reduction of ca. 38% in the annual burned area), and Serra de Monchique the area with largest relative reduction (ca. 56%; Table SM4).

In Serra da Cabreira, the scenario that reflects the highest reduction in burned area at high intensity is the "FBN+FTM dispersed," with a difference of 74 ha (ca. 7%) to the scenario with the lowest reduction on burned area at high intensity ("FBN+FTM compact"). In this study area, and unlike the other study areas, the increase of FBN success rate does not reflect a significant increase in the avoided area burned at high intensity, as a result of its fire regime mostly characterized by pastoral burns, which show typically low intensity. For Pinhal do Interior Sul and Serra de Monchique, placing more treatments close to the FBN ("FBN+FTM compact") instead of dispersing them across the landscape ("FBN+FTM dispersed") resulted in further reducing the annual area burned at high intensity in up to 4% (270 ha) and 7% (147 ha) of the total burned area at high intensity, respectively. In Serra da Estrela, the scenario that reduced the most the area burned at high intensity for most of FBN success rate values was the "FBN+FTM intermediate" scenario, with a reduction of up to 2% (133 ha) of the total burned area at high intensity, when compared against the "FBN+FTM dispersed" scenario.

Relative contribution from mosaics and FBN

Figures 6 and 7 show the relative contribution of the FTM and FBN in obtaining the benefits illustrated in Figs. 4 and 5, as a function of the FBN success rate. Overall, as the FBN success rate increases, the relevance of the FBN increases as the result of a higher number of fires being contained when intersecting the FBN. For the same reason, the relative importance of the FTM decreases. When considering the reduction in burned area (Fig. 6), the FTM are responsible for the majority of the area

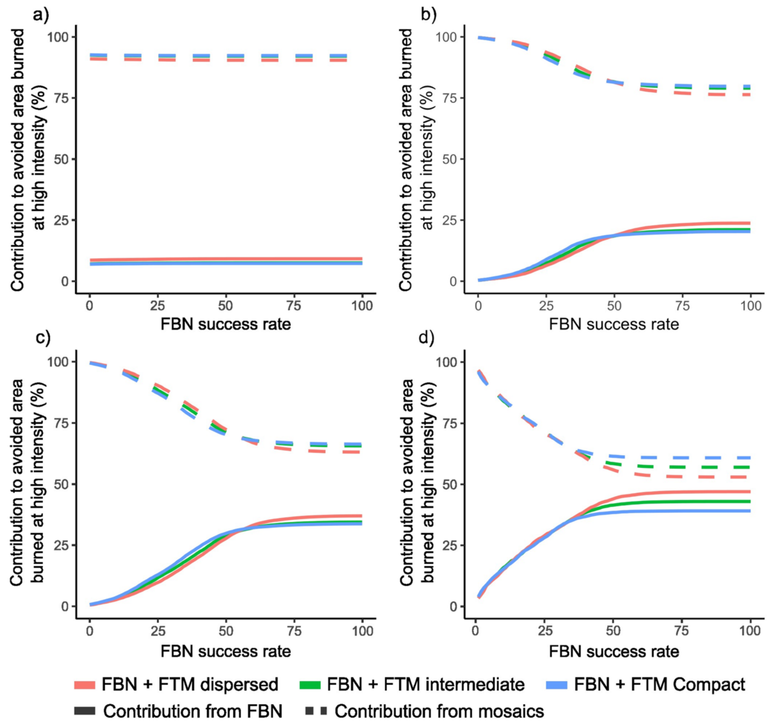

Fig. 7 Relative contribution of FTM and FBN to the overall reduction in area burned at high intensity as function of FBN success rate for **a** Serra da Cabreira, **b** Serra da Estrela, **c** Pinhal Interior Sul, and **d** Serra de Monchique

burned avoided in Serra da Cabreira, while the FBN is more important in reducing the burned area in Serra de Monchique. Both Serra da Estrela and Pinhal Sul show a more balanced contribution from the FTM and the FBN, with contribution values close to 50%. These results are independent from the scenario considered.

Relatively to the contribution of the two approaches in reducing area burned at high intensity, implementing FTM was found to be the most effective approach for all study areas (despite Serra de Monchique being more balanced than the other study areas—Fig. 7). This shows that FTM plays a greater role than the FBN at reducing the extent of area burned at high intensity, while the reverse happens when considering the reduction in burned area, particularly in areas dominated by large wildfires such as Pinhal Interior Sul and Serra de Monchique.

Quantifying the synergy between fuel treatments

Figure 8 shows the estimated synergy obtained from jointly implementing the FTM and the FBN, as a function of the FBN success rate. As explained above, the synergy represents the gain in the benefit from implementing the FBN with FTM, relatively to sum of benefits obtained with the two archetypes implemented individually. The magnitude of the synergy depends on the scenario considered and the FBN success rate assumed. The value of FBN success rate where the highest synergy was found is related with distribution of fires' burn-over probability showed in Fig. 3. The exception is Serra de Monchique, where probably the FTM are not located in the areas burned by fires with very low burn-over probability.

As expected, in all study areas except Serra da Cabreira when considering the avoided area burned at high intensity, the scenario yielding the greatest synergy is the "FBN + FTM compact," as most treatment mosaics are placed near the FBN. The synergy curves vary considerably between scenarios and study areas. For example, considering the avoided area burned in the Serra da Cabreira and Serra de Monchique, the curve rises quickly, indicating significant synergies even when considering conservative FBN success rate (i.e., assuming burn-over occurs even when only a small part of the FBN surroundings have large flame length values). On the other hand, the Serra da Estrela and Pinhal Interior Sul scenarios show a slower synergy increase, reaching the peak at higher FBN success rate values compared to the two scenarios mentioned above. Consequently, it is expected that effective synergy is more easily achievable in the Serra da Cabreira and Serra de Monchique scenarios, but with lower maximum synergy than in Serra da Estrela and Pinhal Interior Sul. We also estimated that the synergy between the two management archetypes is smaller for the reduction in

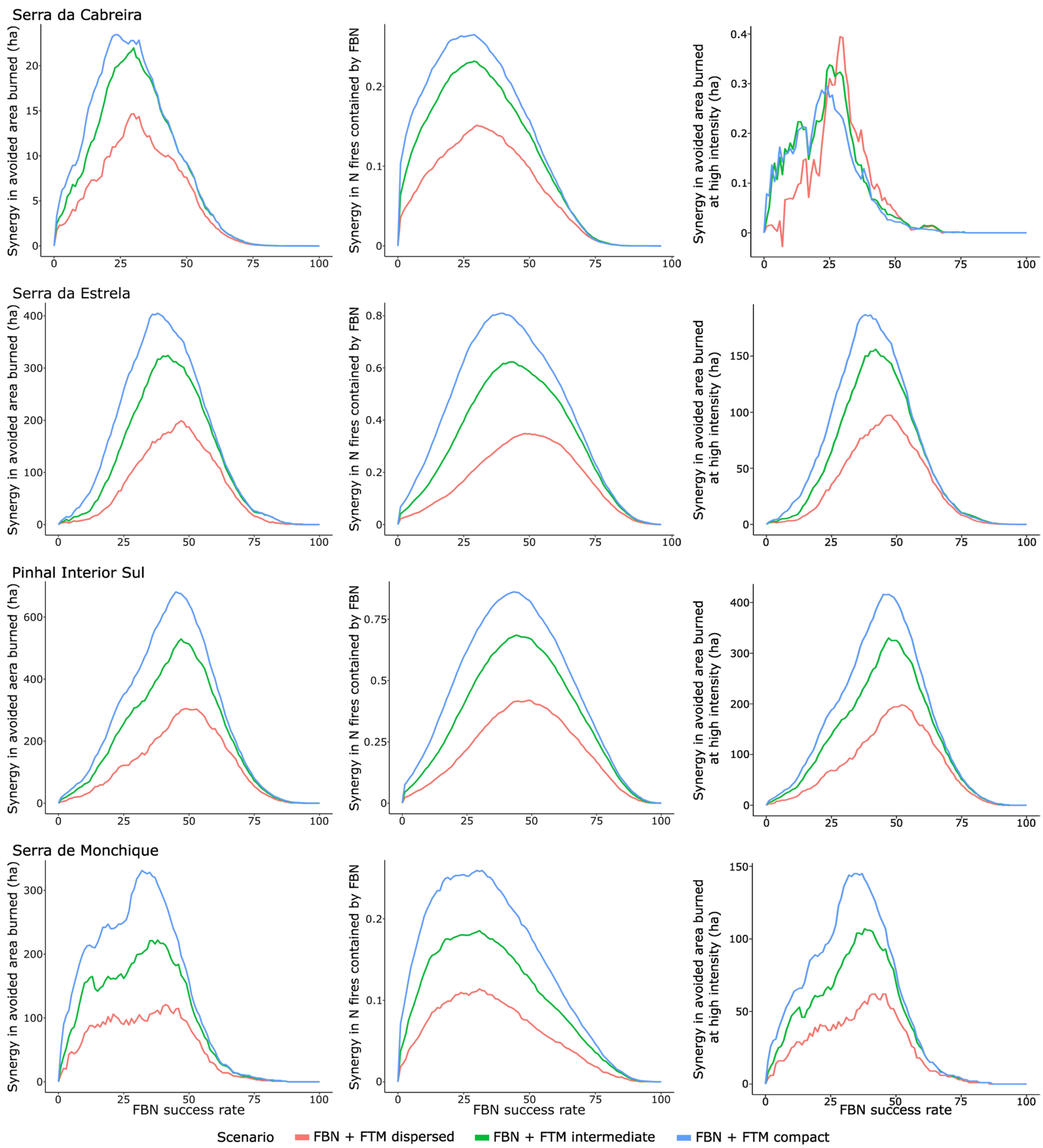

Fig. 8 Synergy between the archetypes of FTM and FBN as a function of the FBN success rate, for the average reduction in annual area burned (left), the average number of fires contained within the FBN (center), and the avoided area burned at high intensity (right)

area burned at high intensity than for the avoided area burned, and practically negligible in Serra da Cabreira.

Table 2 shows the maximum synergy for the three metrics and four study areas. Pinhal Interior Sul shows the largest synergies (maximum value of 681 ha of avoided area burned, 0.86 of number of annual fires contained and 416 avoided burned hectares at high intensity) compared to the sum of the parts value, followed by the Serra da Estrela, and the Serra de Monchique. Finally, the Serra da Cabreira shows the lowest synergy value. Note that when considering FBN success rate of 0 or 100%, the synergy ceases to exist, as it is assumed that no fire is

Table 2 Maximum synergy registered for each metric and study area. Values between parentheses represent percentage change compared to the total hazard without management. No percentage change is shown for number of fires contained as the FBN is not implemented under the default scenario

Study area	Maximum synergy			FBN success rate with max synergy
	Avoided area burned	N fires contained	Avoided area burned at high intensity	
Serra da Cabreira	23 (1%)	0.27	0.39 (0.04%)	24–29%
Serra da Estrela	405 (4%)	0.81	187 (3%)	38–40%
Pinhal Interior Sul	681 (7%)	0.86	416 (6%)	43–45%
Serra de Monchique	331 (6%)	0.26	145 (6%)	30–37%

contained or that all fires are contained within the FBN regardless of fire intensity.

Discussion

After decades of underinvestment in fire mitigation and prevention (Feo et al. 2020; Pandey et al. 2023), governments are now pushing for the implementation of ambitious fire management plans aiming at the reduction of fire risk. Current fuel management plans often rely on the creation or expansion of fuel break networks (FBN) and of fuel treatment mosaics (FTM) across the landscape. Although these archetypes are crucial and often co-exist within policy agendas, guidelines to optimize their simultaneous implementation are scarce to non-existent. Our results identify specific optimal co-implementation scenarios and synergies in terms of avoided area burned, avoided area burned at high intensity, and number of contained fires. Specifically, we found that placing FTM close to the FBN will potentially increase the percent intersected fires that can be contained (for a given FBN success rate), resulting in a reduction in area burned and area burned at high intensity. When analyzing the percent avoided area burned, fires contained and avoided area burned at high intensity, locating most of the FTM close to the FBN (i.e., scenario "FBN+FTM compact") resulted in the largest increase in FBN potential to be used to stop the fire, while locating only 25% of the FTM implemented close to the FBN (i.e., scenario FBN+FTM dispersed) will result in the smallest increase. This result, which is consistent across study areas, shows that placing more FTM near FBN reduces fire intensity in the treated and adjacent areas (Ott et al. 2023), and increases the likelihood that fires intersect a treatment mosaic before reaching the FBN (Aparício et al. 2024). This highlights the synergistic effect from combining the two archetypes.

As expected, the scenario where FBN and FTM are implemented simultaneously, with a larger number of mosaics are treated close to the FBN ("FBN+FTM compact") revealed the highest synergy for all hazard metrics and all study areas, while the scenario with the fewest mosaics close to the FBN (FBN+FTM dispersed) revealed the least synergy (except at Serra da Cabreira, for area burned at high intensity, where the synergy is negligible). The amount of avoided area burned due to the synergistic effect varies with the FBN success rate considered, and with the study area, yielding maxima ranging from 1 to 7% of the total burned area. The extent of avoided area burned at high intensity due to synergy between archetypes was found to be lower than the previous metric, ranging from ca. 0.04 to 6% of the total burned area at high intensity. Although the synergistic effect is higher when placing FTM close to the FBN, it does not necessarily mean "FBN+FTM compact" is always the scenario responsible for the greatest reduction in hazard.

When considering the overall reduction on burned area, our results show that significant benefits can be expected from implementing FBN and FTM simultaneously, with maximum reduction in burned area ranging from 21 (Serra da Cabreira) to 38% (Pinhal do Interior Sul) and a maximum reduction in area burned at high intensity ranging from 36% (Serra da Cabreira) to 56% (Serra de Monchique). We also show that placing treatment mosaics close to the FBN is of particular relevance in areas dominated by forest wildfires (Pinhal Interior Sul and Serra da Estrela), while dispersing the mosaics in the landscape is a more suitable strategy in areas dominated by pastoral burns (Serra da Cabreira). This result is in accordance with our expectation and with previous research that showed that FBN segments that are more important to reduce area burned (typically caused by large forest wildfires) are also those where a burn-over is more likely to occur (Aparício et al. 2022). The Serra da Estrela study area, which is characterized by a mix of forest wildfires, pastoral burns, cropland burns, and occasional peri-urban small fires, shows the highest reduction for the burned area when the mosaic treatments are concentrated close to the FBN, when considering low values of FBN success rate. When considering moderate values of FBN success rate, the balanced disposition of mosaic treatments (FBN + FTM intermediate) is the most effective at reducing burned area. Regarding the avoided area burned at high intensity, the results are similar to those of avoided area burned, but with a considerably lower contribution from the implementation of the FBN, and a higher importance of FTM. This reflects the higher importance of FTM in reducing fire intensity than area burned (McKinney et al. 2022; Ott et al. 2023).

Implications for management

The results of this study provide practical recommendations for improving fire management strategies. Considering that both FTM and FBN are needed as part of integrated fire management plans (Farkhondehmaal and Ghaffarzadegan 2022), understanding where FTM should be strategically placed close to the FBN, or where the mosaics should be spread across the landscape is valuable information which can ultimately contribute to a more efficient fire management strategy. We showed that fire mitigation efforts should be tailored to the specific needs of different regions, and how the ultimate management objective should influence actions on the ground. For example, in areas dominated by shrublands and by a fire regime other than characterized by forest fires, dispersing FTM in the landscape was shown to be particularly efficient, even more when considering the resprouting capacity of the shrubs (Xanthopoulos et al. 2006). In areas dominated by forest fires, the FBN may have a crucial importance in reducing the area burned, and locating FTM close to the FBN may enhance their effectiveness.

By combining different fuel reduction archetypes in a way that maximizes their effectiveness, fire management plans can better reduce fire hazard and risk. In this regard, it is relevant to note that the FBN reduces the extent of areas burned at high intensity by stopping fire spread, while the FTM mostly prevent fires from reaching high intensities, and thus facilitates their suppression. This difference implies that a strategy that relies only on stopping fires at the FBN will allow for continued fuel accumulation in unburned areas, which will result in a higher-intensity burning during future fire events—contributing to the suppression paradox (Ganteaume et al. 2021; Kreider et al. 2024). On the other hand, a strategy focusing only on the implementation of treatment mosaics will reduce fuel load and the area burned at high intensity (Ott et al. 2023), but will not decrease burned area as much as implementing the FBN (when assuming a fairly high FBN success rate).

Additionally, implementing extensive fuel reduction treatment mosaics will most likely require medium- and long-term socio-economic changes in rural areas (Canadas et al. 2023; Guiomar et al. 2023; Lecina-Diaz et al. 2023), as they need to be scaled up (Ott et al. 2023). This is particularly relevant when considering ongoing and projected climate change-driven increase in fire intensity (Wotton et al. 2017), and burned area (Barbero et al. 2015; Turco et al. 2018), and expansion of fire prone regions (Galizia et al. 2023).

There is also the expectation that implementing FTM close to the FBN will be cheaper and faster than dispersing them in the landscape, given the existence of roads in the FBN (Aubard et al. 2020; Thompson et al. 2022), granting an easy access to the treatment locations. Promoting FTM close to the FBN where they are most effective can ultimately release resources to disperse mosaics in areas where the FBN is not as relevant (e.g., in areas dominated by pastoral burning). Hence, the on-ground synergies of co-implementing the two archetypes are likely higher than those quantified in this study.

Finally, the results shown can be used to advocate for the need to deploy fire brigades to the FBN, as it is not expected that a fire would passively stop at the FBN (Gannon et al. 2023; Ortega, Silva, and Molina 2024). Nonetheless, in many countries fire suppression is largely limited to communities and nearby roads (Pereira et al. 2023), leading to the inefficiency of the FBN. Hence, without active suppression at the FBN, it is expected that the majority of fires will not be stopped (equivalent to a 0% FBN success rate), undermining fire management efforts. Notwithstanding, as more resources are deployed in the FBN, a greater number of fires are expected to be contained (equivalent to a higher FBN success rate), leading to a further reduction in area burned of up to four times and reducing the extent area burned at high intensity of ca. two times (at Serra de Monchique).

Limitations and future research

There are some relevant limitations of this study. For instance, fire spread simulations are affected by several sources of uncertainties, such as fuel, weather, and ignitions, that can have a large impact on the simulations (see Benali et al. 2016a, b). These models are also likely to underestimate fire behavior (e.g., flame length), especially during pyroconvective events. Other limitations are related with the methodology developed to access the synergies between FBN and FTM. First, it only considers the moment of the first intersection between the fire and the FBN to determine the probability of a burn-over. This means that if a given fire intersects the FBN at different stages of its spread, only the first intersection is considered (e.g., is either contained at the first intersection or the full fire perimeter simulated is considered, meaning that the fire was never contained). Although this is an important limitation, the alternative approach of calculating burn-over probability (or the resulting FBN success rate) for each fire perimeter at every intersection with the FBN would necessitate processing millions of interactions, making it prohibitive and impractical.

This study uses and further develops the metric of burn-over probability (Aparício et al. 2022) by estimating the flame length of each fire at the moment of intersection with the FBN. We acknowledge that this metric can be improved, as it uses only the flame length to define the burn-over probability (and FBN success rate) in each cell of the landscape close to the FBN, ignoring other crucial factors such as the angle at which the fire intersects the FBN (the head of fire is usually more intense than the flanks and tail; Ortega et al. 2024). Notwithstanding, the burn-over probability was calculated at several distances from the FBN, using flame lengths thresholds that can either generate spotting across the FBN or highly challenge suppression (Tedim et al. 2018). Additionally, the method of intersecting fire footprints with FBN assigns the benefits to individual fuel breaks independently, where coordination for implementing the FBN is not considered. Future work should incorporate the spatial and functional interdependence of fuel breaks to better reflect their collective role in fire containment.

FConstMTT model simulates independent fires that do not interact with each other. This means that it is not possible to simulate true fire seasons, hindering the assessment of inter-annual variability in the effectiveness of the fuel management archetypes (see, e.g., Ager et al. 2021). This limitation can be overcome in the future by forcing temporal scale in the model, namely by modifying the landscape after a fire spread (reflecting a fire occurrence), and by randomly sampling an annual burned area extent from the historical period.

Finally, we showed that fire mitigation efforts should be tailored to the specific needs of different regions. This assumed that there is a single best strategy for each region and ignore that different FBN segments may require different integration with FTM.

Conclusions

Both the implementation and expansion of fuel break networks (FBN) and fuel treatment mosaics (FTM) are being proposed as cornerstones of fire management strategies across nations. Nevertheless, guidelines for their co-implementation have been largely absent and the potential co-benefits of co-implementing them was never quantified. This research highlights the synergies between the two architypes and how fire mitigation efforts should be tailored to different regions and to different management objectives.

We showed that placing FTM close to FBN significantly improves fire containment, reduces the area burned, and minimizes the area burned at high intensity, and should be mainly used in areas characterized by large and intense fires. On the other hand, in areas characterized by pastoral burns or shrublands, should disperse FTM across the landscape resulted in more effective strategy. Combining the two architypes resulted in a synergistic effect in reducing fire hazard, with the magnitude of benefits depending on regional fire regimes and landscape characteristics.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-025-00386-z.

Supplementary Material 1: Figure SM1 – Historical burned area (ha) in a) Serra da Cabreira (annual average of 1926 ha), b) Serra da Estrela (annual average of 11322 ha), c) Pinhal Interior Sul (annual average of 10459 ha), and d) Serra de Monchique (annual average of 5316 ha). Figure SM2 – Number of fires in a) Serra da Cabreira, b) Serra da Estrela, c) Pinhal Interior Sul, and d) Serra de Monchique. Figure SM3 – Percentage of land use classes per study area. Figure SM4 – Location of the study areas and the pyro-regions used in the fire spread simulation. Figure SM5. Landscape fuel management archetypes. Figure from Ager et al. (2013). Figure SM6 – Spatial representation of the three scenarios simulated in each study area. The treated area is constant between scenarios. Figure SM7 – Illustration of the expected effect of implementing FBN and FTM together versus implementing them independently.

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Authors' contributions

B.A.A. – Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; A.B. – Conceptualization, Methodology, Writing – review & editing; A.A. – Conceptualization, Writing – review & editing; J.M.C.P – Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests

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